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Design and Manufacturing Using 3D Printing Technology of A 5-DOF Manipulator for Industrial Tasks

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ABSTRACT

Robotic manipulators have become very necessary in industrial applications all over the world. In this paper, a 5-DOF robotic manipulator is designed and manufactured to simulate a real industrial task. The manipulator is intended to transfer an object with a weight of 30 grams from a known place to another known one, which is a pick and place task. Firstly, all parts of the manipulator are designed using SolidWorks software. During the design, all parts' dimensions are considered. The end-effector of the manipulator is designed based on gear system. Secondly, 3D printing technology is used to manufacture these designed parts. The manufacturing process is very accurate and efficient. Servo motors are considered to do the motion of the manipulator, which are easily and directly connected to the control circuit. As, 5-DOF manipulator is manufactured, five servo motors are used: one motor for every joint. The motion of the motors is controlled by Arduino Uno unit which is a cheap and easy programming unit. Experiments are executed with the developed robot to show its effectiveness and success by preparing three boxes which the robot effectively transfers from one place to another. Eventually, the challenges during the design and manufacturing of this robot are mentioned in this paper.

1. Introduction

This section is divided into three subsections; 1) background about the robotic manipulator and its applications and types; 2) literature review about manipulator design and manufacturing; and 3) the challenge, main contribution, and outline of this paper. These subsections are presented as follows.

1.1. Background

Robotic manipulators became very important and necessary in industrial tasks, [1], [2]. These robots can be used in transferring materials from place to another, lifting heavy objects, collecting the parts and materials and in assembly processes, [3]-[6]. Also, in welding and other machining processes such turning, drilling, grinding, shearing, and milling, [7]-[12]. Using the robotic manipulator in these tasks can save time and effort and increase the rate of production, [13]-[16]. Currently, robotic manipulators are widely found in food and canning factories, automobiles industry and assembly, and equipment manufacturing, [17]-[20]. Industrial manipulator is divided into five types based on its first three joints [21]-[23]; articulated, spherical, SCARA, cylindrical, and Cartesian manipulator. The difference between these types of manipulators is shown in Fig. 1. In the current paper, the articulated 5-DOF manipulator is considered and developed.

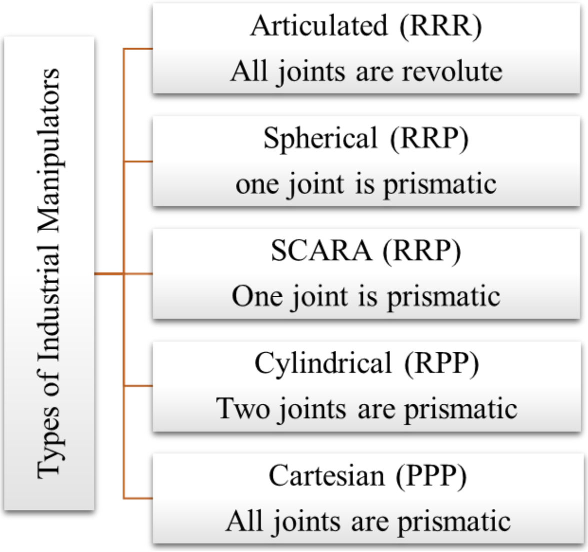


Fig. 1. The types of the industrial manipulator depend on its first three joints. In the figure, revolute means rotational motion, whereas prismatic means linear motion

