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Article

Development and implementation of a wireless-controlled robotic arm for lifting applications with 6 DOF

Nwadinobi Chibundo Princewill[1]*, Takim Steve[2], Omajuwa Edesemi Omawumi[3]

[1]Department of Mechanical Engineering, Abia State University, Uturu, Abia State, Nigeria
[2]Department of Mechanical Engineering, Cross River University of Technology,Calabar, Cross River State, Nigeria
[3]Department of Mechanical Engineering, Gregory University Uturu, Abia State, Nigeria

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*Corresponding author
Email address:
chibundop@gmail.com

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A B S T R A C T

This paper is centered on the design and construction of a Bluetooth-controlled robotic arm with 6 degrees of freedom. It is capable of manipulating given objects as well as lifting and conveying a payload from one point to another. Any smartphone that possesses an Android operating system can be used for remote operations. This offers a background look at robotic arms, from invention to current trend as well as simplification of design to make it more accessible to robotics enthusiasts. The design process for the robotic arm is chronicled in this paper, from the working principle to the development of the kinematic equations, as well as CAD modeling and component selection. Tests are also conducted to ascertain the robot's strength and range of capabilities. The availability of this robotic arm would serve as an indispensable learning tool for experimenting with robotics in training institutions.

1. Introduction

The term robot is defined as a reprogrammable multifunctional operational device designed to manipulate certain materials, parts, tools, or devices through various programmed movements to perform various tasks [1-3]. The aforementioned technological advancements have led to a resultant proliferation of robots that play various roles in our everyday lives, from entertainment to industrial, medical to military; the robots vary in form and purpose with necessary classifications [4, 5]. Service Robots are robots that exist to serve the everyday well-being of humans, with the exception of manufacturing operations. These services can include vacuum cleaning and lawn mowing, as well as courier services and general logistics. The robots operate autonomously or semi-autonomously [6]. Secondly is the Space Robots, which are robots employed in space operations, usually for surveillance and planetary explorations. These robots are known to come with various radio communication features as well as highly resilient mobile capabilities [7]. This is followed by the Military Robots, which often come equipped with radio devices; however, they can also feature bomb-defusing and projectile-launching capabilities. Finally, industrial robots, robotic arms that move in multiple directions and can be programmed to perform many types of repetitive tasks in different environments, such as High pressure and vacuum chambers, terribly toxic areas, as well as hazardous environments where the explosion, infection, radiation or other similar extreme hazards endangering human life. Of all robotic systems, the robotic arm has always received the most attention because its architecture is the simplest of all robotic architectures and therefore appears as part of other more complex mechanical robotic systems [8-10]. A robotic arm is a type of mechanical arm, normally programmable, that works the same way as a human arm. This arm can be the summation of the general mechanism or part of a more complex robot [11, 12]. There are limbs of such a manipulator connected by joints that allow rotational or translational movement. The links of the manipulator can be viewed as a kinematic chain. The end of the manipulator's kinematic chain is called the end effector and corresponds to the human hand. Depending on the application, the end effector or the robot hand can be designed for any task, such as carrying, gripping, turning. Robotic arms function similarly to human arms yet have a much greater range of motion, as their design can only depend on the creator's imagination. The joint that connects the robotic arm segments can rotate and move like a hinge, and the end effector can be designed for any task. Today, these robotic arms are used for tedious and complex tasks that can be completed faster than any human [9, 13, 14]. In spite of the fact that the field of Robotics has existed since the early 1930s, two major factors that make it appear inaccessible to many aspiring engineers in the third world are the cost and the mathematical complexity. In the first instance, the cost of acquiring hardware for training purposes to many learning institutions can prove quite prohibitive and as a result, discouraging. Thus, keeping them out of the reach of entry-level enthusiasts willing to learn and practice on a conservative budget. The second instance, the mathematical complexity, is also a major challenge. The aim of this work is to design and construct a wireless industrial robotic arm capable of being controlled by an Android application via Bluetooth, helping to serve as a training model for demonstrative and educational purposes. This work covers the selection of components, design, simulation, fabrication, and programming of the industrial robotic arm. It goes further to discuss the implementation of the inverse kinematics of the arm.

