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Design and Fabrication of a Manually Controlled Electro-Mechanical Manipulator for Educational Purpose

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Abstract: In the fields of robotics and mechatronics, the use of an experimental platform in the learning process to allow for practical experience and demonstration of the core concepts cannot be overemphasized. A real-life mini robotic arm is indispensable to the learning process in these fields of study. There are commercially available robotic manipulators designed for educational purposes. However, majority of commercially available robots applicable for undergraduate or graduate levels learning are very expensive or have a closed hardware and software architecture. To this end, an easy to fabricate and inexpensive three degrees of freedom electro-mechanical manipulator is hereby presented. Sufficient information and design methodology employed in its fabrication is succinctly detailed including working drawings, components materials specifications and design calculations so that any student can reproduce the manipulator in the laboratory or workshop. In terms of performance, the manipulator gripper successfully lifted differently shaped payloads of 150g each of the test weights without slipping through the gripper jaws both when stationary and when in motion. For the repeatability test, the calculated repeatability was ±0.088 mm this is within the range for common commercial robotic manipulators. The overall cost of materials and standard components was NGN 38,000 (USD 77.00). The produced manipulator is relatively cheaper compared to commercially available educational robotic manipulators.

Keywords: Actuator, Electro-mechanical, Manipulator, Robotics, Mechatronics.

I. Introduction

Automation, artificial intelligence, robotics, mechatronics, drone technology are emerging buzz words in the design of engineering education curriculum development. The fields of Mechatronics and Robotics are emerging as a distinct engineering disciplines in their own right [1-2]. The use of robots in the teaching of Mechatronics, Robotics and Automation in general can be categorized into two: firstly, programming of robotic devices or control software and, secondly, aspect related to the assembly and operation of robotic devices or hardware [3]. The core mandate of a robotic curriculum is the training of students in the development, design, and construction of robots [4], thus to attain this, students must create robots by designing and building the robot itself and establishing its capabilities through software [5].

There is a consensus among engineering educators that experience with the real world cannot be taught just in the classroom, real feel experience is required in the effective training of engineering undergraduates. Thus, when teaching Robotics or Mechatronics related course, the use of an experimental platform in the learning process to allow for practical experience and demonstration of the basic concepts cannot be overemphasized [6].

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The modern robotic arm is the offshoot of the traditional mechanical manipulator which first found its practical uses in nuclear research laboratories where radioactive materials use in experiment requires remote handling for safety and health reasons [7]. From this humble beginning, the common mechanical manipulator has evolved into the now very sophisticated robotic arm. Basically, a robotic arm is an integration of two entities; the electro-mechanical manipulator and the computer. Robotics is generally placed in the field of automation. Automation systems are generally made up of three main subsystems, namely mechanical, electrical and software. The interactions among these components affect the integrated system in terms of reliability, quality, scalability, and cost [8].

The working knowledge of the functioning of the electro-mechanical manipulator is thus crucial in the study of robotics. The fundamental difference between a modern robotic arm and the classical electro-mechanical manipulator is the replacement of human control by a programmable computer system. The manipulator is a bio-mimetic of the human arm. Like the human arm, a robotic arm mechanism or manipulator consists of arms (links) and joints (steering gears). The modelling and kinematics analysis of the manipulator structure studies the mapping relationship between the end position of the arm and the output of every joint [9].

In recent times, educational robots have begun to make appearances in campuses and households, changing the traditional way of teaching and learning. They serve as objects of study as well as being instructors in their own right. There are many varieties of physical or virtual robots now available commercially, from the very complex to not so complex. These robots' intrinsic perfect systems and mature hardware or software had succeeded in minimizing the difficulty of learning robotics and automation. However, there is a fundamental disadvantage; they limit the creativity of their users. Moreover, majority of commercially available robots applicable for undergraduate or graduate levels learning are very expensive or have a closed hardware and software architecture [10]. These put limits to how far a student can task their ideation and creative skills in the use of these robots to understand the fundamentals of robotics.