1.2. Literature Review

Designing and implementation the robotic manipulators was considered by previous researchers. In [24], Khalid et al. designed a 2-DOF articulated manipulator for assembly tasks. Two servo motors were used for doing the motion. Their work was implemented in simulation environments only. Manufacturing the robot in real environments was not conducted. Fahruzi and his group [25] implemented a 4-DOF articulated manipulator for detecting the objects' position using a camera. In their work, three servo motors were used to do the motion. In addition, Arduino Uno Microcontroller was used to control the manipulator motion. Their results showed errors in the detection process. In [26], Farman et al. designed and manufactured a 3-DOF articulated manipulator to pick and place task based on color sorting using a camera. They made the mechanical calculations for the manipulator and used the servo motors for the motion. In addition, the motion of the motors was controlled by Arduino microcontroller and MATLAB software. Tests to check the accuracy and the repeatability were conducted and errors were found by the camera and the manipulator end-effector. In [27], Reddy and Eranki designed a 3-DOF manipulator for lifting a sheet using suction cups. In their design, two joints were revolute, and one is prismatic. Their design was with the help of Creo-Parametric and they only work in simulation environment which was Autodesk-Inventor 2017. Manufacturing the robot in the real environment was not considered. Noshahi et al. [28] developed A 4-DOF SCARA manipulator for pick and place task. The manipulator was manufactured using Aluminum material and for doing the motion of the robot, DC motors were used. To control the motion of the robot, PIC18F452 microcontroller was used, and H-bridge circuit was required to help in connecting the motor with the microcontroller. Their experiments with the robot presented satisfactory results. In [29], Ahmed et al. designed and implemented a 4-DOF manipulator to do industrial task. The manipulator was manufactured using Aluminum sheets. Three stepper motors were used to do the motion of the first three joints, whereas the gripper joint used a servo motor. Arduino unit is used to control the motors' motion and TB6600 motor drive was used to connect the stepper motors with Arduino. The main problem with them was modifying the speed of the stepper motors. Kruthika et al. [30] developed a 5-DOF manipulator for feeding elderly people. DC motors were used for the manipulator motion and a force sensor was put at the manipulator end-effector to detect the pressure amount applied on the object. Arduino Mega2560 was used to control motion and therefore L298 H-bridge was required to connect the motors with the Arduino platform. For a clear presentation, this literature is presented in Table 1.

Table 1. Comparison between the designed robotic manipulators by previous researchers

Researcher	Year	Number of DOF	Task	Used Motor	Controller	Drawbacks
Khalid et al. [24]	2021	2-DOF	Assembly task	Servo motor	MATLAB	Simulation environment only was considered.
Fahruzi and his group [25]	2021	4-DOF	Detecting of objects' position	Servo motor	Arduino Uno Microcontroller	Errors in the detection process.
Farman et al. [26]	2018	3-DOF	Pick and place task	Servo motor	Arduino microcontroller and MATLAB	Errors were found during the task
Reddy and Eranki [27]	2016	3-DOF	Lifting a sheet	Their design was by Creo-Parametric, and they only consider simulation environment which was Autodesk-Inventor 2017.		
Noshahi et al. [28]	2019	4-DOF	Pick and place task	DC motor	PIC18F452 microcontroller	H-bridge circuit was required to connect the motor with the microcontroller.
Ahmed et al. [29]	2019	4-DOF	Industrial task (Its type was not mentioned)	Three stepper motors and one servo motor	Arduino unit	TB6600 motor drive was used to connect the stepper motors with Arduino. Also, problems with modifying the speed of the stepper motors.
Kruthika et al. [30]	2017	5-DOF	Feeding elderly people	DC motor	Arduino Mega2560	L298 H-bridge was required to connect the motors with the Arduino unit.

1.3. Challenge, Main Contribution, and Outline

From the above discussion, we deduce that the main challenge is to design and manufacture a more than 3-DOF manipulator which can reach most of the points in its workspace. Servo motors as they are easily programmed and can be connected directly to the control unit compared with the DC and Stepper motors. This can help avoid using any additional interfacing unit between the motor and the control unit. In addition, the accuracy, and the repeatability of the robot to do the required task should be as high as possible and avoid any errors. The cost of developing the robotic manipulator should also be as small as possible.

The main contribution and novelty of this paper is discussed in the following points:

- A cost-effective principle (approximately 180$) of a 5-DOF robotic manipulator for doing an industrial task is developed and manufactured.
- The manipulator parts are designed using SolidWorks software. The end-effector is designed in an effective way to fit with other manipulator parts and therefore does the task effectively.
- 3D printing technology is used to manufacture all parts of the proposed manipulator and therefore high accurate parts' dimensions are obtained.
- Servo motors are used to do the motion of the manipulator as they are easy to be programmed and directly connected to the control unit (Arduino uno).
- Arduino uno unit is used to control the motion of the motors which is cheap and easy in programming.
- The main task of the developed manipulator is to transfer an object from a known location to another known location. Therefore, there is no need for any external sensor and all work depends only on the Arduino programming.
- To check the repeatability of the manufactured robot manipulator, three boxes of 30 grams are put at three different known positions. The manipulator is used to transfer them to another known positions. The results show that the manipulator works effectively and successfully.