2. Materials and methods

This section comprehensively describes the design and construction methods employed for the robotic arm and its controller. Being a mechatronic system, the robot comprises of a mechanical interface, an electrical/electronic interface, and a software interface. Hence, the choice of material for its exoskeleton, motor requirements, microcontroller capabilities, and the kinematic code are addressed.

2.1 Choice of exoskeleton material

In order to develop a reliable exoskeleton for the robotic arm, capable of withstanding physical stress and lifting a payload, it was important to make certain that the 3D-printing filament material utilized was going to be strong enough to resist shearing but also light enough to not pose a significant weight burden to the servo motors. Choosing higher-torque servos could pragmatically make the relative weight a non-issue.

The key material properties that were put into consideration were: Strength and resilience, Temperature resistance, Relative lightness, and Availability. From the factors listed, PLA (Polylactic acid) tends to satisfy the requirements. Not only is it biodegradable thermoplastic, it can be readily acquired and melted for use by the 3D printer as a result of the fact that it can be economically produced from renewable resources. In addition, it offers the much-needed strength features for the robotic arm. These key physical properties are tabulated in Table 1.

Table 1. Physical properties of polylactic acid (PLA)

Density	1.180 g.cm^{-3}
Tensile Modulus	3600 MPa
Yield Strength	60 MPa
Flexural Modulus	3800 MPa
Flexural Strength	83 MPa
Elongation at break	6%
Melting Point	150-170° C

2.2 Robotic structural design

The robotic arm has six degrees of freedom, including the gripper. The implication is that it physically comprises six servo motors interlinked in series by thermoplastic structures forged using a 3D printer. The initial CAD (computer-aided design) concept model of the robot was designed using Autodesk MAYA (Figure 1). Upon satisfaction with the overall artistic look and feel of the robot, a more detailed CAD model was designed on Dassault Systemes' SolidWorks software – this time with a greater degree of control and accuracy regarding spatial dimensions and precise weight calculations (Figure 2). Upon performing mass calculations on the model, the following parameters were obtained (Table 2). The Articulated Robotic Arm with arrows showing its 6 axes of rotation is presented in Figure 3.