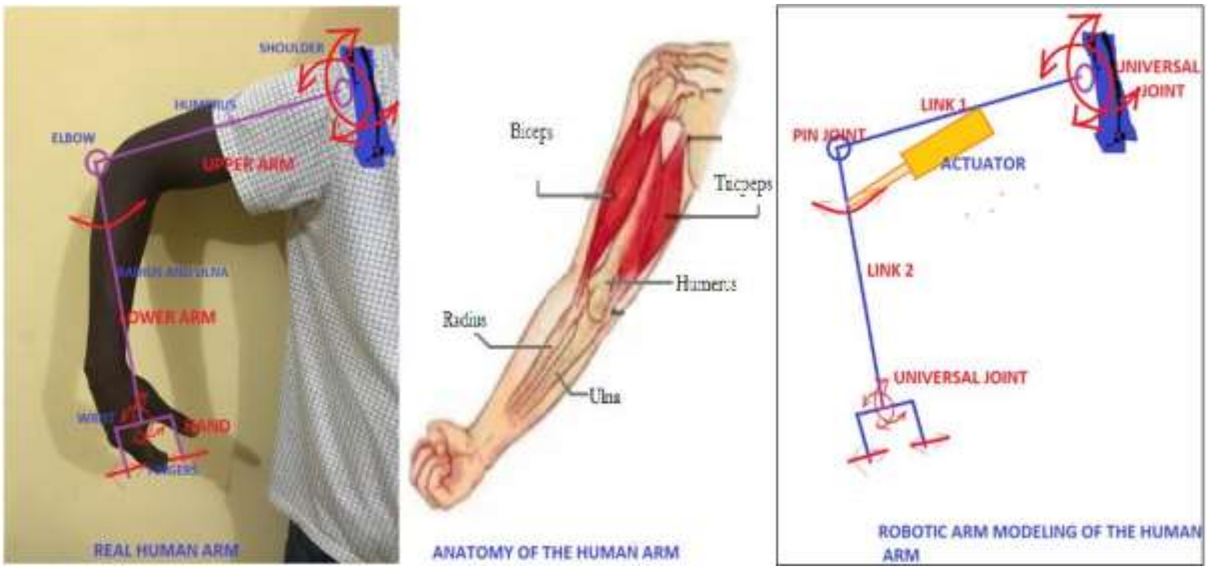
It was recommended that robotic control research can advance more rapidly if robotic arms of valuable performance were highly reduced in price [11]. To meet this challenge, and because the electro-mechanical manipulator is the basis of the robotic arm, a simple, easy to build and using off the shelf components electro-mechanical manipulator is hereby proposed, designed and fabricated. Sufficient details about its fabrication are included in this paper so that interested instructors or students of robotics, automation or mechatronics can easily reproduce one based on these details alone.

II. Materials and Methods

This section presents the methods and materials used in the design and fabrication of the electro-mechanical manipulator.

A. The Concept

The manipulator was modelled after the human arm. It is a form of an articulated manipulator, sometimes also called a jointed, elbow, or anthropomorphic manipulator. The human arm consists of three main parts; the upper arm (humerus), the lower arm (ulna and radius) and the hand (wrist, fingers, and thumb). There are two rigid links representing the upper and the lower arm sections. A pin joint between the links represent the elbow.



(a) (b) (c)

Figure 1: The modelling stages of the electromechanical manipulator based on human arm (a) a human arm, (b) the anatomy of the human arm (c) the manipulator equivalent of the human arm. (Source: (a) and (c) The authors; (b) from www.slideshare.net)

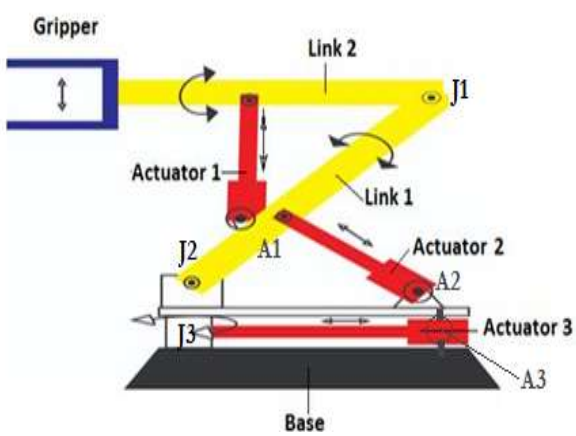


Figure 2: The Schematic of the Concept (Source: The authors)

The interface between the upper link and the base represent the shoulder, though unlike the shoulder, it is not a universal joint but rather a swivel joint. The gripper constituted the hand; it has only two 'fingers' unlike the five digits on the human hand. The interface between the gripper and the lower arm constitute the wrist. For sake of simplicity, the wrist is immovable (Fig. 1). The equivalent of biceps and triceps muscles as an actuator for the arm movements are the linear actuators. The schematic of the manipulator concept is as presented in Fig. 2.

B. Design Parameters

Based on the concept in Fig .2, the manipulation is conceived to have 3-degree of freedom. The number of degrees of freedom in a manipulator should match the number required by the task. The proposed workspace or envelope which is the maximum and minimum linear and angular reach of the manipulator gripper is as shown in Fig. 3. The lift capacity, or pay load is fixed at 150g. This is the maximum load the gripper is expected to lift or carry. The links are to be fashioned from 35mm by 35mm, 1mm thick mild steel hollow square pipe. The length of each link was fixed at

300mm. The links (J1-J3) and actuator (A1- A3) joints are pin joints (Fig.2). The gripper was fashioned from acrylic sheet 3mm thick.

C. Materials

The manipulator links and base are to be made from 35 mm X 35 mm, 1mm thick hollow square steel pipe. Hinge pins, actuator's outer housing, nut housing and motor housing are mild steel. The gripper is made from acrylic sheets 3mm thick. The motors, nuts and screws are standard parts.

