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4-degree-of-freedom voice-controlled robotic arm

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ABSTRACT

People with impairments who utilize robotic arms have a great deal more independence in their daily lives. The robotic arm can help persons with specific needs by using voice control, which is practical. The working mechanism is fashioned to have four degrees of freedom (4-DOF) with the inclusion of a jaw or gripper. The Arduino microcontroller, the speech module, and the arm are the main components of the robotic arm, which is a lightweight model driven by four motors. The servo motor is used to supply the rotational motion in the arm's three rotary joints and end effector. Rotation in two directions is made possible by the geared DC motors employed, which alter their direction of rotation if the polarity is flipped. The automatic voice recognition technology aids in comprehending spoken words picked up by a microphone. The HM2007 processor, the brains of the speech recognizer, is necessary for the speech recognizer to function. Digital commands are created from analog speech input. These commands are used as input to the Arduino thereby resulting in a system whereby the human voice gives a continuous control signal to operate a real and functional robotic arm.

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1. INTRODUCTION

Robots are conquering more and more fields of application-from healthcare to agriculture [1]–[3]. Robots even contribute to climate protection: To achieve the ambitious climate targets, renewable energies, and environmental technologies are being produced on an unprecedented scale. In addition, modern robots work energy-efficiently and are used to directly reduce energy consumption in production. Thanks to their precision work, fewer rejects and defective goods are produced, which has a positive effect on the use of resources and output [4].

Many fields are seeing a significant rise in the use of robots. It is not uncommon to hear about them in the news nearly daily: about drone attacks in battle, about robots visiting the elderly in nursing homes, or about cars that can park or even drive themselves [5], [6]. Additionally, research is being done to develop more social robots that can read facial expressions and carry on conversations. Industrial robots that are restricted to specific regions appear to be giving way to devices and systems with higher levels of autonomy.

Specifically, a robotic arm is a mechanical arm that can be programmed and performs tasks akin to those of a human arm [7]–[9]. It can be an independent mechanism or an element of a more complex robot. Similar to an articulated robot, such a manipulator has joints that provide either translational (linear) displacement or rotating motion. The linkages of the manipulator can be thought of as forming a kinematic chain [10]. The manipulator's kinematic chain ends with the end effector, which resembles the human hand [11].

Devol and Angleberger created the Unimate #001, the first robotic arm, in 1959. Devol received a patent for his robot concept in 1961, and he and Engelberger founded Unimation, which stands for "universal automation," the first robot business in history. In order to help a hot die-casting process, the first robot was placed in a General Motors plant in New Jersey [12]. Later, Unimation created robots to help with welding and other tasks in the quickly expanding automotive industry. By granting licenses to Nokia in Finland and Kawasaki Heavy Industries in Japan to produce and market the Unimate by 1966, Unimation opened up a global market for the usage of programmable robot arms [10].

Robotic arms are used in manufacturing the most. A typical robotic arm is made up of seven metal segments joined by six joints. The robot's microcontroller rotates individual step motors attached to each joint. Robotic arms are devices that may be instructed to perform a certain task or duty with extreme accuracy, promptness, and efficiency [13], [14]. They are often motor-driven and frequently used for heavy and/or highly repetitive tasks that must be carried out quickly and consistently over long periods of time. They are notably valued in the industrial production, manufacturing, machining, and assembly industries.

From a purely mechanical standpoint, an industrial robot arm typically consists of a variety of joints, articulations, and manipulators that collectively imitate the motion and capabilities of a human arm [15]. A programmable robotic arm can function both independently as a piece of equipment and as a standalone robot element of a larger and more complex piece of equipment. Today, a huge number of smaller robotic arms that are benchtop mounted and electronically controlled are used in a variety of industries and workplace applications. Larger versions might be floor-mounted, but regardless, they typically have between 4-6 articulating joints and are made of strong, resilient metal (commonly steel or cast iron). Again, from a mechanical standpoint, the main joints of a robotic arm-including the shoulder, elbow, forearm, and wrist-are fashioned to closely match their human counterparts [16].

This work developed an inexpensive, lightweight 4-degree-of-freedom voice-controlled robotic arm based on Arduino Uno and Bluetooth technology. The developed robotic arm accurately resembles the motion of a human arm extended while lifting, moving, lowering, and releasing an object with the capability of picking up and placing an object. By contrasting it with a human arm, and allowing a mental image of a human hand lifting a container to emerge, the job is done by the waist, shoulder, elbow, arm, wrist, and fingers. This is the driving force behind the number of parts selected. Speech recognition, or teaching the system to recognize human speech, is a pivotal concept in voice control that is taken into account [17]. With the aid of speech recognition technology, the system can comprehend the words spoken aloud but not their meaning. Speech recognition, at its most basic, enables the user to interact with the computer or appliance while completing other tasks simultaneously.

