Teleoperated Robotic Arm for Medical Applications using Internet of Robotic Things (IORT)*

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Abstract*– Humans live in a world of technology. We aim to recruit improving technology in saving precious humans' lives and time. This project is a robotic arm to be controlled remotely over the internet using wear on the human arm giving the full range of motion and degrees of freedom. The project will be used where human control is needed yet isn't available. It will help save time in medical applications and replace the human presence in dangerous zones. Concerning the medical industry; it has first been introduced in the 1980s by Canadian physicians and was used to perform eye surgery. The use of the project is vital when medical interference is needed in crucial times but the traffic or any reason preventing the doctor from reaching the patient is present. It should also be considered that in case of a global pandemic, such as Covid-19, the doctors themselves are also subjected to danger when put in direct contact with the patients, and hence the treatment process could be from distance in such cases.

I. Introduction

To be able to get to the final product, we had to go through several steps. Starting with studying biomechanics and how the human arm works and recruiting this information to be able to complete the mechanical design of the arm and finally apply mechatronics engineering and integrate the electronics with the physical, hardware design created. It should be noted that this project relies on the concept of the Internet of Robotic Things. We have designed two separate subsystems; the first being the gloves worn by the operating human and the robotic arm itself. Both subsystems are connected -where the human controls the robotic arm- through the internet of Robotic things.

While planning any mechatronics project and reaching the final step of implementation, we are required to start by brainstorming the different ideas of the projects that have been carried out and extract the information we require to produce the desired work. As we know our project is the "Tele-operated Robotic Arm in medical applications using the Internet of robotic things". Therefore, we have based our research on different types of robotic arms, each serving a different application including the medical one. The main four robotic arms we have looked into were the pollen robotic arm, the Deka robotic arm, the Da Vinci robotic arm, and the hydraulic robotic arm. Everyone with different functions, theories of operations, sensors, actuators, and end effectors. Our target was to produce the perfect robotic arm based on design, material, cost, sensors, actuators, and degrees of complexity.

Starting with the pollen robotic arm, it is made of 3D printed material. 3D printing is usually either PLA, TPU, or NYLON. As we know, the 3D printed material is much lighter than any metallic material and also helps decrease weight by supporting the design with openings as shown below. The opening support as well the concept of air ventilation in case of any overheating occurring. [1]

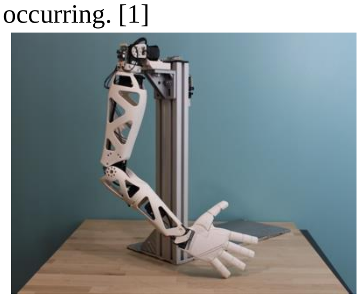

Fig. 1 Pollen Robotic Arm

The following robotic arm is the Deka robotic arm. This robotic arm has been made and used in the food industry. It is supporting the fact of avoiding labor usage when speaking of pick and place or other uses. For the robotic arm to be useful and certified, it has been revised by the Food and Drugs Administration to ensure perfect safety and burnished food. The Deka robotic arm has 10 degrees of freedom actions with significant accuracy involved. All the actions are controlled by the MYO armband which senses precise movements and base upon it signals are sent to perform the same task. [2]

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Fig. 2 Deka Robotic Arm

The Da Vinci robotic arm on the other hand has provided the most helpful service for the medical industry. The Da Vinci organization has made the most accurate robotic arm that can perform work not done by surgeons themselves and avoid faults and failures appearing. It is based on the parallel configuration which describes the easier movement of the end effector without being forced to move the entire links of the robotic arm, unlike the series configuration as the pollen robotic arm and the Deka robotic arm. [3]

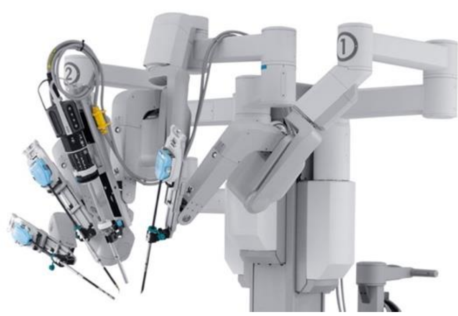

Fig. 3 Da Vinci Robotic Arm

II. Mechanical design

Fig. 4 Robotic Arm

It should be noted that to design this project and the shown robotic arm, we had to study the biomechanics of the human body and especially the arm to have a deep understanding and hence we would be able to design and create an arm to imitate exactly the human arm movement. As shown in Figure 4, the design is based on the shape of a human arm. At first, the strain wave gear and the first differential play the role of the human shoulder. The second differential then performs the function of the elbow and finally the forearm and hand look and act exactly like the human one. In the next sections, each of the mentioned parts will be explained in more detail.

