Building a Robotic Arm to Automate the Process of Patient Care “Measuring Vital Signs” During Coronavirus Pandemic

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***Abstract*—*Objective*: The purpose of this project was to build a fully controlled robotic arm that could reduce the risk of infectious diseases transmission especially coronavirus to frontline medical staff by making them able to perform their tasks such as measuring vital signs without being in a close distance with the patients. *Methods*: A humanoid right robotic arm from plywood sheets consisted of four links of different lengths. The healthcare robotic arm had four Degrees of Freedom (DOF). The total arm length was 60 cm with four continuous servomotors. We simulated the arm by AUTOCAD at first to test the mechanism capabilities. We inserted XYZ point of the position we wanted the arm to move. Using inverse kinematics in MATLAB simulation, we got some angles. We converted the resultant angles into Pulse Width Modulation (PWM) by using excel sheet to map the angles into PWM. The motors stopped at the wanted position using bang bang control. *Results*: The arm could reach any inserted point within the range of the DOF. *Conclusion*: In summary, we built a fully controlled prototype for a humanoid robotic arm to assist the medical staff. *Significance*: The proposed robotic system can help all medical staff in the fighting against the outbreak of the coronavirus by protecting them from infection, thus reducing the burden on them and protecting them from the virus.**

Keywords—Covid-19, infectious diseases, pandemic, vital signs, healthcare robotic arm.

I. Introduction

COVID-19 has no mercy in threating people’s lives all over the world. Nationally, statistics from World Health Organization (WHO) had shown that 282,582 confirmed cases with 16,332 deaths from 3 January 2020 until the end of June 2021 [1]. There are many Healthcare workers “HCW” in any healthcare facility who struggle against this pandemic as they are in a close contact with the infected individuals while performing their work. Covid-19 catches several HCWs and causes severe acute respiratory syndrome coronavirus “SARS-COV” and the result is death. Globally, over 10,000 HCWs in Africa caught coronavirus according to the WHO reports until September 2020. This number is still in an increase and reaches 570,000 cases in 37 nation - including Egypt- with 2500 dead HCWs. In Egypt, there are 750 infected HCWs with 56 dead ones [2].

Putting masks, keeping physical distance and other extra precautions of personal hygiene to cope with the changes in our daily life because of the outbreak of covid-19 are not enough as HCWs have to contact with patients directly for example when taking a blood sample from the patient. Robots are a magical solution to reduce the risk of spreading coronavirus and to save many HCWs from catching the virus as we can depend on them in disinfecting hospitals, delivery of food and drugs, and collecting vital signs [3], [4].

We aim to build a robotic arm that related to what we face during the period of Covid-19 to assist the medical staff in doing some of their tasks in a fast and safe manner, thus not only protecting them from the virus but also reducing the burden on them. A healthcare robotic arm can significantly reduce the risk of infectious diseases transmission to frontline HCWs by making them able to perform their tasks without being in a close distance with the patients. Building a healthcare robotic arm can automate the process of patient

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care at any time especially during coronavirus pandemic directly and safely. We are mainly focused in the control of the arm which will make a lot of functions like any nurse such as measuring the patient's vital signs like patient's temperature and heart rate.

We build a right robotic arm with four motors that attached to a fixed body. First, we insert the XYZ point of the position I want move the arm to. Then we pass the point to inverse kinematics using MATLAB that produces angles as each motor has its angle. The motors moves with PWM, so we convert the angles into PWM. Bang-bang control is suitable for our motors to stop it at its certain position depending on the feedback of its magnetic encoder. After the previous steps, we move the motors to its destination and stop at it.