2. METHOD

Figure 1 shows all the necessary primary components of the developed microcontroller-based robotic arm that is operated by voice. The voice recognition module receives the vocal inputs via a microphone. The microcontroller receives the digital output corresponding to the speech command. The four robotic arm motors are controlled by signals produced by the microcontroller. The four motor drivers determine the way the four motors rotate [18]. The mechanical strength of the arm is capable of lifting, moving, lowering, and releasing an object while closely resembling or referring to the motion of the human arm, which consists of a shoulder joint, elbow joint, wrist joint, and lastly, the fingers, all of which are interconnected.

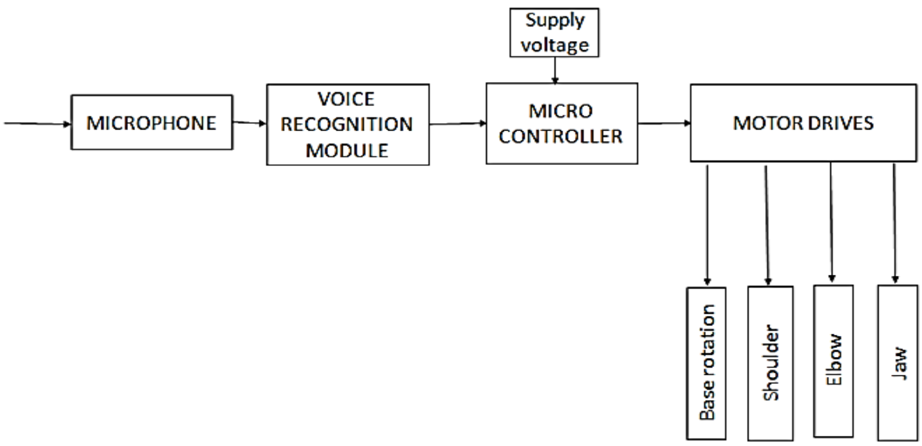

Figure 1. Robotic arm main components

2.1. Robotic arm mechanical design process

With the addition of a jaw or gripper, the robotic arm's mechanism was designed to have four degrees of freedom (4-DOF). The robotic arm architecture's computer-aided design (CAD) model was created and rendered using Autodesk Fusion 360 ® software. To compute the forward kinematics expression of the robotic arm using an open chain manipulator, the relative position and orientation of the two subsequent links were defined using a general method [6]. The robotic arm's design process included numerous analyses using the D-H representation.

2.2. Kinematic analysis using Denavit-Hartenberg convention

The Denavit-Hartenberg parameters, or D-H parameters, are a set of four parameters used in mechanical engineering to describe a specific protocol for attaching reference frames to the links of spatial kinematic chains or robotic manipulators. The robotic arm manipulator's forward kinematic was calculated using the D-H parameter. The convention's processes were used to determine the D-H parameters of a serial link [19]. The CAD model of the developed joint is shown in Figure 2, a schematic of the robotic arm showing the chosen joints axes is depicted in Figure 3 while Figure 4 is a representation of the chosen joints axes. The D-H parameters used for the robotic arm are contained in Table 1 and this was used for MATLAB kinematic analysis.