D. The gripper

The gripper concept is as presented in Figure 4. The screw is directly coupled with the shaft of the DC motor and turn with it. The motor is capable of bi-directional rotation by changing its terminal polarities. The motor was attached to one of the two fingers or jaws (herein referred to as the thumb). The screw (diameter 5mm, modified ACME) engaged a nut fixed with the base of the other finger (herein referred to as the finger). A particular rotation of the screw by the motor advances the base of the finger out of the hollow base of the thumb thereby opening the hand to accommodate the payload. Rotation in the opposite direction by the screw closes the hand. The jaws are padded with a rubber overlay. Rubber is preferred as it has a relatively high coefficient of friction with other types of surfaces [12]. The gripper is expected to hold the payload by frictional force.

In Fig. 4, the grip force is denoted by F (in N), the mass of the payload is m (in kg), acceleration due to gravity as g (m/s^2), sideway acceleration due to the motion of the manipulator arm is a (m/s^2), the grip force is calculated using the equation below:

$$F = \frac{m(g+a)}{\mu} * f.S. \qquad (1)$$

Where μ is the coefficient of static friction and

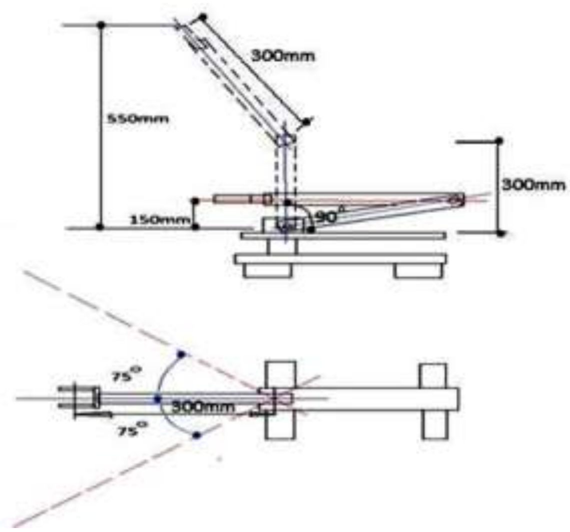


Figure 3. The manipulator work envelope. (Source: The authors)

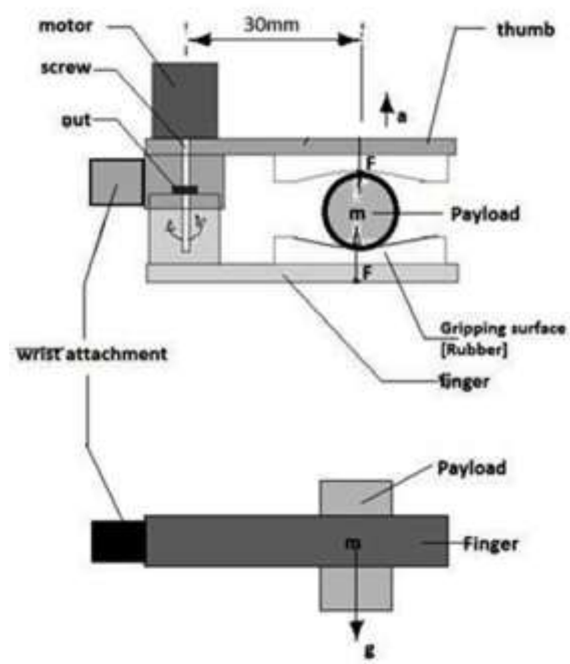


Figure 4. Gripper concept and force analysis diagram (Source: The authors)

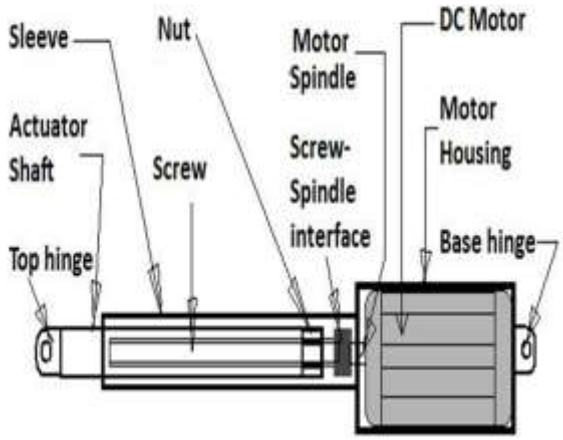


Figure 5. Linear actuator concept (Source: The authors)