II. MATERIAL AND METHODS

A. Mechanical Calculations and the Prototyping Material

Initial design from plywood sheets to test motor capabilities and the mechanism performance. In the real life, the fabricated arm with motors and plywood material weighed 0.65 kilograms. We calculated the max load or force by dividing torque over distance; take the shoulder motor for example, as it was the most important motor due to carrying the whole armload. The torque of this motor was 30 kg.cm and the whole arm length was 60 cm. If we divided 30 kg.cm over 60 cm, we got 0.5 kg. This meant that the end effector of the whole arm could carry until 0.5 kg and it might reach 0.6 when overstressed. We could apply this formula at other arm links:

$$F = \frac{\tau}{l} \ldots (1)$$

Where: $\boldsymbol{F}$ (kg) is the max load at the link end effector, $\boldsymbol{\tau}$ (kg.cm) is the motor torque, and $\boldsymbol{l}$ (cm) is the arm length.

Our material was plywood hinged over rotational supports or joints. Every four plywood sheets made a box or link. To calculate the weight of one sheet, we needed to know that plywood density was 680 kg/m3. For example, we would calculate the upper link of 15 cm in length. We would use this equation and we could apply for other arm links:

$$\rho = \frac{m}{V} \ldots (2)$$

Where: $\boldsymbol{\rho}$ (kg/m3) is the plywood density, $\boldsymbol{m}$ (kg) is the sheet mass, and $\boldsymbol{V}$ (m3) is the link volume.

B. Forward Kinematics

Kinematics can provide very exact computations in a variety of situations, such as putting a gripper in space. Designing a system to move a tool from point A to point B. We have two types of kinematics; first is forward kinematics as the robot arm's joint relations (rotations and translations) are provided and the task is what the end effector's orientation and position are and the second is inverse kinematics as the required end-effector position and orientation are provided and the task is what joint rotations and orientations are required [5], [6].

We have five steps of forward kinematics steps; get a pencil and paper, figure out your axes., remember your end effector, calculate the DH parameters, and the last one is to create a table of link parameters [7], [8].

C. Inverse Kinematics

We used iterative numerical method to calculate the joint angles given the desired position of the end effector. This method uses the Jacobean matrix ($\boldsymbol{J}$) which is a linear approximation of a differentiable function near a given point as basis to calculate the joint parameters [9]. Consider the notion $\boldsymbol{\theta}$ to be the joint variables and e to be the end effector position. the Jacobean is matrix of a partial derivative of the entire system that Defines how the end effector e changes relative to instantaneous changes in the system as in:

$$J = \frac{de}{d\boldsymbol{\theta}} \ldots (3)$$

And the Jacobean matrix is: $$J = \begin{bmatrix} \frac{\partial e_X}{\partial \theta_1} & \frac{\partial e_X}{\partial \theta_2} \cdots & \frac{\partial e_X}{\partial \theta_M} \\ \frac{\partial e_Y}{\partial \theta_1} & \frac{\partial e_Y}{\partial \theta_2} \cdots & \frac{\partial e_Y}{\partial \theta_M} \\ \frac{\partial e_Z}{\partial \theta_1} & \frac{\partial e_Z}{\partial \theta_2} \cdots & \frac{\partial e_Z}{\partial \theta_M} \end{bmatrix} \ldots (4)$$

We want the joint variable so,

$$\mathrm{d}\theta = J^{-1}\,\mathrm{de} \ldots (5)$$

After we computed the Jacobean numerically, we calculated the inverse of the Jacobean using two methods.

The first one is pseudo-inverse. We have this equation:

$$J^{+}.\,de = d\,\Delta\theta \ldots (6)$$

Where: J^{+} is the pseudo inverse and equals to:

$$J^{+} = (J^{T}J)^{-1}J^{T} \ldots (7)$$

The second is Jacobean transpose. It is simple using the transpose of the Jacobean as the inverse of the Jacobean is:

$$J^{-1} = J^{T} \ldots (8)$$

D. Motor Selection and Hardware Components

We have calculated the weight of each part in previous section, so we could calculate the torque of the motors.
To control arm movements, we had two choices to use servo or stepper motors, but we have chosen to use servomotors because of large torque, low weight, cost, feedback of servomotor. We used four servo motors to control arm movements in four DOF.

We used arduino to take the feedback of the motors and control them. We also used (SMPS Input 220Vac / Output +12Vdc/20A) to power the microcontroller and servomotors.