A. Harmonic Drive

The strain wave gear is the first component to start the reduction mechanism to increase the torque. It is based on harmonic drive motion and is considered one of the most expensive mechanical components in real life. The assembly of the strain wave gear is shown in Fig-5, Fig-6, and Fig-7. Concerning the mechanism and how it works, the basic components we are using inside are gears. For the gears to function accurately with reduced friction and precise movements giving us the torque needed, we have placed bearings of sizes we have chosen based on the strain wave gear design. The figures below show the details of the strain wave gear internally and externally and how it is connected to the first differential in a way without falling off. Bolts are used to help connect both parts carefully as well. [4]

The harmonic drive strain wave gear is considered the main and most important component in our robotic arm providing the first motion by the NEMA 23 stepper motor and initially starting the torque reduction needed. The theory of operation is simply involving the drive on the input shaft, the flex gear, and the ring with internal gears as the output shaft of the strain wave gear. the harmonic drive is supposed to be designed as an ellipse shape to help supply the initial movement. The next step is the flex gear which is manufactured differently from the rest of the parts and made of TPU 3D printed material as it is much flexible than the PLA and NYLON. The flex gear is 2 teeth less than the internal gear ring for the motion to be transferred to the output shaft, and by that, we name the harmonic drive strain wave gear as the most essential component in the robotic arm providing the starting movement of the arm.

Fig. 5 Flex Gear

Fig. 6 Strain Wave Gear Extraction

Fig. 7: Strain Wave Gear

B. Differential

The differential includes the planetary gears, the bevel gears, different types of bearings, the NEMA stepper motors, belts, and pulleys. The main movement is generated from the strain wave gear. The motor connected in the strain wave is the NEMA 17 stepper motor. The value of the torque produced from the stepper motor is 4.563 Nm, after calculating the proper actuator sizing of the motor we were required to study the parameters of the motor. The research we have made proved that the strain wave gear itself produces a better torque than when placing the motor standing alone. The motor then passes the torque to be increased by the pulleys and belt connected. The robotic arm is designed mainly for medical applications; however, in the long-term plan we aim at using it in other industries that can require the arm to carry heavy objects, hence, we should increase the torque produced from the driving motor of the strain wave gear for the robotic arm to be able to hold the object and maintain stability.

In the belt formation, we have placed the component called tensioner to adjust the tension of the belt. The shaft at the end of the belt is connected to the pulley which then passes the energized torque to the sun gear. The sun gear is a part of the planetary gear. The bevel gears follow the planetary gears by combining the other half of the differential, but the main reason is to control the movement of the first differential which is considered the shoulder of the robotic arm. The bearings are responsible for reducing the friction between two components and allow smoother rotation, and by that, it cuts down the amount of energy consumption. Fig-8, Fig-9, and Fig-10 below show the differential as a standalone system, its exploded view, and the differential as a part of our system. [5]

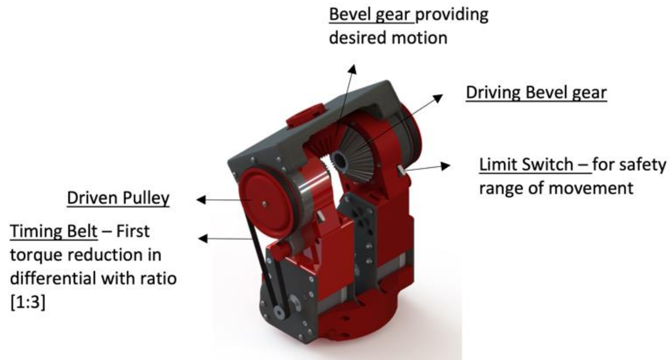

Fig. 8: Differential

Figure 9 shows the unfastened differential making it clear for the user that it includes the shown components. The stepper motor as shown is placed in the bottom of the differential to transfer the motion into the driving pulley, where the belt receives and maximizes the torque by three times for the larger pulley to pass on the motion to the planetary gears. the planetary gears then multiply the torque produced by the timing belt five times. Bearings are used almost everywhere for the smoother movement of the components. The type of lubrication we have used was grease, as we have chosen it based on the bearing tables for accurate movements.