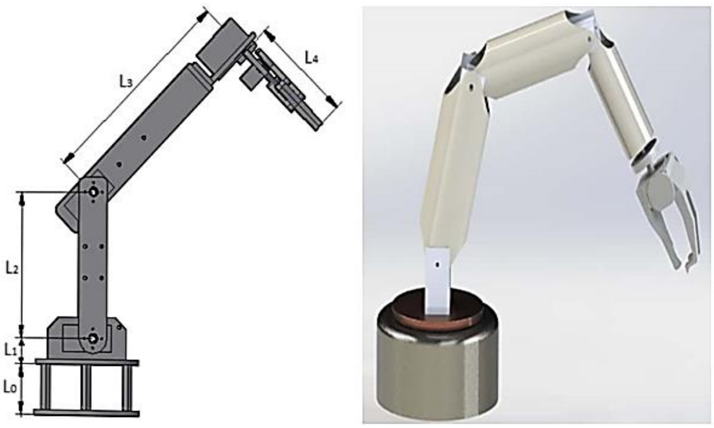

Figure 2. CAD model of the developed robotic arm

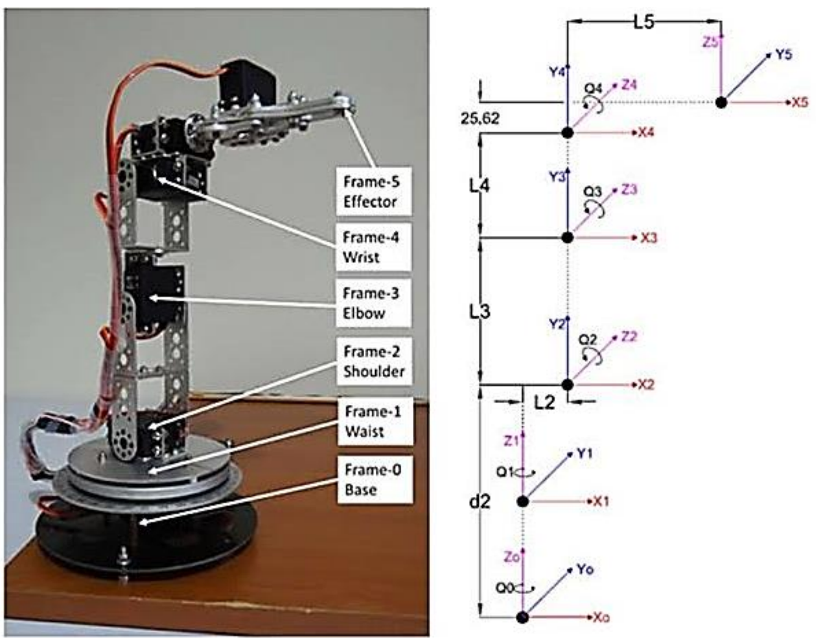

Figure 3. The location of the end effector (gripper) central point of the robotic arm is given as (x, y, z)

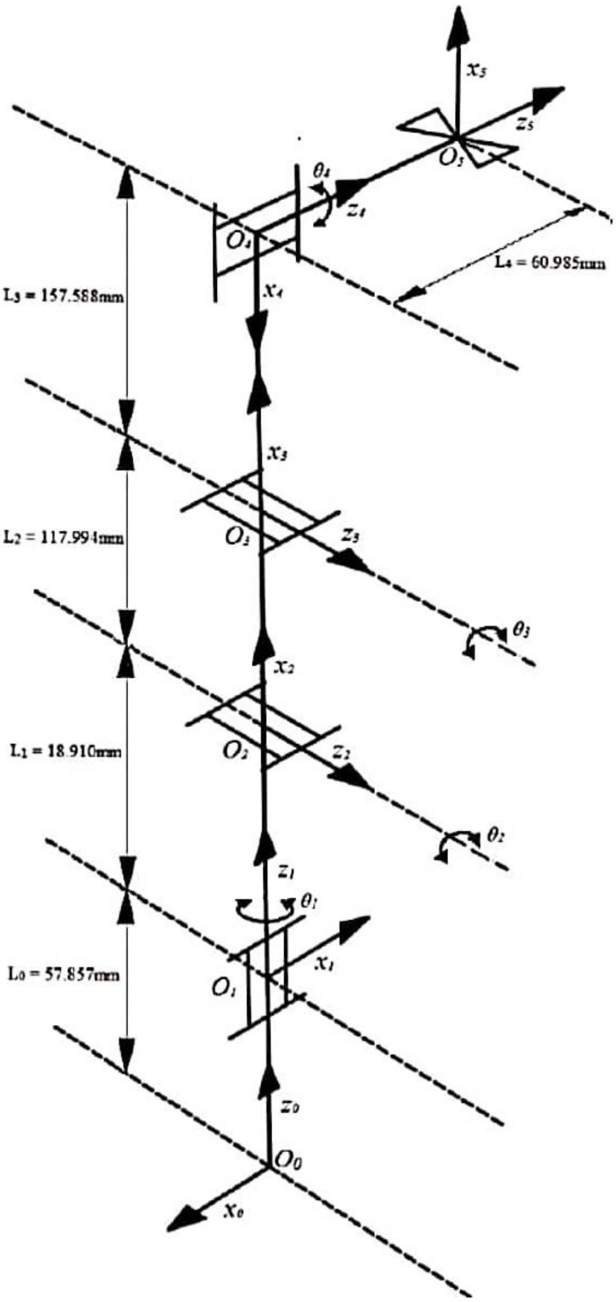

Figure 4. Schematic of robotic arm showing the chosen joints axes, where Oi is the i^th frame origin