The steps conducted to design, manufacture, and control of the 5-DOF manipulator are presented in Fig. 2.

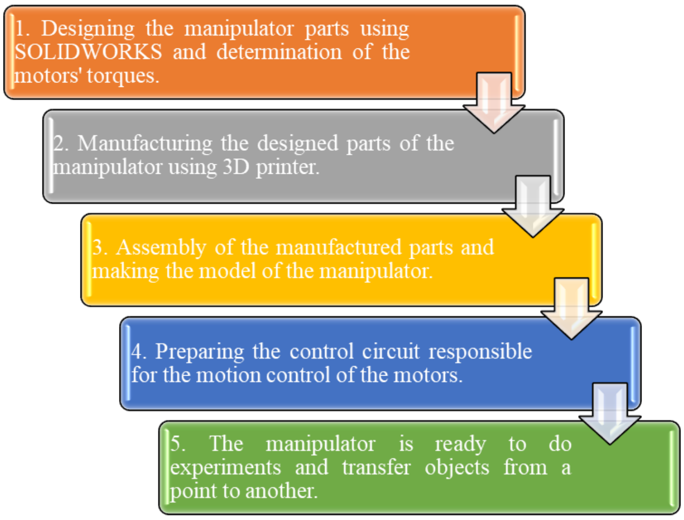


Fig. 2. The conducted steps to develop the 5-DOF manipulator

The rest of the paper is divided into the following sections: Section 2 shows the mechanical design of the manipulator parts and presents some calculations about the motor torque and the gear system used with the end-effector. In Section 3, manufacturing the manipulator parts using 3D printing technology is presented. Section 4 shows the assembly process of the manipulator parts, the control of the motor motion using Arduino unit, and the experiments with the three boxes to check the repeatability of the developed manipulator. Section 5 concludes the main points in this paper and presents some recommendations for future work.

2. Mechanical Design and Calculations

In this section, the proposed manipulator is designed using SolidWorks Software. This software is used because it is easy to design, easy to make any change to the model, the design operation can be performed in a fast time, and any type of model whether complex or simple can be designed, [31]-[34]. The complete design is shown in Fig. 3. During this design, some points are taken into consideration: 1) the robot should be more effective in carrying out the task, 2) the end-effector should fit more with the rest of the robot parts to be easier and more effective to control it, and 3) the base is designed in a proper form to fix the robotic arm on a stable surface (wooden board), so that it can work smoothly.

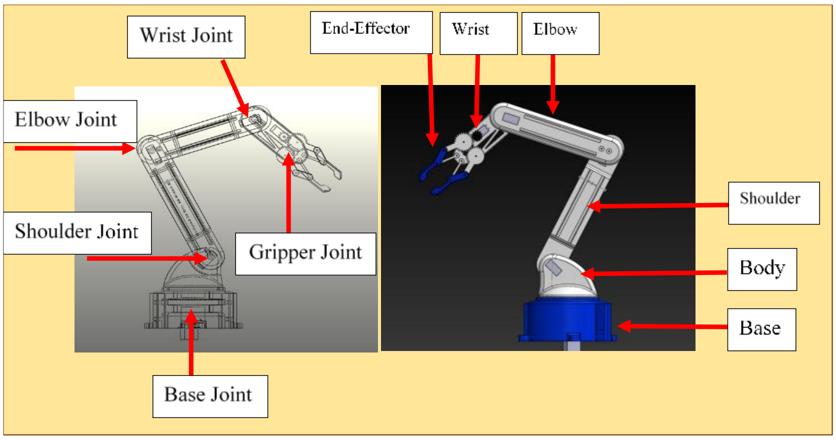
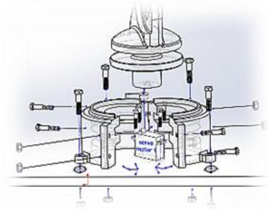
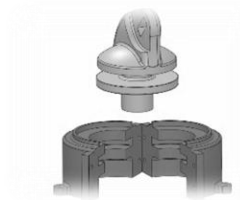
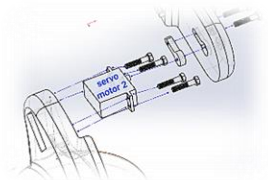
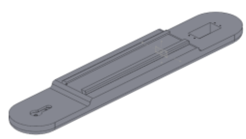
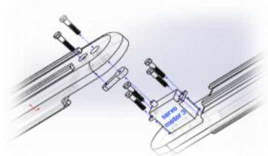
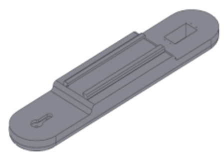
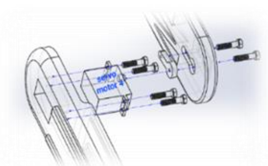
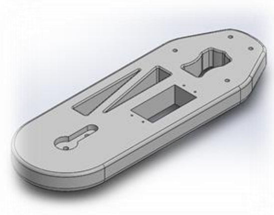