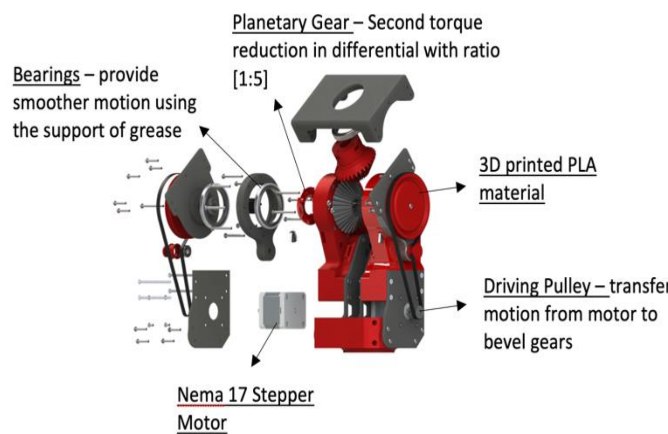

Fig. 9: Differential Extraction

The following figure clarifies the way of holding the entire system including the robotic arm and the stand. The box is made of steel to equalize the weight exerted by the parts it is holding. The box is also useful for carrying electrical components such as power supplies and microcontrollers. A camera is placed on the top for visualization into the VR for real-life usage.

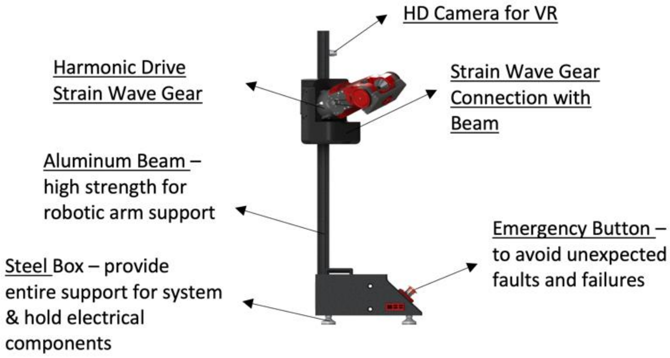

Fig. 10: Assembly with Strain Wave Gear and 1st differential

C. *Forearm and Hand*

The forearm and hands were designed to look and act as humanely as possible. Considering the fingers or hand itself; it was one of the most complicated parts. Hence, we have spent much time thinking of a design that works specifically on our robotic arm function. We got to the conclusion shown in Fig 11. The hand and fingers are made of acrylic material which supports the lightweight idea of the robotic arm. A special mechanism is used for the fingers to achieve an exact movement. 5 servo motors are used for the fingers and 1 servo motor is used for the wrist. All servo motors are controlled by the flex sensors placed on the second subsystem.

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Fig. 11: Forearm and Hand

D. *Materials*

Concerning the materials used, the robotic arm is mostly made of 3D printed materials. We have used PLA and TPU as the main ones, where TPU is used for the flex gear used in the strain wave gear and the PLA is almost used for the rest of the differentials and the rest of the strain wave gear. However, the fingers are made of acrylic plastic. As we know, acrylic is lighter than PLA which benefits us as the hand is placed at the end of the robotic arm which supports the moment concept affecting the weight.

E. *Support Box*

The support system -shown in Fig 12- of the robotic arm has been designed to hold the weight exerted and the electrical components to be placed and arranged correctly. The box is made of steel to provide the weight needed to equalize the weight applied on top, while the beam is made of aluminum to help decrease the weight and at the same exact time hold the robotic arm accurately.