Table 1. D-H parameters for the robotic arm

I	αi-1	ai-1	d1	Θ_i
1	0°	0	0	Θ_1
2	90°	0	0	$90°-\Theta_2$
3	0°	L2	0	Θ3
4	90°	L3	0	$180°-\Theta_4$
5	0°	0	0	180°

The Li are the links and Ѳi the representation of the joint angles. The equations contained in Figure 4 reflect the forward kinematics of the robotic arm and provide values for the joint angles that may be utilized to determine where the end effectors-the grippers-are located. A response feedback algorithm system was incorporated into the design to test if the robotic arm was properly positioned and whether, after determining the inverse kinematics of the robotic arm, the solution would successfully be at the required location. The location in space would be obtained by running through the feedback system algorithm, which would then obtain the inverse kinematics through the forward kinematics to obtain the location [20]–[23]. The location is then compared to the target stated location. The first discovered solution that produces the accurate position in space is also chosen.

2.3. Workspace of the robotic arm

When more than two links are aligned together or when the geometric limit of links is reached, the phenomenon known as singleton occurs in the robotic arm [24]. No matter how the joints are moved, once the point is reached, the robotic arm will not move the end effector in a specific direction. The singleton points were calculated equating the Jacobian Matrix’s determinant to zero. The singleton points were practically avoided.

2.4. Torque requirements for the joints

The final control element (the actuators) is fixed at each joint of the robotic arm, taking into account the individual motions of the robotic arm links. In order to overcome the limitations or resistance of the link to motion, the actuator, the last control device, applies torque at the joint. Gravity and inertial effects are the causes of any restrictions or resistance to motion. Due to its own weight, the robot is pulled and propelled toward the center of the earth by the gravitational force on its links, which causes it to experience an oncoming or resistive torque.

As a result, a portion of the torque produced by the actuator, the final control device, is needed to counteract the resistive or approaching torque caused by the gravity effect. In order for the final control element device to have the appropriate torque rating chosen for each joint, the induced gravity of the resistive torque acting on the links of the robotic arm was computed accordingly [25]. As a result, the maximum horizontal reach of the arm is taken into account when calculating the torque needed for each joint. Figure 5 shows the free-body diagram of the robot arm when stretched out.

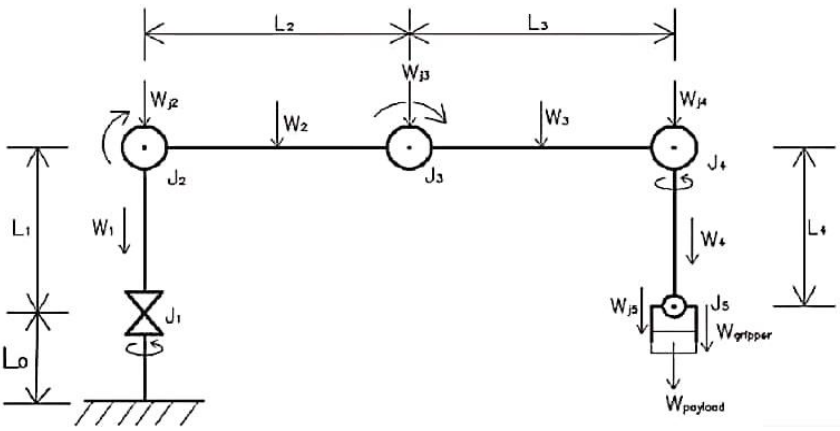

Figure 5. Image showing the free body diagram of the robot arm when stretched out

2.5. Hardware and software selection

The project is divided into two sections. The hardware section comprises all the physical component mechanisms and the software section which is an encoded architecture of layered computer instruction that enables signal processing to be achieved. The hardware materials used as determined from the design and drafting processes are as follows.

a. Arduino UNO microcontroller (ATmega328): Used for receiving command signals from the Android application via a Bluetooth communication interface, interpreting the received command and send corresponding output pulse width modulation signals to the required servo motors to perform the desired pick and place task.
b. Four units of MG99R servo motors: High torque rugged servo motors used as connectors between the arms of the robot. It is an electromechanical device that was used to provide 1DOF at each joint of the Arm. Since 4 servo motors were used, the robotic arm developed has 4 degrees of freedom.
c. HC-05 Bluetooth module: The Bluetooth module is a low energy Bluetooth (BLE) enabled device capable of bidirectional serial communication with a suitable communication interface. It will be used as a mode of communication between the Android application and the AT-mega328 microcontroller.