E. Bang-bang Control

It is a sort of control system that switches things on or off mechanically or electrically when reaching a specified objective (set point). Bang–bang controllers as in Fig. 1.

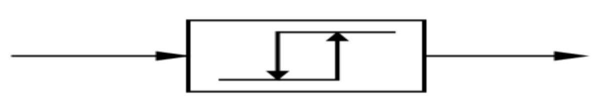

Fig. 1. Bang-bang control symbol

Our servos are continuous servos, when we give any motor a PWM it reaches to it and considers this position is the origin so it continues rotating with any PWM we give but it has differences in velocity. We used the embedded encoder of the servo to take feedback so we can detect its position. After detection of position, we can hold the servo but the servo will rotate again. Here comes the Bang-bang control role. The motor holds the position temporary and if the position changes, the motor starts rotating in the opposite direction as shown in Fig. 2.

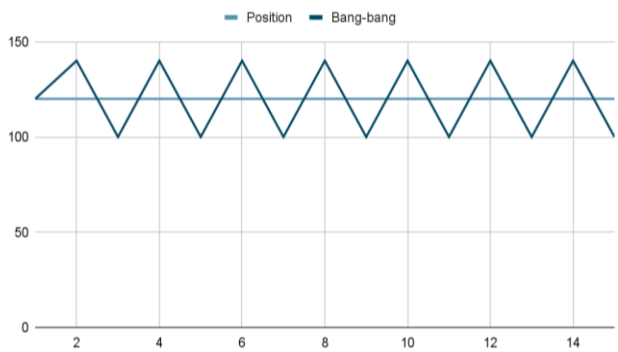

Fig. 2. How bang-bang control works.

III. RESULTS

A. Prototyping Used Machines

We used two machines to build the final prototype as in Fig. 17 which are laser cutter (MORN MT-L1410), as shown in Fig. 13 to make the arm links and router simplex as shown in Fig. 14 to make the fixed body. We cut the sheets to make boxes of our desired design 2D mounted assembly. We cut every link separately then make a box contains every motor then joined with the next link.

B. Forward Kinematics

After applying DH parameters, the next table shows the homogenous transformation matrix and the next figure shows the output is after substituting with the values of Θ1, Θ2, Θ3, Θ4:

TABLE I

The transformation matrix after applying DH parameters

Link	a_i	α_i	d_i	Θ_i
1	0	Pi/2	0	Θ_1
2	0	-Pi/2	L_2	Θ_2
3	L_3	0	0	Θ_3
4	0	Pi/2	0	Θ_4

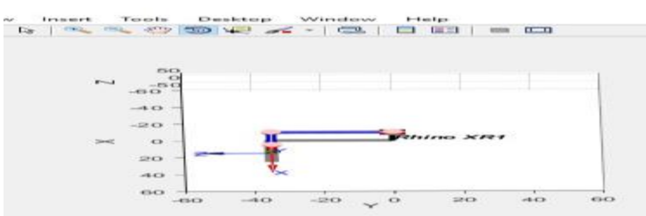

Fig. 3. The output after substituting with θ_1=0, θ_2=0, θ_3=0, and θ_4=0.

C. Inverse Kinematics

For the Jacobean transpose and pseudo inverse, we made one experiment that showed how the end effector was reaching the given positions using the Jacobean transpose and pseudo inverse methods at position (10, 50, 0) with Jacobean execution time: 0.430788 seconds and pinv execution time: 0.434738 seconds as shown in Fig. 4.

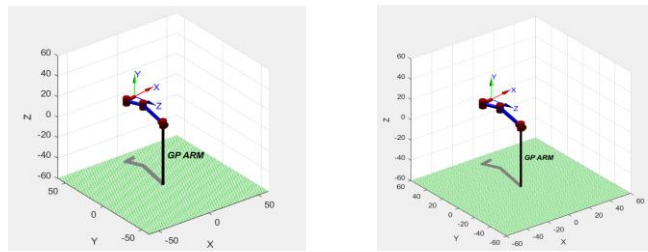

Fig. 4. Robot configuration using Jacoean method (left) and pseudo inverse (right).