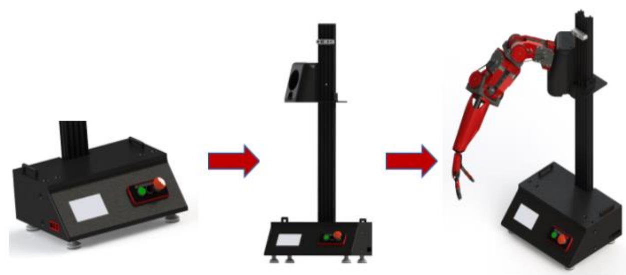

Fig. 12: Support Box

III. KINEMATICS

A. *Introduction*

Kinematics is the branch of classical mechanics that describes the motion of points, objects, and systems. The reason we had to tackle kinematics in our report is that we are working on a robotic arm and we need to know the motion of its components; whether by forward kinematics or inverse kinematics. To solve the arm kinematics, we will need a sketch and an understanding of the motion of the arm, and to know the degrees of freedom and hence be able to define the different present joints; and whether they are revolute joints or prismatic joints.

MATLAB software was used after following the Denavit-Hartenberg method was able to compute and find out the parameters needed, we will turn to computer software to help us determine and visualize the motion of the arm. [6]

B. *DH Convention*

Forward kinematics is a transformation matrix used in order to compute the relationship between the joints of the robot manipulator and the position and orientation of the end-effector. On the other hand, we have the inverse kinematics which is used to calculate the joint parameters needed from the position of the end-effector. In our case, we are required to apply the forward kinematics on the robotic arm which consists of 7 degrees of freedom motion. The first step is to draw the frames based on the DH convention. It's a convention used to select frames of reference in robotics applications and it was introduced by Jacques Denavit and Richard S. Hartenberg in 1955.

Concerning the theory of operation, it consists of 4 parameters which are associated with a particular convention for attaching reference frames to the links of a robotic system. Shown in Fig-13 is the frames drawn with the DH convention, while table 1 shows the parameters in the table according to the frames shown in Fig-13. Finally, Fig-14 and Fig-15 show the use of computer software MATLAB in the forward kinematics procedure to find and plot the position of the end-effector. [7]

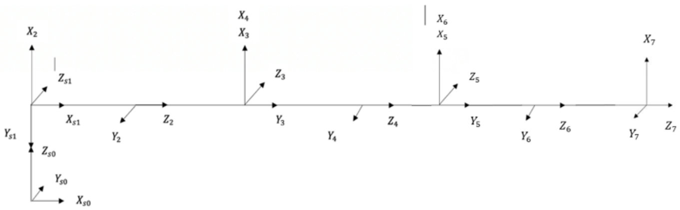

Fig. 13: DH-Convention

TABLE 1
DH CONVENTION PARAMETERS

i	θ	d	a	α
1	θ_1^*	L_1	0	$-\frac{\pi}{2}$
2	$\theta_2^* - 90^o$	0	0	$-\frac{\pi}{2}$
3	θ_3^*	$L_2 + L_3$	0	$\frac{\pi}{2}$
4	θ_4^*	0	0	$-\frac{\pi}{2}$
5	θ_5^*	$L_4 + L_5$	0	$\frac{\pi}{2}$
6	θ_6^*	0	0	$-\frac{\pi}{2}$
7	θ_7^*	L_7	0	0

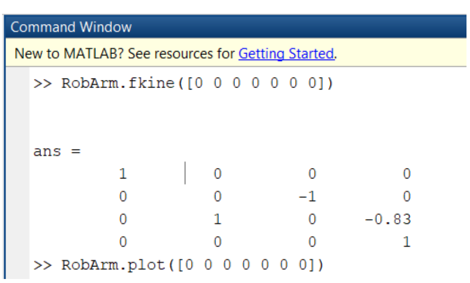

Fig. 14: MATLAB code

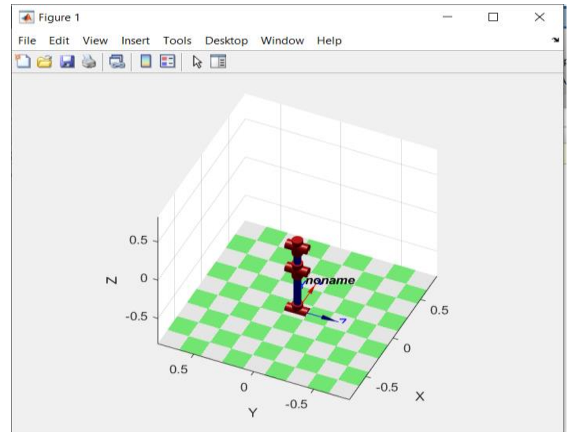

Fig. 15: Plot

IV. CONTROL

A. Control Schematic

The arm works on the MQTT protocol which is an IoT (Internet of Things) protocol. As shown in the schematic below in fig-16, the system is divided into 3 parts. The left-side part (the human arm) uses VR technology to have the same view as the robotic arm. It relies on sensors converting the physical human movement into electrical signals which are then sent to a programmed microcontroller connected to the internet to send the data (human arm movements) to the MQTT server -which is the second part of our system.