Fig. 3. The complete design of the 5-DOF manipulator. The left side shows the joints, and the right side shows the links of the manipulator

2.1. Design Using SolidWorks

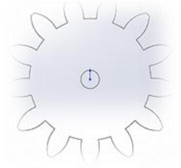
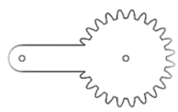
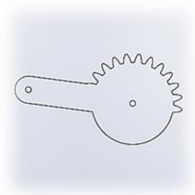
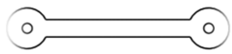
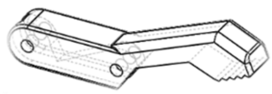
SolidWorks software is used for the design process. The main components of this robot from the base to the wrist are discussed in Table 2. The end-effector is discussed alone.

Table 2. The components of the developed 5-DOF manipulator

The part	Definition and Dimensions	Illustrating Figure
The Base link and joint	It is a cylindrical part consisting of two separate parts that are joined together by means of four anchor bolts, and it is the fixed part of the arm. Circular tracks are designed on the inside of the base so that the entire robotic arm can move in a circular and smooth manner. The dimensions of this part are as follows: the external diameter is 200 mm, the internal diameter is 100 mm, and the height is 100 mm. The base joint includes a servo motor which rotates the robot around its base.	
The body	It is a cylindrical shape with a circular disc in the middle that overlaps at the base to move in a circular motion around the Y axis. The used dimensions of this part are as follows: the body diameter is 70 mm, the body height is 200 mm, the disc diameter is 175 mm, and the disc height is 20 mm.	
The shoulder Joint	The shoulder joint allows the robotic arm to move up and down by the help of servo motor.	
Shoulder Link	The shoulder link is connected to the body of the robotic arm by a single joint which typically provides one degree of freedom of movement and allows the shoulder to move up and down. The dimensions of this link are as follows: the height is 400 mm, the width is 70 mm, and the thickness is 30 mm.	
Elbow Joint	This joint allows the wrist of the robotic arm to be bent and straightened by using a servo motor. It connects the elbow link with the shoulder link.	
Elbow link	The elbow link is connected to the shoulder link via a single joint. Also, it is connected to the wrist link via another single joint. Every joint provides one degree of freedom of movement. The dimensions of this link are as follows: the height is 350 mm, the width is 70 mm, and the thickness is 30 mm.	
Wrist joint	This joint allows the robotic arm to rotate the wrist link and the end-effector (the tool or gripper at the end of the arm) around its axis by using a servo motor.	
Wrist link	It is connected to the end-effector via one single joint. Its dimensions are as follows: the height is 204.27 mm, the width is 70 mm, and the thickness is 15 mm.	

The end-effector is particularly important in the robotic arm as it is used to do the main job, which is transferring the materials from place to another. In our design, it depends on gear system and is composed of fingers which are opened and closed using servo motor. The components of the end-effector are shown in Fig. 4 and discussed in detail in Table 3.