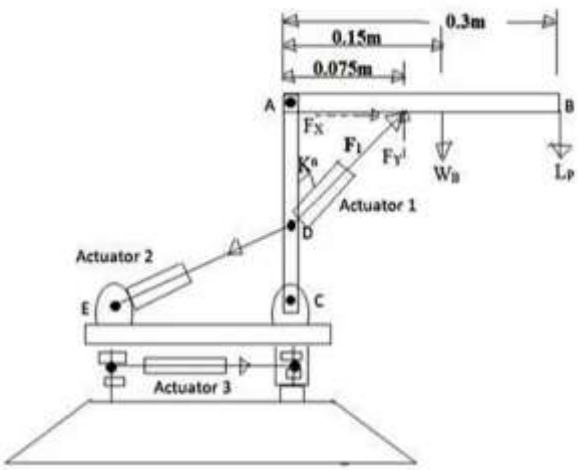


Figure 6. Force analysis on manipulator links and actuators (Source: The authors)

f.S. is the factor of safety taking as 2. A conservative value of $\mu = 0.2$ is assumed. The sideway acceleration is assumed to be negligible since the manipulator is expected to execute motion at nearly constant velocity. Hence with the design payload of 150g, the gripping force is 14.72N.

Jaw torque = Jaw length x Grip force (2)

Effective jaw length is the distance from the motor spindle to the centre of gravity of the payload which equals 30mm (0.03m) (Fig. 4).

Jaw torque =0.03*14.72 = 0.442Nm

Thus the specifications for the Gripper: 14.72 N say 15N of grip force, 0.442Nm of torque.

E. Design of the actuator

The concept of the linear actuator developed is as shown in Fig. 5. The fundamental of the actuator mechanism is the screw-nut relative motion. The rotary motion of the screw is translated to the linear translatory motion of the nut. As the motor rotates the screw, the nut and by extension nut housing either advance out of the outer housing or retract depending on the motor spindle direction of rotation.

To determine the minimum force, the actuator must produce to actuate the manipulator links and by extension to lift the payload, consider the force diagram in Fig. 6.

L_p= pay load
W_b= weight of boom
F_1= Actuator 1 Force
K^o = Angle between actuator 1 and the Mast [AC] when Boom [AB] is horizontal.

For the actuator motor rating determination, the following assumptions were made:

i. F_1 is maximum when boom AB is horizontal.
ii. Among the actuators, Actuator 1 is expected to carry weight/ load (F_1).
iii. Actuator 1 is the basis of design for actuators 2 and 3.
iv. All hinges are assumed to be frictionless.
v. The motor bearings of the actuators are expected to bear the trust forces.
vi. The screws of the actuators only do the work of raising or lowering the loads/forces.

L_p = a maximum pay load of 150g is expected to be carried by the gripper

Therefore, $L_p = 0.15 * 9.81 = 1.472N$
W_b = Weight of boom or Link 2 (35 * 35mm square pipe of thickness 1mm was used). Length of boom, 0.3m, mild steel density; 7840kg/m^3

Mass of the boom = 319.6g = 0.3196kg
$$W_b = 0.3196 \text{ kg} * 9.81 = 3.135N \quad (3)$$

Taking moment about A
$$F_y * 0.075 = (W_b * 0.15) + (L_p * 0.30) \quad (4)$$
$$F_y = \frac{(3.135 * 0.15) + (1.472 * 0.30)}{0.075}$$
$$F_y = 12.158N$$
$$F_y = F \cos k^o, \quad (5)$$

k^o is to be 30^0 (pre-configured)

$$F = F_y/\cos k^o = 12.158/\cos 30^0 = 14.039N \quad (6)$$

F= 14.039N (load expected on Actuator 1)

Taking gripper weight, frictions at the hinges as well as on the bearing into consideration, F= 20.00N was used in subsequent calculations. It is a common practice in machine design to use a value greater than the calculated value in order to increase the factor of safety [13].

The screw to be employed in the actuator is to have a nominal diameter of 5mm. The threading is ACME thread (Kerk 3/16" [5mm] diameter lead screw, https://www.haydonkerkpitman.com) For the modified ACME thread, 5mm nominal diameter, root diameter (d_c) =4.14mm, pitch (p) = 1mm.

With d=5mm=0.005m
Force P to overcome friction at the screw i.e to turn the screw [13],

$$P = F \tan(\alpha + \text{Ø}1) = F * \frac{\tan\alpha + \tan\text{Ø}1}{1 - \tan\alpha\tan\text{Ø}1} \quad (7)$$

F= 20N
$$\text{Tan } \alpha = \frac{p}{\pi d} = \frac{1mm}{\pi 5mm} = 0.0637 \quad (8)$$

Ø1= virtual friction angle, tan Ø1= μ1
$$\mu 1 = \frac{\mu}{\cos\beta} \quad (9)$$

where μ (coefficient of friction between screw and nut) is taken as 0.15 [13]
β= semi angle of the ACME thread.
For ACME thread $2\beta = 29^0$, $\beta = 14.5^0$
Therefore
$$\mu_1 = \frac{0.15}{\cos 14.5} = 0.155$$