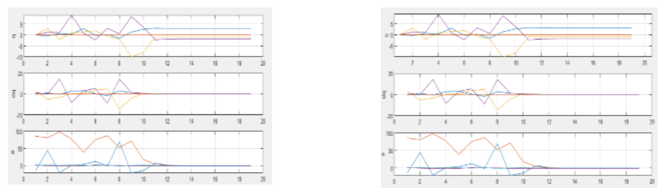

Fig. 5. Plot iteration state, Jacobean method (left) and pseudo inverse (right) where q: solution of joint angels in radians, dq: change in joint angels, and e: error.

D. Validation of Motors and Bang-bang Control

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

Our servomotors provide high torque with high speed but the accuracy of our robotic arm would not be accepted. Therefore, we used trial and error method to provide the best torque that achieves best accuracy. For the largest motor, we used the gearbox to get better control. We used flexible shaft coupling in second DOF. Arduino has 8 bits resolution that gives us a narrower range of feedback signals. For the power supply, we used a step down converter to get this 6v.

We used Bang-bang in our system. It depends on feedback from the encoder. Bang-bang control provided good accuracy in our application. The limitation of this control method was that the motor sometimes consumed more time to identify the position and that made the motor rotating in CCW and CW to stop. In addition, the bang-bang control needed a microcontroller with high resolution to give a wider range of readings of the encoder.

IV. Discussion

Our arm consists of some links and joints. There will be sensor at the end effector in x-y plane, so we wanted the arm to work as a manipulator. It must be rigid. The links should avoid tangency and resist bending and breaking. Plywood or we can call it rigidity links with joints is the best mimic for a humanoid arm and gives us stability. It was the easiest manufacturing in prototyping. We chose plywood to test functionality and for rapid prototyping. However, for reliability, we could use other materials such as the previous mentioned materials as plywood had some drawbacks. The other materials drawbacks were the cost. Some of them needed to complex machines. Some materials were difficult to find them. Heaviness was one of the drawbacks [10].

We applied the concept of DH parameters in our robot and substituted with the values of {a, α, d, Θ} for each link as shown before and then put the table in Matlab to get the final transformation matrix (T) and to simulate the robot's position.

The problem with numerical solution is that we must choose a good initial value for joints variables, we cannot guarantee a particular configuration as it differs according to the choice of the initial values. Finally, the numerical solution can be computationally expensive. On the other hand the numerical solution provide a good approximation to the desired solution without the tedious process compare to the analytical process also it's much feasible than the analytical solution especially in complicated configurations [9], [11], [12].

The Jacobean transpose method is faster than the pseudo inverse method as the result showed. Regards to the quality, there was no deference between the result produced by the two methods. however, it is safe to say is that quality of Jacobean transpose method is not good compared to the pseudo inverse method because the Jacobian is already an approximation to the solution and in this method, we do more approximation (a huge one) by taking the transpose of the Jacobian as the inverse of the Jacobian which leads to a low quality. On the other hand, pseudo inverse method is slower, but the quality is better [11].

To apply good bang-bang control we need to a high resolution microcontroller. At first, we used STM32F104, it has a resolution of 12 bit. However, we had a problem with the communication protocol with Matlab inverse kinematics. In bang-bang implementation, we needed delays to move the arm and then check if the arm reached the wanted position. It would be better if we used the timer concept so we could avoid this blocking to achieve a better real time application.

V. Conclusion

In summary, we built a fully controlled prototype for a humanoid robotic arm to assist the medical staff. We introduced a robotic system that will help all healthcare workers who are exerting their best in the fighting against the outbreak of Covid-19 crisis in different medical institutions by protecting them from catching this virus infection, so they can perform their tasks safely and quickly. Providing a relative cheap product for all medical institutions to face the coronavirus pandemic.

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