Table 3. The components of the end-effector (gear system) and their dimensions

The part	The Dimension	Illustrating Figure
Drive gear 1 (Spur gear)	Diameter = 25.5 mm Number of teeth = 13 Thickness = 5 mm	
Driven gear 2 (Spur gear with link)	Diameter = 47 mm Number of teeth = 24 Thickness = 5 mm Length of link = 38 mm	
Driven gear 3 (Partial toothed gear with link)	Diameter = 47 mm Number of teeth = 12 Thickness = 5 mm Length of link = 38 mm	
Coupling link	Length = 66.5 mm Width = 12.25 mm Thickness = 5 mm	
Gripper	Length = 105.77 mm Width = 20 mm Thickness = 15 mm	

2.2. Motor Torque Calculation

The torque of the used servo motors is calculated in the worst bearing position of the robotic arm, as shown in Fig. 5. Therefore, the maximum torques of each joint is calculated based on the following equation:

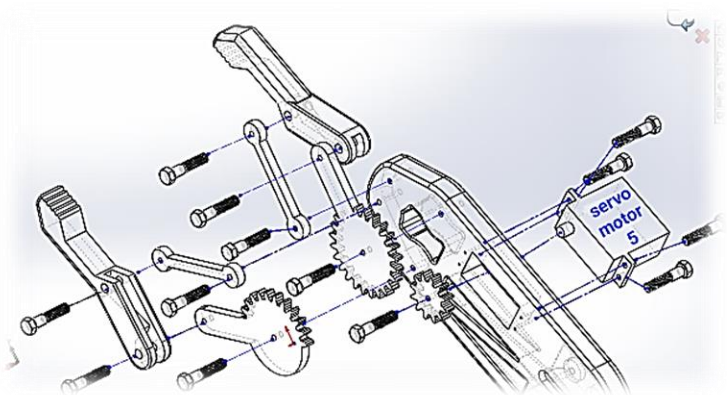


Fig. 4. The components of the end-effector (gear system)

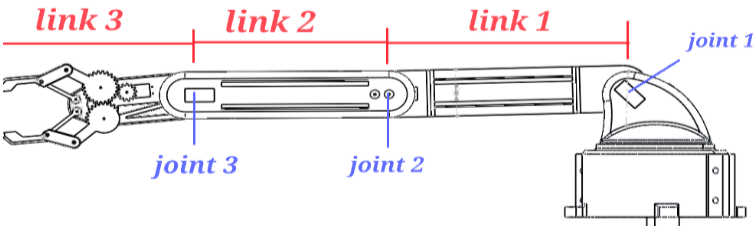


Fig. 5. The method used for calculating the torque of the used motor on each joint. Joint 1 in the Figure is the shoulder joint

$$\text{Max}\, Torque = T_{joint\,1} = \left(W_{link\,1} * \frac{L_{link1}}{2}\right) + \left[W_{link2} * \left(\frac{L_{link2}}{2} + L_{link1}\right)\right] + \left[W_{link3} * \left(\frac{L_{link3}}{2} + L_{link2} + L_{link1}\right)\right] \quad (1)$$

Equation (1) shows the method used for calculating the torque of the used motor on the shoulder joint. The same method is followed for the motors used with the elbow and wrist joints.

2.3. Gear System Calculation

As mentioned above, the end-effector is composed of three main gears as shown in Fig. 6.