Substituting,
$$p = 20\left[\frac{0.0637 + 0.155}{1 - (0.0637 * 0.155)}\right] = \left[\frac{0.2187}{0.9901}\right] * 20 \quad (10)$$

P= 4.418N
Torque (T) required to turn the screw is given by
$$T = p * \frac{d}{2} = 4.418 \times \frac{0.005}{2} = 0.011Nm \quad (11)$$

Power required to drive the screw (P_w)
$$P_w = \frac{T * 2\pi N}{60} = \frac{0.011 * 2\pi}{60} N, \quad (12)$$

N is the speed of the electric motor in revolution per minute (rpm)
$$P_w = 0.00116N$$

0.00116 $= \frac{Pw}{N}$, thus a motor with power to speed ratio equal 0.00116 or more shall be adequate to power the actuator.

F. Motor selection

The manipulator is expected to be operated by three identical actuators. A motor with power to speed ratio equal 0.04 or more shall be adequate to power each actuator as previously calculated. Azgiant 895 motor with power rating 368W, 12 DC volts, 5mm spindle was selected (available at www.aliexpress.com). It has shaft speed of

6000rpm. This gives power to speed ratio of 0.061 which is greater than 0.00116.

The gripper motor is expected to develop a gripping force of 15N, and 0.442Nm of torque Based on these requirements, D20-060-380-10D 3V Brushed DC gear motor was selected to power the gripper (available at https://m.alibaba.com>motor).

G. Control switch and power source

The control switch panel is designed to have four bi-directional switches made up of a switch for each of the link actuators (2 in number), one for the base actuator and the remaining one for the gripper. The manipulator operator visually guides the links and the gripper to achieve the desired grasping/lifting operation by depressing the switch controlling the desired link's actuator. Pressing the switch in a direction advance the actuator rod out of its sleeve and correspondingly moves the attached link. Pressing the switch in the opposite direction retracts the actuator rod to the sleeve. Based on the power ratings of the motors, a battery bank of four 9V alkaline cells (Duracell) served as the power source and it is housed below the manipulator base.

H. Performance evaluation.

The performance evaluation of the manipulator was based on two goals set out in the design parameter: (i) ability to lift and transport the design payload repeatedly without slippage during manipulation; and (ii) the ability of the gripper reference point to consistently reach the maximum vertical reach of the manipulator design work envelope. For the payload test, materials of three different geometries (a cuboid, a cylinder and a sphere) made from plastic but with identical masses were lifted and manipulated and observations were made of tendencies to slip through during movement of the gripper.

For the second evaluation, a Repeatability test was set up according to the schema presented in Fig 7. During the repeatability test, the manipulator was operated via the control switches. The griper reference point was repeatedly made to touch a dial gauge (Mitutoyo, Max. range 2.5mm; accuracy, $\pm 5\mu m$) mounted on the vertical stand in such a way that the vertical height of the gauge contact point above horizontal reference datum corresponding to the design maximum vertical reach of the manipulator. Initially, the gripper reference point was made to contact the dial gauge at the design maximum vertical reach. The reading on the gauge was noted. Next, the manipulator was operated to repeatedly retract from and approach the gauge. Dial gauge reading for each cycle of retraction from and touching of the gauge was recorded. This was repeated ten times. This method of repeatability test was based on Distance repeatability test as described in ISO 9283-1998 standard [14]. Dial and digital indicators are measuring equipment frequently used for the robot position repeatability not only at university´s laboratories but also at research workplaces or industrial practice [15]

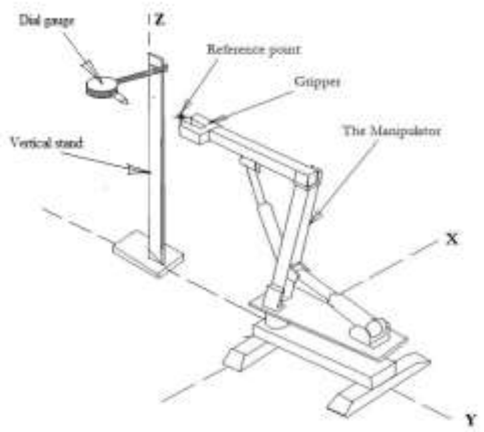


Figure 7: Repeatability test set up
(Image source: The authors)

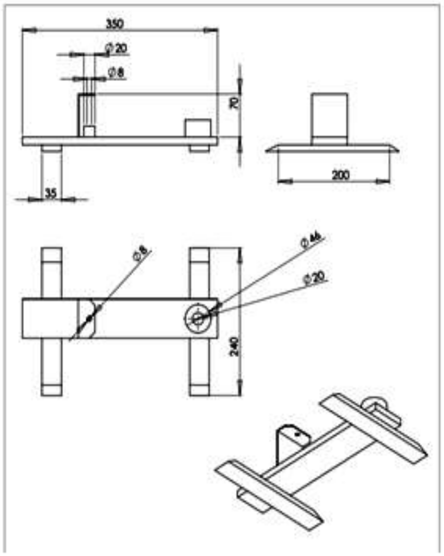
Distance repeatability test is the closeness of agreement between several attained distances for the same command distance, repeated n times in the same direction. Distance repeatability (RD) for a given command distance is calculated as follows [14]

$$RD = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_j - D_m)}{n-1}} \qquad (13)$$

where Dj is the individual distance measured and Dm is the command distance; n is the number of repeated trials.