d. Power supply unit (Lithium-ion batteries): The lithium-ion cells were connected in a series-parallel arrangement to give the power required to operate the arm. The minimum estimated power to be supplied by the battery is 28 W (i.e., 7 V and 4 A). One lithium-ion cell is rated 3.7 v and 2200 mA. Hence, four lithium-ion cells were connected in a series-parallel arrangement.
e. Adafruit servo motor driver shield: The motor driver shield provides 16 Pulse width modulation channels that were used to drive up to 16 different servos by using just the serial data (SCA) and serial clock (SCL) pins of the Arduino microcontroller. The shield has ICs with unique addresses which are used in addressing each pulse-width modulation (PWM) channels via the Arduino microcontroller. The shield is required as it minimizes the number of Arduino pins required to control the servos as well as provide effective power to the servos.

The software interface was developed using MIT app inventor. The application developed was downloaded to and launched on an Android mobile phone.

2.6. Overview of working methodology

The voice-activated pick-and-place robotic arm developed is installed on a stable platform for stability and accuracy. The base, shoulder, elbow, and wrist are the four primary joints that make up the arm. The wrist is connected to the end effector, which is a two-jaw gripper. A servo motor is used to operate each joint, providing one degree of freedom in relation to the associated pieces. The elbow joint, however, is immovable in relation to the shoulder link and is fixed. The arm has four degrees of freedom as a result. The arm's shoulder may rotate 180 degrees primarily due to the motors that act as a joint between the base link and the shoulder link.

Through a servo, the arm may also rotate 180 degrees with respect to the shoulder joint. The wrist joint also allows for 180-degree rotation. A motor driver IC installed on a motor driver shield and managed by the Atmega328 microcontroller allows for linear motor control as the gripper opens and shuts. The Android application system that interfaces with the Arduino microcontroller via the Bluetooth communication protocol provides the applied input pulse, signal, or controlling signal.

The program converts voice commands into text (bytes) commands when the desired voice command is received from an Android application, and then sends the text commands to the microcontroller using the Bluetooth protocol. The controller decodes the received message before converting it to a digital PWM signal that is utilized to trigger the arm’s necessary pick and place action. Figures 6 and 7 show the circuit diagram and the block diagram of the robotic arm. The flowchart of the operational sequence for the robotic arm is shown in Figure 8.