The MQTT server receives various messages from both sides (human and robotic arms) and depending on the topic in which this message is published, it sends its content to all the topic subscribers. Now the robot arm side receives the data through the server and acts upon it using the mechanical and electrical configuration in the system to provide 6 degrees of freedom alongside the individual fingers' movements. The process is showcased on an LCD attached to the robotic arm box

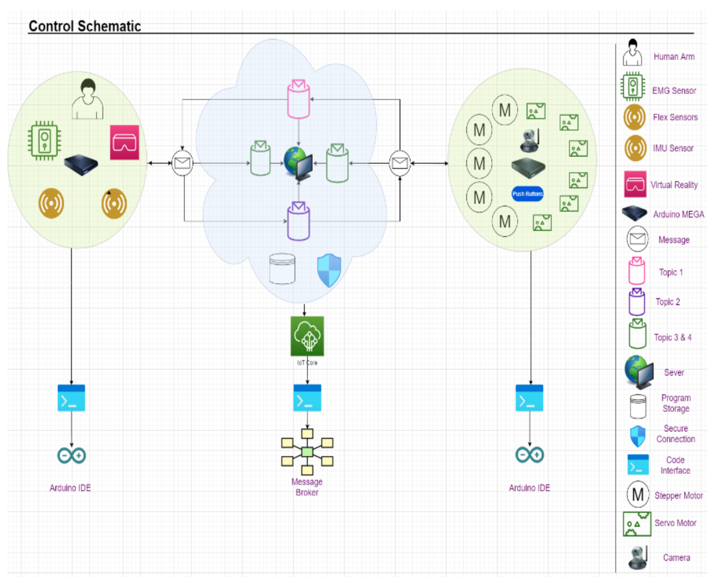

Fig. 16: Control Schematic

B. *Internet of Things*

If we were to dig into the terminology, we will find that it's quite self-explanatory, it's an integration of the internet, data analytics, and processing to our real world. IoT brings the power of the internet, data processing, and analytics to the real world of physical objects. We can say that the IoT is the place where the physical world meets the digital world in this hyper-connected world we live in.[8] Many devices are created to be a part of a global IoT or a local IoT, however, this does not mean that if an object or a machine that has been already created without that purpose in mind, cannot serve the network. In this case and project, the "thing" to be controlled or added to the internet of things is the robotic arm which is to be controlled.

C. *MQTT*

The message queuing telemetry transport; it's a publish/subscribe messaging protocol. The reason we chose this protocol is that it would offer lightweight data transport since it's a lightweight protocol (meaning that it's simpler, easier, and faster to manage than other communication protocols) and this is its most common use and it is exactly what we need in our project. Lightweight protocols also tend to perform faster than other protocols as they leave out unessential data and use compression techniques with the data communicated. Another advantage that has led us to use MQTT is the fact that it's supported by a lot of popular programming languages through open-source implementations. [9].

The protocol needs to define two types of entities in the network; a message broker and a client. Any device used on the network to receive all the messages from the clients and sends these messages to the appropriate receivers is a message broker. On the other hand, we have the client, which is any device used to interact with the broker; whether by sending or receiving messages. This happens through a series of steps, starting by establishing the connection between the client and the broker. Next, the client subscribes to any topic. And other clients could subscribe to this topic as well.

Next, any client could publish a message under a certain topic (by sending the topic and the message to the broker) and then the broker reroutes these messages to all the clients subscribing to this topic. To have a deeper understanding of this protocol, we will apply it and explain it by seeing it in action in our project. As shown in Fig 16, in the control schematic that we have 2 clients, the human slave arm being the first client and the robotic arm being the second client while maintaining one server only which is the message broker shown in the schematic.

Inside the cloud shown in the upper part of the figure, we can see the server surrounded by 4 symbols, these symbols refer to the topics present in the system. It should be noted that the presence of the topic doesn't necessarily mean that the topic is always being used and always have messages being routed to and from it. Considering the topics shown, the most important topic is the topic in which the slave human arm client publishes the sensors' readings.