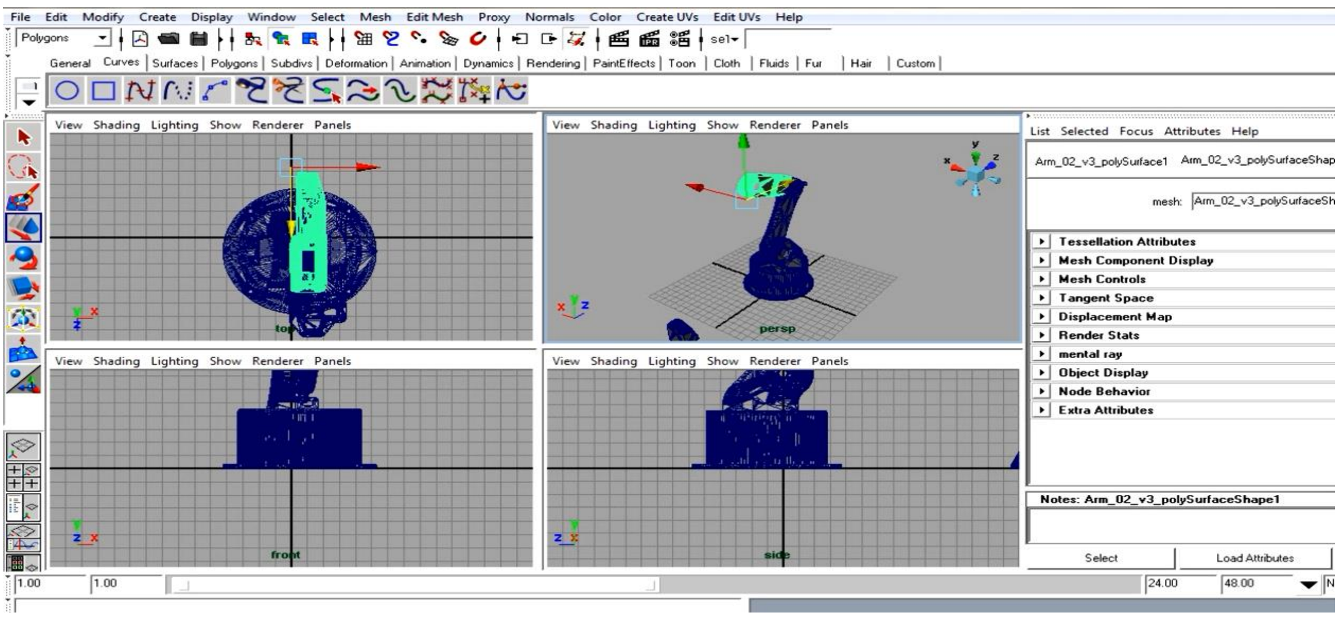

Figure 1. Screenshot of the initial design process on Autodesk Maya

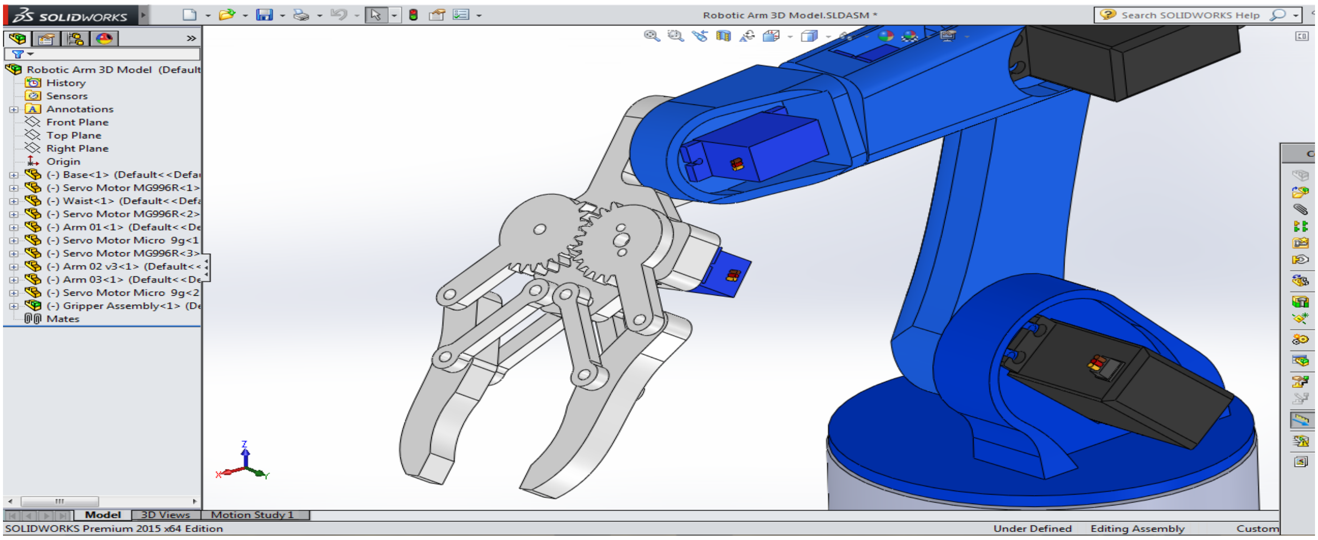

Figure 2. Screenshot of the modeling process on SolidWorks with greater detail

Table 2. Principal mass parameters

Mass	453.17g
Volume	453166.56 mm^3
Surface Area	178518.55 mm^2
Centre of Mass (mm)	
X	64.02
Y	-82.20
Z	152.87

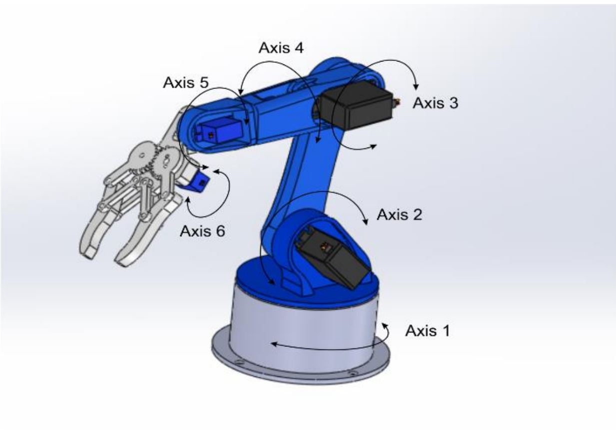

Figure 3. The Articulated Robotic Arm with arrows showing its 6 axes of rotation

With the robot's six degrees of freedom, the movements of the joints are shown in Table 3.