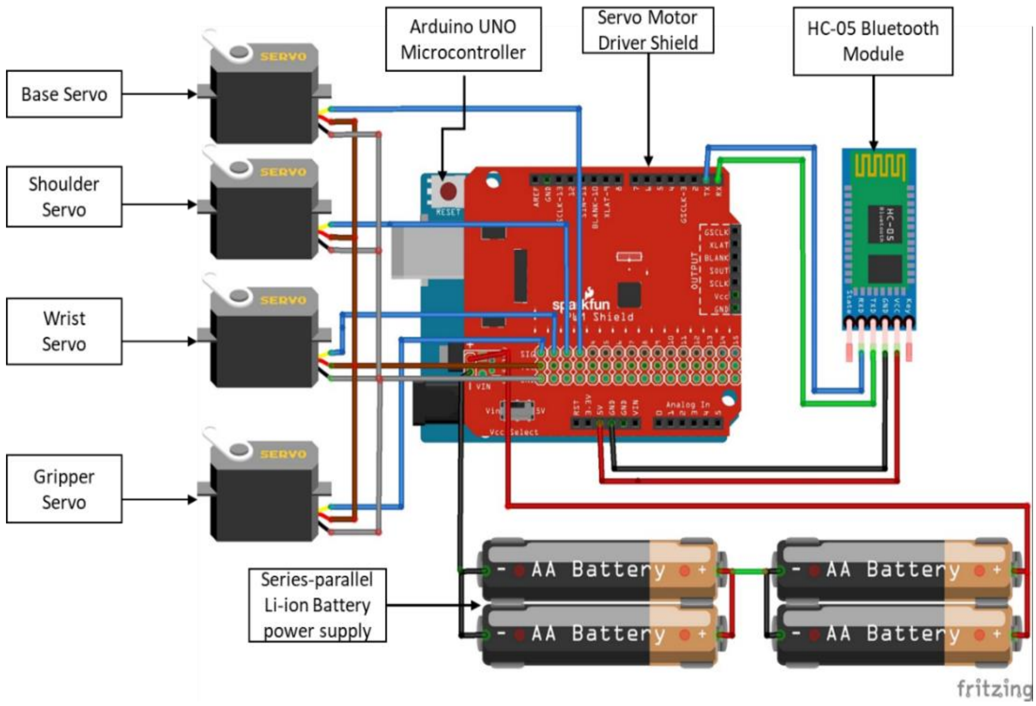

Figure 6. Circuit diagram of the robotic arm components connection

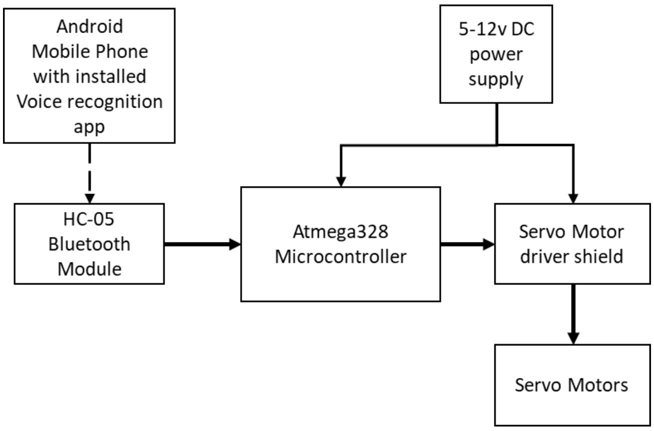

Figure 7. Block diagram of the robotic arm

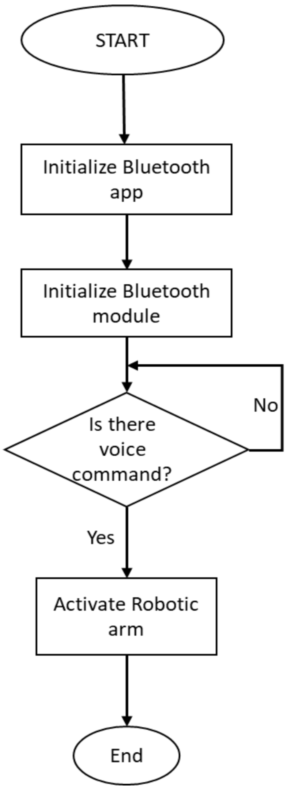

Figure 8. Robotic arm operational flowchart

3. RESULTS AND DISCUSSION

3.1. MATLAB kinematic analysis results

The common approach of describing serial manipulators' dynamics and kinematics known as Denavit-Hartenberg (D-H) is the idea on which the MATLAB toolbox is based. The D-H parameters given in Table 1 were used to create a vector of link objects as shown in Figure 9.

Due to the revolute nature of all joints, the joint angles alpha are changeable. The robot is succinctly described by this technique, with the zeros serving solely as placeholders for the joints' angle variables. The robot has four revolute joints, and their configuration is shown by the letters RRRR [25]. The Denavit-Hartenberg parameter is used to define the configuration, and gravity acts in the z-direction by default. By adopting the plot approach, the robot was graphically represented as stick figures, complete with the robot's name, axes, and joints. MATLAB was used to retrieve the graphic representation of the robot stance corresponding to each set of joint angles.