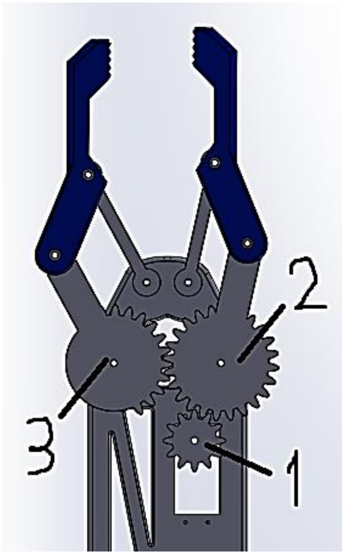


Fig. 6. The gear system in the end-effector part

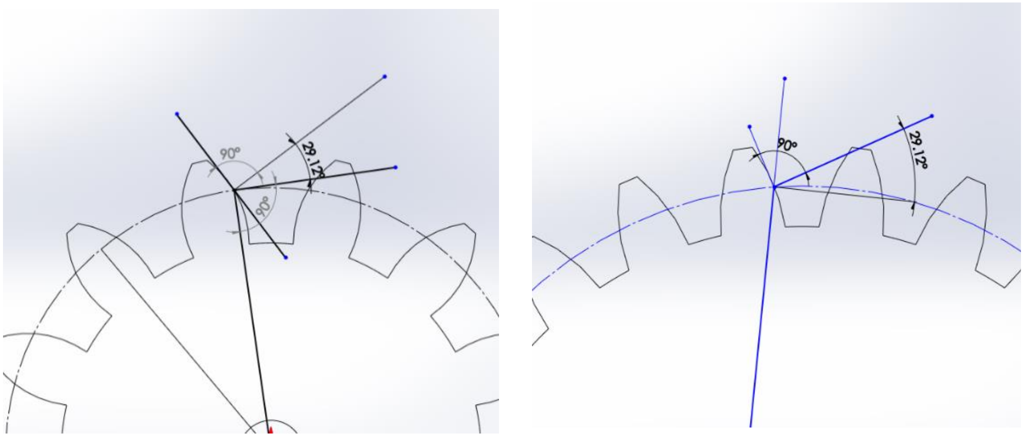
The diametral pitch (Pd) of the used three gears are equals and are calculated as follows:

$$\begin{aligned} \text{Pd for gear 1} &= \frac{N}{D} = \frac{13}{25.5} \cong 0.511 \\ \text{Pd for gear 2} &= \frac{N}{D} = \frac{24}{47} \cong 0.511 \\ \text{Pd for gear 3} &= \frac{N}{D} = \frac{12\times 2}{47} \cong 0.511 \end{aligned} \quad (2)$$

The pressure angle α is also equal for the three gears (α1 = α2 = α3), as shown in Fig. 7.

3. Parts Manufacturing Using 3D Printer

In this section, the manufacturing of the parts of the robotic arm using the 3D printing technology, is discussed. 3D printing has many advantages such as the production process is accurate and fast, flexibility, cost effective, and the waste of material is reduced, [35]-[37]. 3D printing is very important in manufacturing [38]-[40], particularly with robotics, [41]-[43]. The printing process involves making and printing various parts such as the shoulder link, elbow link, base, and end effector. In addition, the sensitive parts such as the spur gear, spur gear with link, partial toothed gear with link and coupling link. The material used is plastic which is light and therefore the used motors have small torques. Therefore, the cost will be minimized. During the printing process, the plastic material provides the necessary durability and strength for the hand while the precision and accuracy is considered. This innovative use of 3D printing technology allows us to design and create a highly functional robotic arm that can move freely in 5-DOF. Overall, this work presents the effectiveness and the potential of 3D printing technology in the field of manufacturing robotic arms. Therefore, 3D printing is promising in designing prosthetic limbs that can be tailored to meet the specific needs of individuals. The faced challenges during the 3D printing process are discussed in the following subsections.

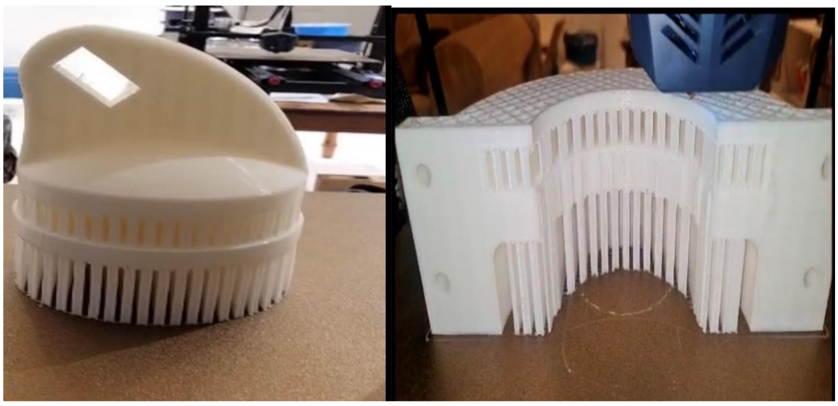


(a) (b)