2.3 Torque calculations and motor selection

A servomotor is attached to each arm joint to trigger movements on the robot's linkages. This servo motor applies the required torque to the gimbal to overcome the initial resistance against the movement linkage. This initial resistance to motion comes from gravitational and inertial effects. The gravitational force acting on each ring attracts it and, under the influence of its own weight, accelerates it toward the center of the earth, exerting a drag on it. Because of this, the optimum torque produced by the servo motor is required to overcome the drag torque (due to gravity). It was therefore necessary to calculate the value of the resisting torque acting on each rod under the action of gravity to ensure that a servomotor with sufficient torque was selected for each joint. The section modulus that gravity exerts on the joint is highly dependent on the position of the robot. Intuitively, of course, the torsion of the shoulder joint is much greater when the arm is stretched horizontally [2].

Table 3. MOI-Output coordinate system values

Axis No.	Name of the Joint	Motion	Motor No.
1	Base	Rotates the whole assembly	1
2	Shoulder	Rotates upper arm	2
3	Elbow	Rotates forearm	3
4	Wrist Pitch	Rotates gripper along the X-axis	4
5	Wrist Roll	Rotates gripper along the Y-axis	5
6	Gripper Hinge	Opens and closes the gripper	6

Thus, to calculate the torque required for each joint, the ceiling value was chosen. From Figure 4, let the motors be denoted by Mn, the respective links denoted by Ln, and the respective weights of the links be denoted by WMn, the notations become:

- M_1 = Waist or base joint
- M_2 = Shoulder joint
- M_3 = Elbow joint
- M_4 = Wrist Joint
- W_{L2} = Weight of L_2
- W_{L3} = Weight of L_3
- W_{L4} = Weight of L_4
- W_{EE} = Weight of end effector (gripper)
- $W_{payload}$= Weight of payload
- W_{M2} = Weight of M_2
- W_{M3} = Weight of M_3

- W_{M4} = Weight of M_4
- W_{M5} = Weight of M_5 (end effector)

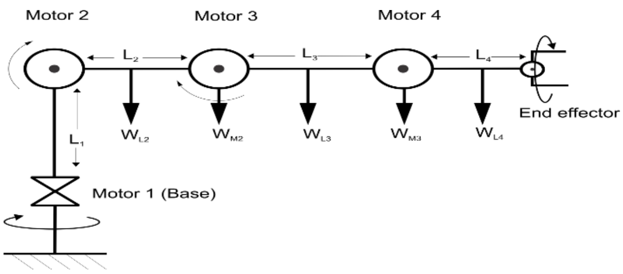

Figure 4. Free-body link diagram of the robotic arm in a stretched-out pose

The calculation of the resistive torque which is exerted on each joint due to gravity is as follows:

- Resistive torque at M_1 due to gravity is at 0 (since there is no vertical rotation) and is disregarded.
- Let resistive torque at M_2 due to gravity = T_{2g}
- Let resistive torque at M_3 due to gravity = T_{3g}
- Let resistive torque at M_4 due to gravity = T_{4g}

$$T_{2g} = W_{L2}\left(\frac{L2}{2}\right) + W_{M3}L_2 + W_{L2}\left(L_2 + \frac{L3}{2}\right) + (W_{M4} + W_{L4} + W_{M5} + W_{EE} + W_{payload})(L_2 + L_3) \quad (1)$$

$$T_{3g} = W_{L3}\left(\frac{L3}{2}\right) + (W_{M4} + W_{L4} + W_{M5} + W_{EE} + W_{payload})(L_3) \quad (2)$$

T_{4g} = 0 N-m since the wrist rotation does not result in vertical motion against gravity (3)

In order to model it efficiently, the expected weights of the servo motors also had to be factored into the torque calculations even prior to the motor selection itself. The most convenient option was using the average servo motor weight (which can vary from 40-56 grams) for a mechatronic system of this weight class.