III. Results and Discussion

The working drawings for the fabrication of the individual components of the manipulator are as presented in Figs. 8 to 15. The assembly drawing as well as the picture of the developed electromechanical manipulator is as presented in Fig. 16. The circuit diagram for the control switches is as depicted in Fig. 17. M1, M2 and M3 are motors for actuators 1 to 3, while M4 is the gripper motor. In terms of performance, the manipulator gripper was observed successfully lifting differently shaped payloads of 150g each of the test weights without slipping through the gripper jaws both when stationary and when in motion. For the repeatability test, the calculated repeatability was ±0.088 mm; this is a reasonable value given that factors such as speed of motion and the efficiency of the manipulator's joints do affect the overall accuracy. This cannot be precisely controlled for each trial run since the manipulator control is manually operated instead of being run by a programmable computer as is the case for robotic arms. The overall cost of materials and standard components was NGN 38,000 (USD 77.00). This is relatively cheap in comparison with Wlkata Mirobot (2021 upgrade version), a 6-axis open source mini industrial robotic arm, with maximum payload of 400g designed for educational purposes which was priced at USD 1540 (https://ozrobotics.com, as at 04/01/2022). The basic information (as measured) for the manipulator prototype is as presented in Table 1.



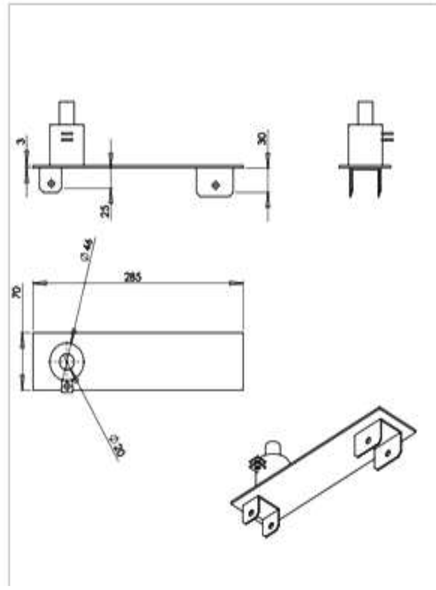
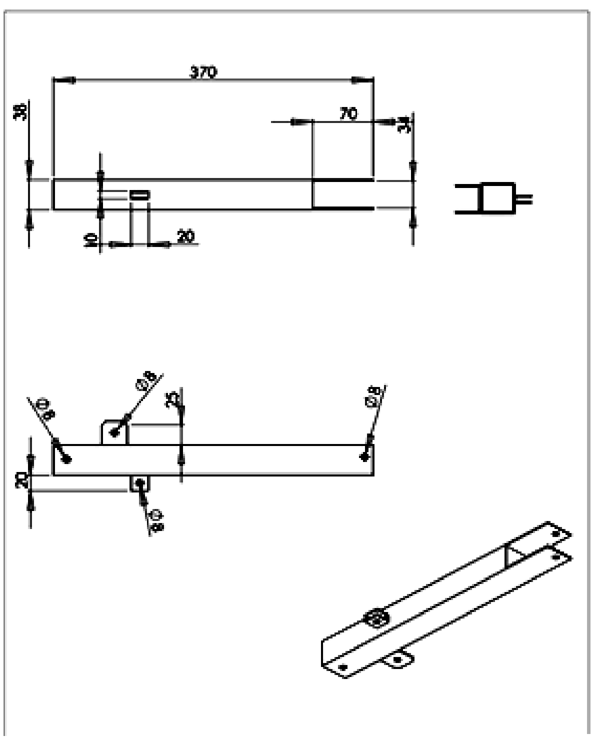


Figure 8. The Base

Figure 9. The Shoulder

(Source: The authors)