The microcontroller collects and processes the data from the sensors shown and then publishes it in that topic. Obviously, the robotic arm client is programmed to subscribe in that topic which means that the message broker gets to route the messages shared in this topic into that client. After the microcontroller on the robotic arm side receives the data, it sends the suitable signals to the actuators according to the signals it has received in order to copy the exact movement made by the human arm.

There are 2 topics which are used to declare whether or not the client is still up and running on the system. This means that maybe the human slave arm system is working but the operator is yet to make any movement, this will result in the sensors topic to be idle with no messages published and might cause inconvenience in the system and not being able to find out whether that is a problem with the system or just simply a lack of movement by the operator. At this point, the mentioned topics help in such a matter.

Each microcontroller is programmed to send a message in the respective topic with a timer to indicate the presence and the readiness to send or receive any data. In the event of the absence of this message, it would be very simple to point out the problem and know that it is not about the lack of movement of the operator, at which point the troubleshooting process starts.

D. *Process*

The Flowchart of the process of how the system control works and how the integration between both subsystems take place is shown in Fig-17.

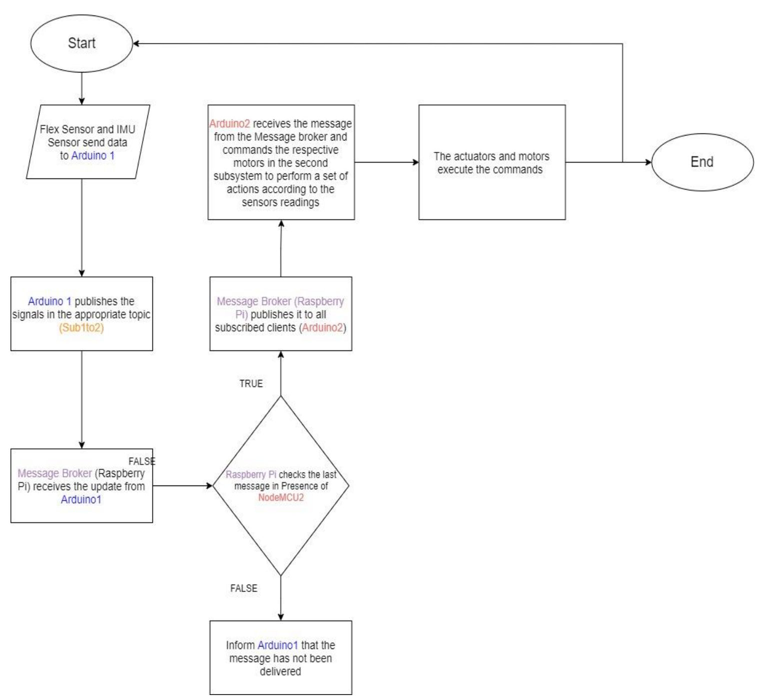

Fig. 17: Flowchart

V. Conclusions

The world has witnessed the introduction of autonomous and semi-autonomous robotic arms in the industrial field. It's about time the field gets a literal human arm control of the robotic arm. It's a huge advancement in this field since the robotic arms present are either completely autonomous, semi-autonomous, or manual control allowing partial human intervention using push buttons or various input devices. However, with this robotic arm, human intervention is present with the human arm itself being the input device. Human intelligence is merged with tireless machines to obtain the desired result.

The results achieved through the work in the project is a robotic arm to be controlled using IORT aimed to imitate exact human arm's movements (6 DOFs) and operate in zones where humans aren't safe in or take a certain movement from a professional in a medical field for example. Advancing technology is recruited (such as VR) to serve the project and ease the control process for the human in control through giving him a full virtual view of the environment and surroundings of the robotic arm. In Fig 18, 19, and Fig 20 both subsystems are shown in operating mode next to each other with the robotic arm imitating the exact position and orientation of the slave human arm. It should also be noted that in Fig 20, the operator is wearing the VR referred to earlier in this paper. The Virtual Reality option is able to give the operator a better sense of the environment around the robotic arm in which he is operating.

Fig. 19: Real-Life Presentation of the project. (2)

Fig. 18: Real-Life Presentation of the project. (1)

Fig. 20: Real-Life Presentation of the project. (3)

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