From theoretical data:

- Weight of servo motors = 56g
- Density of the filament material = 1.18gcm-3
- Length of Link 2 = 10.6cm
- Length of Link 3 = 11.7cm
- Length of Link 4 = 10cm
- Weight of M4 nut and bolt = 2.5g
- Weight of M2 nut and bolt = 1.5g

Using the derived equations to calculate the given estimates, the torques acting on M2, M3, and M4 were found to be 10.37kg-cm, 9.36kg-cm, and 6.26kg-cm, respectively. So, from those values, the 11kg-cm torque TowerPro MG996R servo motor was selected (Figure 5) for the three joints (Base/Waist, Shoulder, and Elbow), while the 1.5kg-cm torque TowerPro SG-90 servo motor was selected (Figure 6) for the two wrist joints and the gripper end effector.

2.4 Limb kinematics

Since the robot is designed to perform in 3D space, the end effector is required to follow a planned trajectory in order to manipulate objects or carry out the task in the workspace. This requires the control of the position of each link and joint of the manipulator to control both the position and orientation of the tool. To program the tool motion and joint-link motions, a mathematical model of the manipulator is required to refer to all geometrical and time-based properties of the motion. The kinematic model describes the spatial position of joints and links and the position and orientation of the end effector. The derivatives of kinematics deal with the mechanics of motion without considering the forces that cause it. The relationship between movements and forces and the moments that cause them is a dynamic problem. Kinematics and dynamics are important when designing a robotic arm. Previously developed mathematical spatial description tools are used to model robotic manipulators. The kinematic model shows the relationship between the position and orientation of the end effector and the spatial positions of the joints. The differential kinematics of manipulators refers to differential motion.

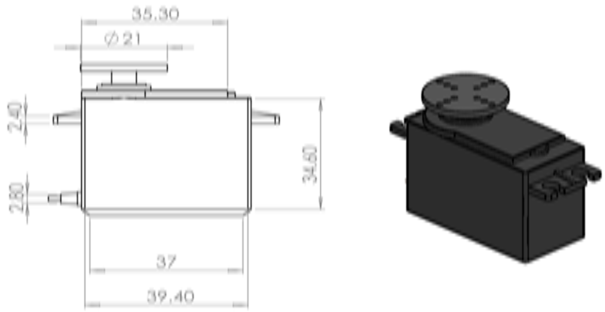

Figure 5. The MG-996R metal gear servo motor and it's dimensions

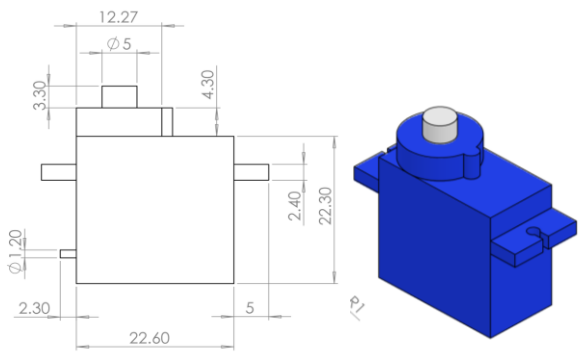

Figure 6. The SG-90 servo motor and it's dimensions

2.5 Kinematic analysis using the Denavit-Hartenberg convention

The Denavit-Hartenberg (D-H) notation was used in computing the kinematics of the robotic arm. It is also illustrated in Figure 7.

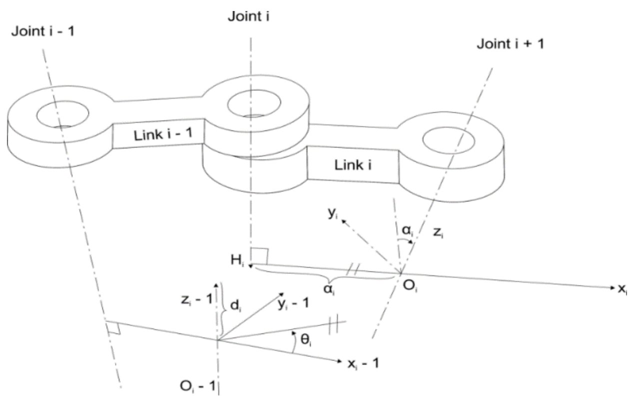

Figure 7. The Denavit-Hartenberg parameters

The illustration shows that the frame(s) is rigidly attached to the distal end of the coupler(s) and moves with the coupler(s). The n-DOF manipulator will have (n+1) frames, with frame (O) or base frame serving as the reference inertial frame and frame (n) as the instrument frame. Figure 8 shows a pair of adjacent limbs, limb(i-1) and limb(s), their associated joints, joint(i-1), joint(i) and joint(i+1), and the axes (z - 2), (i-1) and (i).The frame (i) is assigned to the link (i) as follows:

- The Z-axis coincides with the (i)-axis and its direction is arbitrary. The choice of direction determines the positive direction of the common variable ϴ
- The X-axis is perpendicular to the Zi-1 axis, and the Zi points are offset from the Zi-1 axis, which means that the Xi-axis is directed along the common normal
- The origin of the coordinate system (i) lies at the intersection of the joint axes (i+1)
- Y-axis completes the right-hand orthonormal coordinate frame.

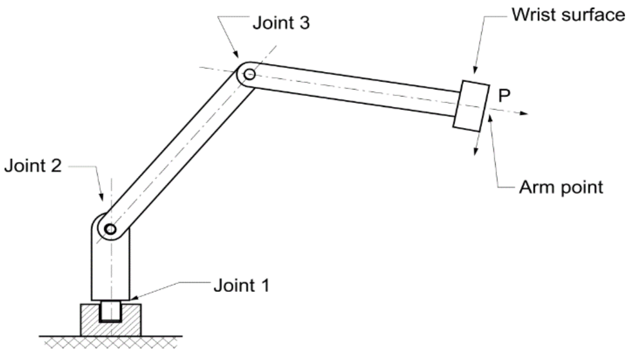

Figure 8. Partition diagram of the manipulator

2.6 The articulated arm kinematic model

The arm matrix is divided into three parts:

- The first partitioned matrix
- The second partitioned matrix
- Final arm matrix

To determine the arms point transformation matrix, frames are first matched, and the resulting joint-to-joint parameters are tabulated. The joint offsets are assumed to be zero for all three joints. The Joint Link parameter for the arm is presented in Table 4. So, if we give the values of the length of the limbs and the angles of the joints, we get the position of the wrist as follows:

X = 8.73cm; Y = 8.66cm; Z = 9.87cm

These would effectively form the basis for the positional code written into the Arduino UNO microcontroller.

Table 4. Link parameters of the robotic arm

Link i	ai	αi	di	θi
1	0	90	0	45
2	10	0	0	85
3	10	0	0	110

2.7 The servo controller selection

The robot controls its servo motor by sending digital pulses to the onboard circuitry. This type of signal is known as a pulse width modulated (PWM) signal. Digital pulses are sent to the servo at 20-millisecond intervals, and depending on the duration of the pulse, the servo horn moves through an angle of 180 degrees. The servo operates as a complete circuit that generates the PWM signals to control the servo based on code compiled in machine language by the computer to the microcontroller. The Arduino UNO (Figure 9) was the most suitable microcontroller/servo-controller for the work as a result of its vast supply of support libraries and tools for easy implementation, owing to its open-source background. It is a low-cost, extremely flexible, and easy-to-use programmable microcontroller that can be integrated into a wide variety of robotic and IoT applications alike. The presence of 14 digital pins meant that a surplus number of slots were available for the 6 servo motors, and the presence of a USB jack meant it could easily interface with the computer after writing code for the robot for easy data transfer.

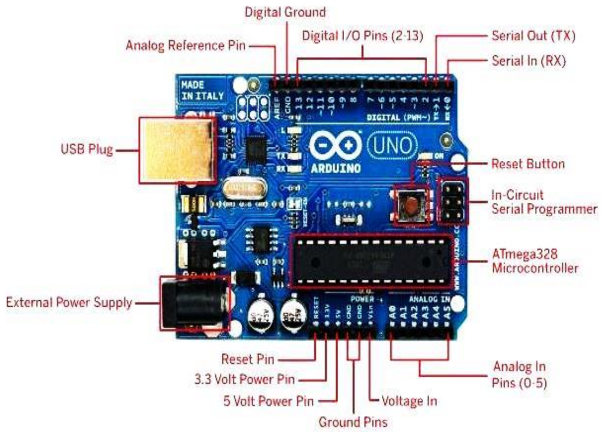

Figure 9. The Arduino UNO and its pin configuration

The control code for the robot was written using the C++ language in the Arduino IDE application on my computer, compiled, and uploaded onto the microcontroller board.