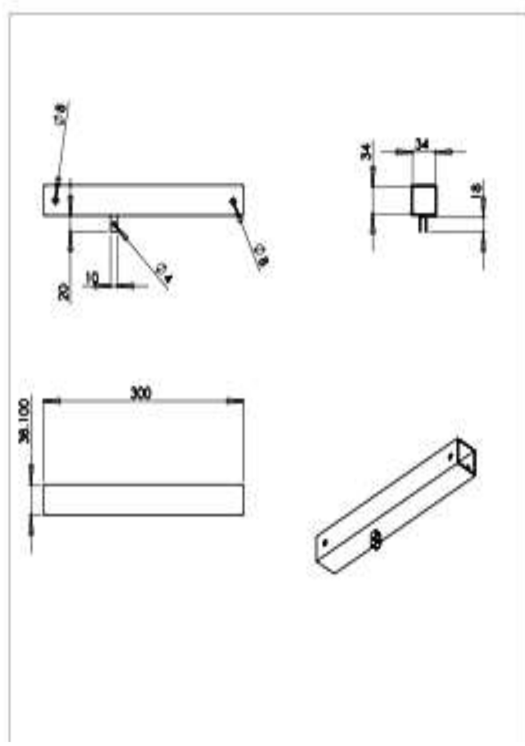


Figure 10. Upper Arm (Link 1)

Figure 11. Lower Arm (Link 2)

(Source: The authors)

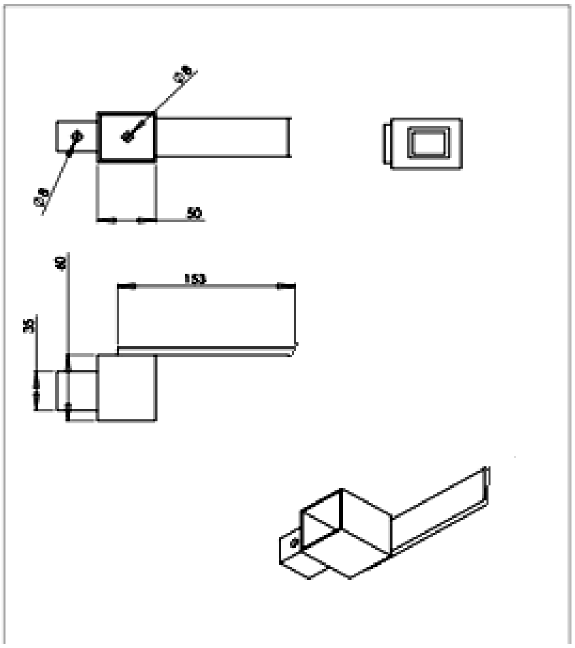


Figure 12. The gripper frame (Thumb)

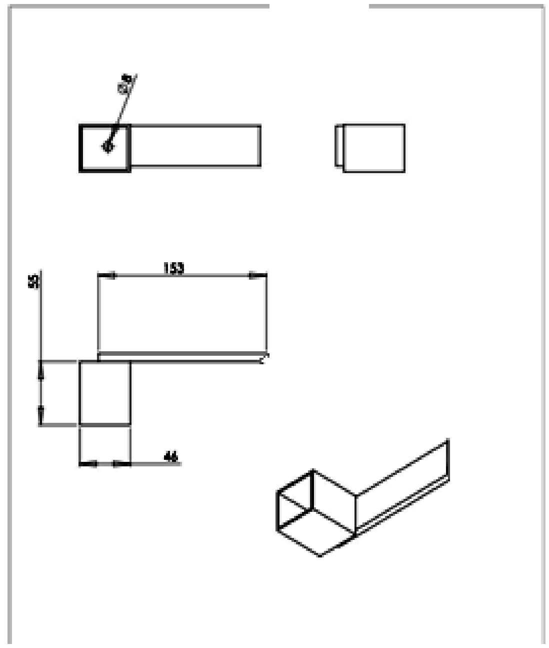


Figure 13. The gripper frame (Finger)

(Source: The authors)