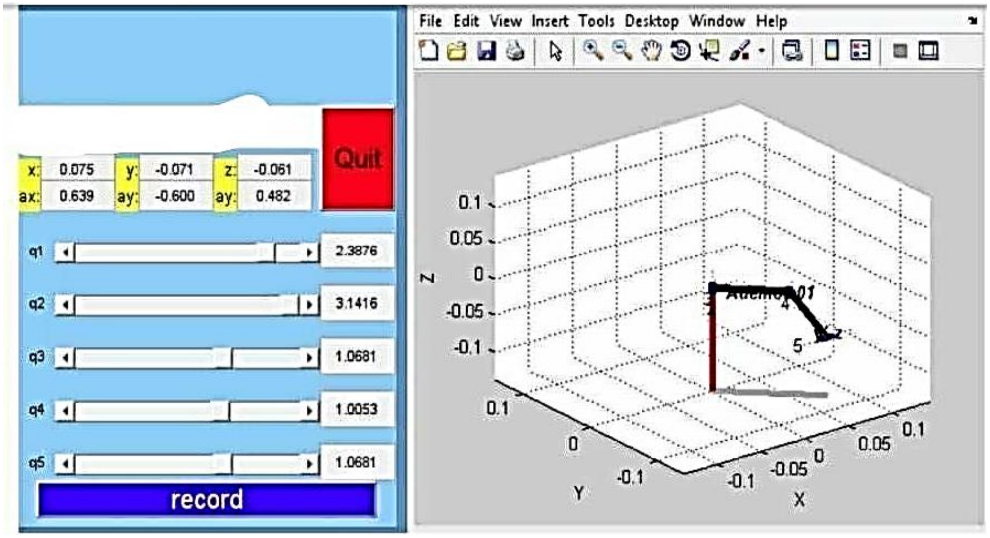

Figure 9. Simulated robotic arm using the teach method

3.2. Determination of maximum vertical and horizontal reach of arm

The maximum servo torque listed in the datasheet determines the maximum allowable torque. The arm’s working space was restricted to a length that requires 85% of the maximum servo torque because the maximum torque of the servo employed is 9.4 kg cm (0.92 Nm) at 4.8 v. (i.e., 0.782 Nm). The results of extending the arm with and without applying a payload of 150 g are shown in Table 2. Figures 10 and 11 show the graphs of vertical and horizontal reach versus servo torque respectively. Figure 12 shows the actual robotic arm developed in operation.

Table 2. Waist servo torque with respect to horizontal and vertical reach

S/N	Horizontal Length (Cm)	Vertical Height (Cm)	Applied Weight (Without Payload) (Kg)	Weight (With Payload) (Kg)	Torque Without Load (Nm)	Torque When Loaded (Nm)
1	5	29.58	0.4	0.55	0.196	0.270
2	7	29.17	0.4	0.55	0.275	0.378
3	9	28.62	0.4	0.55	0.353	0.486
4	12	27.50	0.4	0.55	0.471	0.647
5	15	25.98	0.4	0.55	0.589	0.809
6	20	22.36	0.4	0.55	0.785	1.079
7	24	18.00	0.4	0.55	0.942	1.295
8	27	13.08	0.4	0.55	1.059	1.457
9	30	0.00	0.4	0.55	1.177	1.619

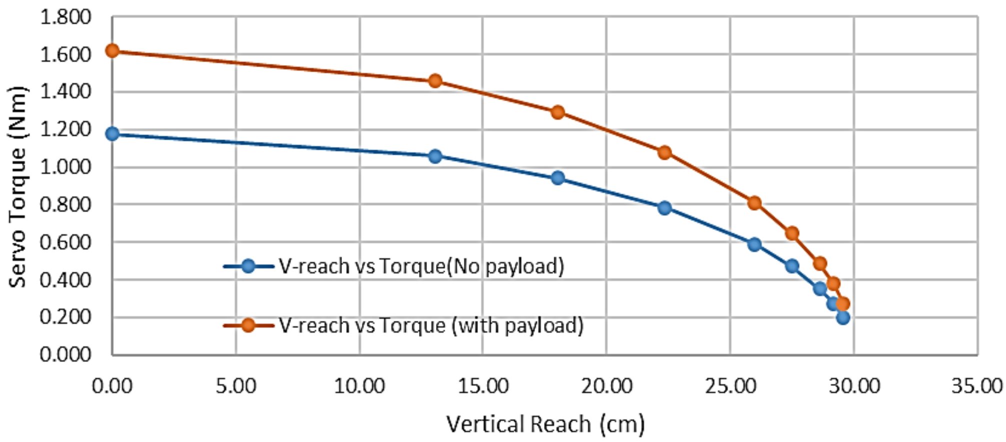

Figure 10. Graph of vertical reach (cm) vs servo torque (Nm)