2.8 The telecommunication module

The robot was designed to be controlled wirelessly with a mobile phone assuming the role of a remote controller. On the end of the phone was an Android application with sliders meant to control the respective angles of each servo motor on the robot, and on the receiving end was the robot itself, meant to read the instructions from the phone and send the respective PWM signals. Since the phone already comes with its own antenna, a telecommunication module was added to the Arduino UNO board, which would help the robot receive the byte data from the remote controller. Bluetooth (IEEE 802.15) was chosen as the communication medium of choice between the two terminals because of its affordability and noise resistance. The HC-05 in Figure 10 is a 5V-powered module that allows seamless data transmission between the robot and the mobile phone.

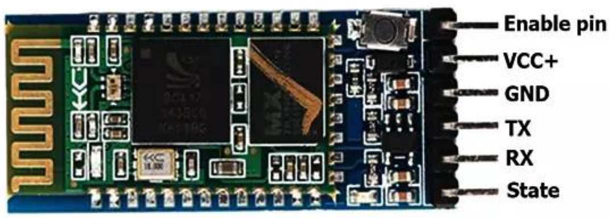

Figure 10. Pin-out configuration of the HC-05 Bluetooth module

2.9 The remote controller application

In order to effectively generate commands for the HC-05, the Android remote controller application was designed for the mobile phone. This was achieved using the Javascript programming language on the node-based App Inventor platform developed by the Massachusetts Institute of Technology. Unlike the Arduino IDE, instructions are developed by manually plugging the required code blocks to form a larger function on a specialized Graphical User Interface as opposed to scripting the instructions on a text editor. The program was developed and exported as an Android application package file (APK) for download and installation on an Android smartphone. In order to make the program easily installable, it was uploaded to a Google Drive folder, and the link was embedded onto a QR code chip to be attached as a sticker on the body of the robot.

2.10 The final robotic arm model

The final model of the robotic arm - with its circuit board, servos, and Bluetooth module – is shown in Figure 11. The model was designed using Dassault Systeme's SolidWorks 2015.

Figure 11. The fully assembled structure of the robotic arm

3. Results and Discussion

The robotic arm was developed with the structural frame designed with a computer using SolidWorks. Subsequently sculpted with a 3D-printing machine using polylactic acid as the polymer filament of choice, as shown in Figure 12.

The robot's Arduino UNO board was connected to the computer via USB, and the codes were uploaded. There were three programs that were written and uploaded into the Arduino board:

- The first was the motion control program which granted the robot the ability to move its arm using the developed kinematic equations that were obtained for it.
- The second was the individual servo control program which allowed the user to angle the servos independently of each other.
- The third was the firmware layer program which included the necessary libraries to enable the robot to recognize the interfaced components without needing to write new code whenever a component gets replaced.

The remote controller was initially designed to be able to save the steps and actions of the robot and play them continuously upon command, as is the case in an industrial setup, but to ensure compatibility with even the lowest tier Android phone, a separate application had to be written and simplified. This second application simply controlled the robot with the use of sliders for the servo motors. For the Arduino, the board had to be powered with a 9V battery through its 12V DC power jack.

In order to ascertain the load-carrying capacity of the robot, various workloads were weighed and lifted by the machine until the servos stopped angling upwards on command, as shown in Figure 13. The maximum load mass was discovered to be 0.646kg or 646 grams.