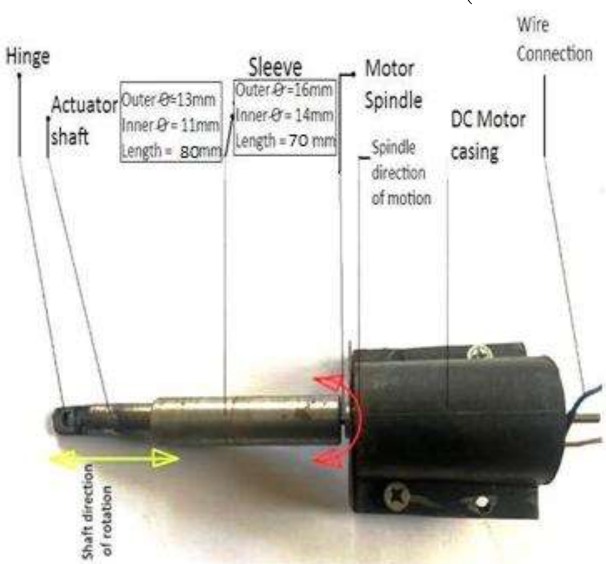


Figure 14. The developed Actuator

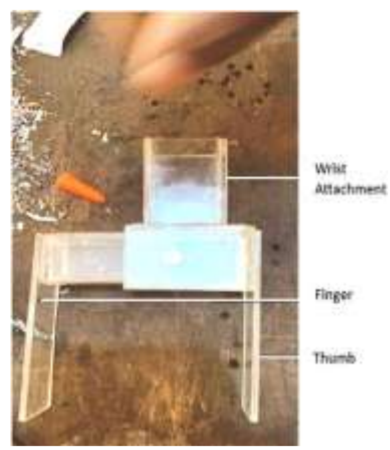
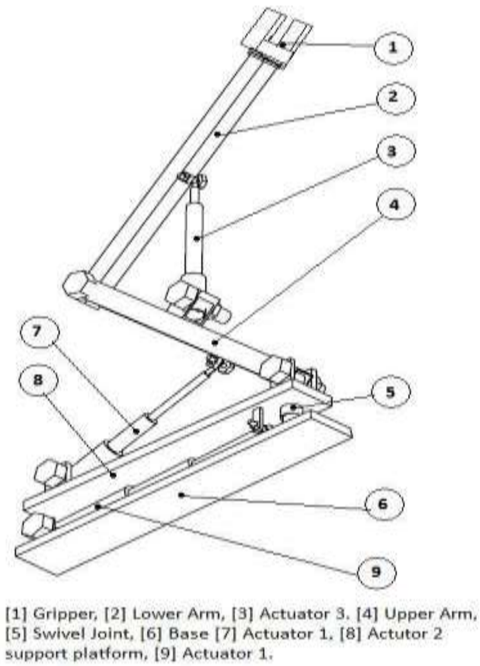
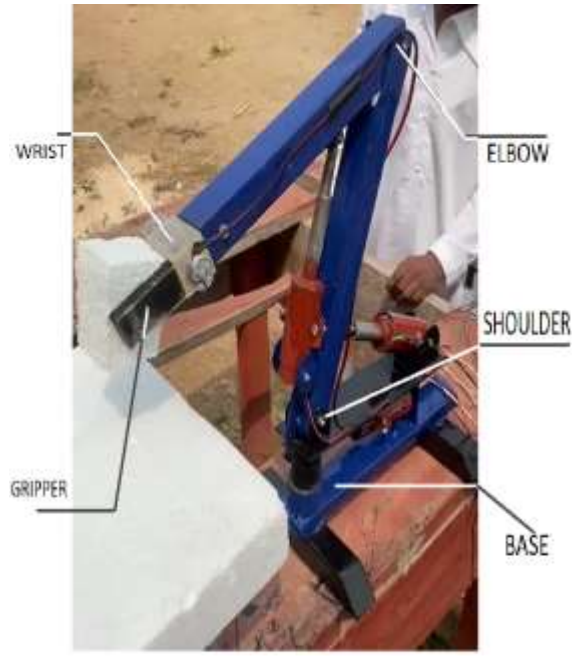


Figure 15. The Fabricated Gripper (without the motor and the rubber padding)

(Source: The authors)





(a) (b)

Figure 16. The Manipulator (a) Assembly drawing, (b) Manipulator during demonstration (Source: The authors)

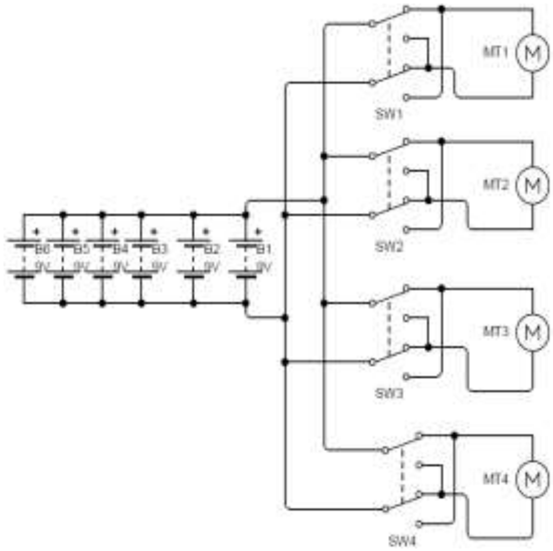


Figure 17. Control switches circuit diagram. (Source: The authors)

Table 1. The Manipulator Basic Information

Manipulator Specifications	Manipulator Motion Range
Axes: 3 Payload: 0.15 kg H-Reach: 550 mm [from shoulder level] Manipulator Mass: 3.7 kg Structure: Articulated Mounting: Floor, Table top	J1...... +60°-90° J2...... +80° -0° J3...... ±75°

IV. Conclusions

The electro-mechanical manipulator detailed in this paper fulfilled the stated goal of affordability and simplicity. It is also useful in the teaching of the fundamentals of the robotic arm, electromechanical actuators and linkages as students in these fields can acquire necessary practical understanding in the process of reproducing the manipulator. The manipulator components can be improved upon in the process of reproduction as deemed fit, thus allowing for creativity. The materials of construction are readily available, and standard components are not very expensive going by the overall cost of the materials used in the fabrication.

Acknowledgement

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