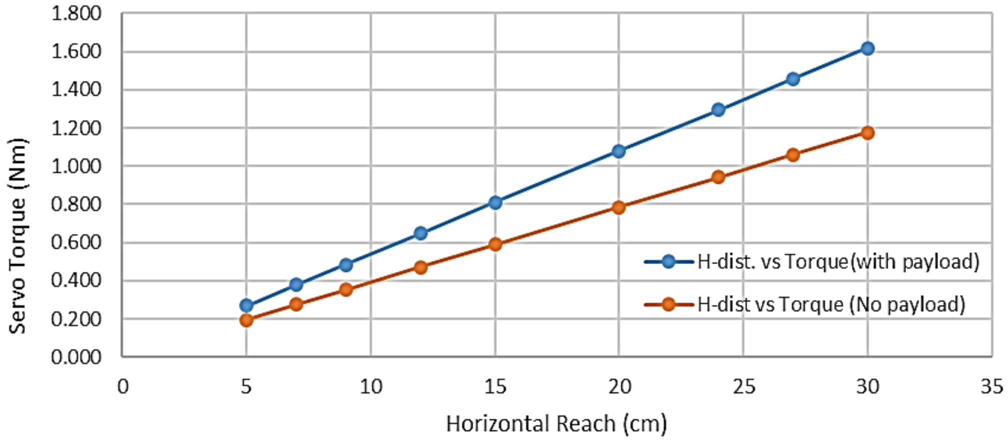

Figure 11. Graph of horizontal reach vs servo torque

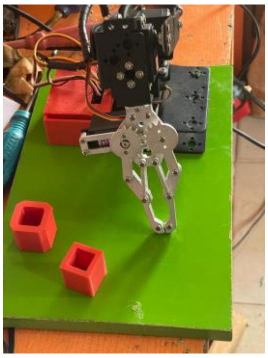

Figure 12. Developed robotic arm in operation

Since the load applied at each joint is known, the torque at each joint (servo torque) was also evaluated to be sure the maximum permissible torque was not exceeded. The torque at each joint was observed and recorded as tabulated in Table 3.

Table 3. Joints servo torques with and without payload

S/N	Joint	Load (without payload) (kg)	Load at joint (with payload) kg	Horizontal reach (m)	Torque (without payload) (Nm)	Torque (with pay load) (Nm)
1	Waist	0.4	0.55	0.135	0.53	0.728
2	Shoulder	0.35	0.5	0.135	0.46	0.662
3	wrist	0.09	0.24	0.07	0.06	0.165

3.3. Speed of the arm

The speed of servos varies depending on configuration and varying loading throughout the joint. The total motion anticipated for the procedure is calculated as the average speed of the joints and is expressed in degrees traveled per second. Each joint was simulated from zero degrees to its maximum deflection of 180 degrees in order to ascertain the speed of the joints. It was observed how long the rotation took. When the arm was loaded, that is, the gripper had grasped an object, the procedure was repeated. The outcomes are listed in Table 4.

Table 4. Joint speed when loaded and unloaded

S/N	Joint	Speed at no load (°/s)	Speed when loaded (°/s)
1	base	60	55
2	Shoulder	80	65
3	Wrist	120	120

3.4. Response of the arm to voice commands

A series of tests were performed on the android application to determine the strength of connectivity and how fast the arm responds to voice commands. The outcome of the tests are tabulated Table 5 and the corresponding graph shown in Figure 13.

Table 5. Arm response time with respect to command distance

S/N	Distance (m)	Command	Response Time (s)
1	0.25	Up	3.0
2	0.25	Grab	3.0
3	0.50	Up	3.0
4	0.50	Grab	3.0
5	1.0	Up	4.5
6	1.0	Grab	4.5
7	1.25	Up	4.5
8	1.25	Grab	4.5
9	1.75	Up	4.5
10	1.75	Grab	4.5
11	2.0	Up	5.0
12	2.0	Grab	5.0
13	2.5	Up	5.0
14	2.5	Grab	5.0
15	3.0	Up	6.0

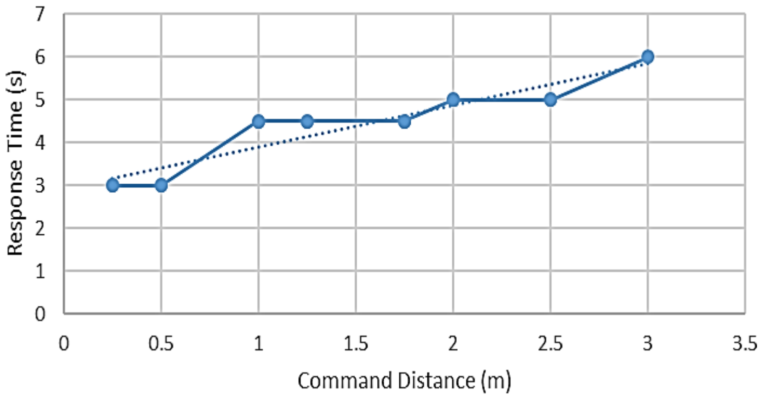

Figure 13. Graph of response time versus command distance

4. CONCLUSION

A voice-activated robotic arm has been built and programmed. Additionally, a suitable Android application has been created to control the robotic arm. The pick-and-place arm's action has been made as stable as possible using the Denavit-Hatenbarg forward kinematics technique. The use of electromechanical joints produced a tidy, environmentally friendly design that is reliable. Additionally, Bluetooth technology was used to enable remote control of the robotic arm.

The arm can be expanded to carry out repetitive and laborious tasks in a variety of material handling and processing industries, including the food industry, the garment and textile industry, the beverage industry, the printing industry, steel rolling mills, etc. Not only will the use of arms in industrial processes increase output quality and quantity, but they will also reduce waste brought on by human error and weariness. Additionally, it will shield workers from potentially fatal injuries.

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