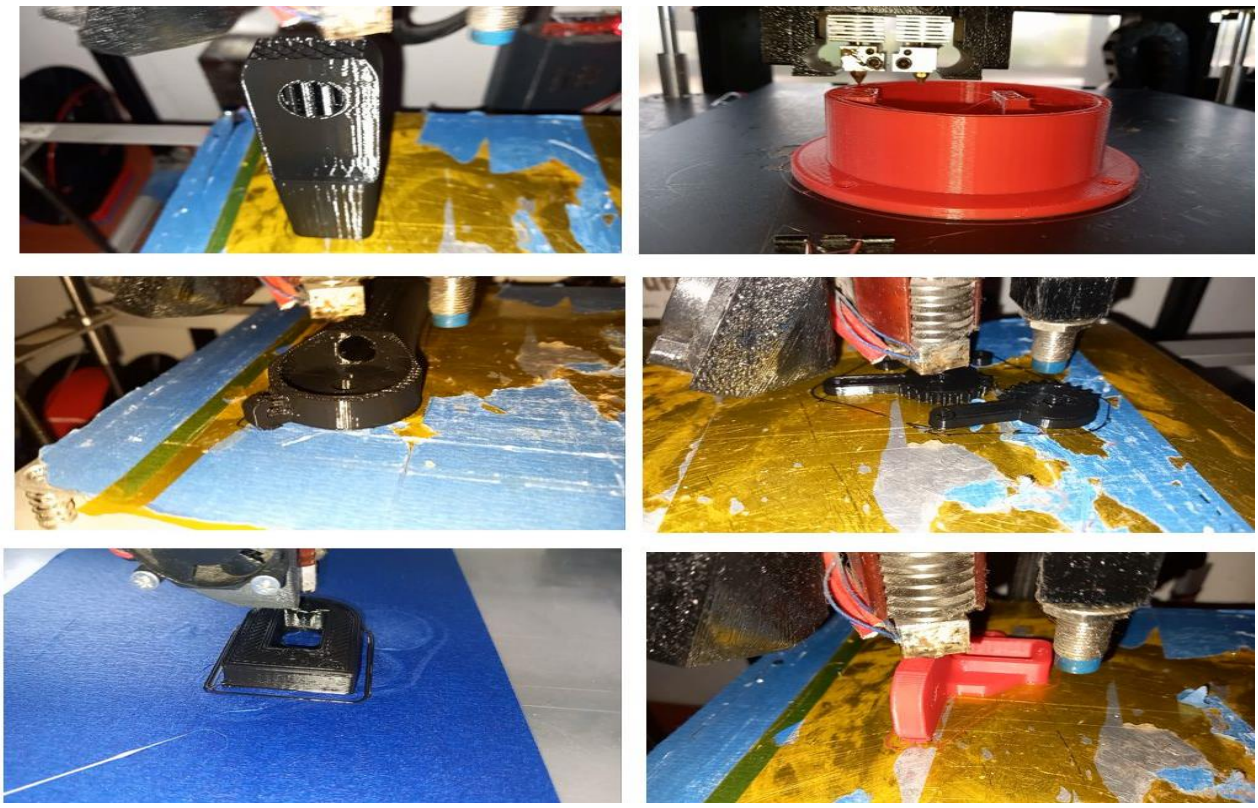

Figure 12. The sculpting process of the robot's structural framework

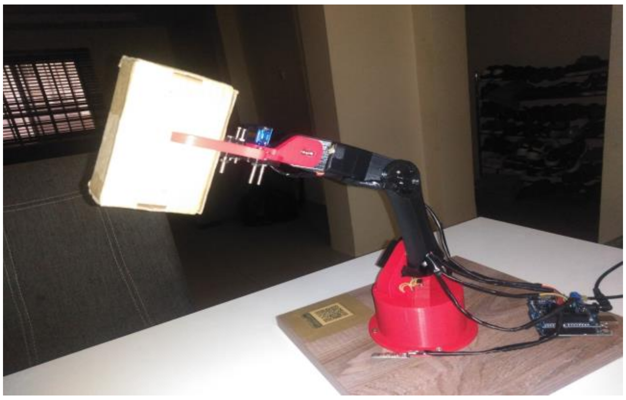

Figure 13. Testing the load-carrying capacity of the robotic arm

4. Conclusion

The study aims to develop a wireless-controlled robotic arm with 6 degrees of freedom and a two-finger grip. It has also been shown that the robotic arm can be deployed at any scale to suit a variety of interests depending on programming. This work covered all aspects of structural design and analysis. Projects like this can be done to encourage students who want to venture into this field, especially in a developing country like Nigeria, with a robotics/mechatronics industry in its infancy.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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