Fig. 7. The pressure angle for (a) gear 1, and (b) gear 2 and 3

3.1. Solid Shape

In the beginning, we printed the body part as a solid shape, but it was found that it was too heavy and consumed a lot of plastic material. As the body does not need to move a lot after installation, it was printed with small hollow square shaped gaps as shown in Fig. 8 (a). This design saves some of the plastic material and reduces weight while still providing the necessary support for the design. In addition, it takes short time rather than the solid form with less cost price. while the design has square gaps and the plastic material during printing becomes semi-molten and it can be contracted or expanded due to temperature changes, therefore we used support to save the parts and prevent bending or distortion. Printing the base part is shown in Fig. 8 (b).



(a) (b)

Fig. 8. Printing the (a) body part, and (b) the base part

3.2. Effect of Temperature Change on Plastic

The joints of the manipulator, shown in Fig. 3, are considered during the printing process. Holes were made at the robot links for fitting the servo motors which are responsible for the motion, as shown in Fig. 9. During the printing process, the temperature change affects the plastic material which is expanded with the increase of temperature and be in semi-molten shape and contracted with decrease of temperature and be in solid shape. Therefore, the temperature affects the diameter of designed holes for the servo motors. Therefore, these diameters were increased to face any possible contraction in the plastic material to easily fit the servo motor.

Fig. 9. Hole after link printing for fitting the servo motor

3.3. End-Effector Parts

The parts of the end-effector are called sensitive because they are small and there is a possibility of being damaged due to their movement or over time. Therefore, we printed many of them, and for some of them, the thickness is increased. This can help to develop and operate the robotic manipulator with optimal efficiency. These parts are shown in Fig. 10.

Some videos for the 3D printing process for the manipulator parts are provided as attachments to this paper.

4. Experiments

This section is divided into three subsections: The first subsection shows the assembly of the parts of the manipulator, the second section shows the programming using the Arduino unit, and the third section shows some experiments conducted with the implemented robot.

Fig. 10. Printing the small parts of the end-effector

4.1. Manipulator Assembly

For the installation of the proposed 5-DOF robotic manipulator, a table with dimensions of 140 cm height and 75 cm width, has been designed. This table is made from wood and is painted white color. It is drilled with holes of 65 cm diameter close to its end to mount the robotic arm using screws, as shown in Fig. 11. Between the screw holes, a hole for the servo motor is also drilled that is installed under the body, allowing it to move to the right or the left. The space between the body and the base is lubricated to ensure smooth movement and prevent friction.

Fig. 11. The used table for installing the robot

The body is assembled with the base onto the table and the servo motor is mounted at its specific location. Before completing the assembly process of the rest of the robot arm parts, the servo motor is connected to the Arduino unit to evaluate its motion. It is found that the body part can rotate left to right and right to left efficiently. In another meaning, the test was successful and remarkable. Therefore, we continued to assemble the other parts of the robot such as the shoulder, elbow, wrist, and the end-effector and the servo motors are placed at their specific locations. It should be stated that a suitable power source (battery) for the motors is considered to allow the motors to work effectively. The voltage of the used battery is 12 Volt. The motor at each joint is assessed and is found that it works in an efficient way. Some photos taken during the assembly process are shown in Fig. 12. At the end, the robot arm becomes ready to do the desired job.

4.2. Motors' Control Using Arduino Unit

To control the motion of the used motors, Arduino Uno unit is used. Arduino uno is an open-source platform which contains the microcontroller which is responsible for the control process. The programming language of this unit is based on C++. The Arduino unit is cheap, simple, widely used with many projects, and easy in its programming, [44]-[46].

Servo motors are selected compared with the DC and stepper motors due to the following reasons, [47]-[50]. The servo motor is easy to be programmed. In addition, the servo motor has three wires: one wire for the voltage, another one for the ground, and the last one for the control signal. In another meaning, the servo motor is connected directly to the Arduino uno unit. Compared with the DC and stepper motors, they need a motor drive to be connected with the Arduino. In another meaning, the DC and stepper motors cannot be connected directly with the Arduino unit. As in our design, we have five joints, therefore, we use five servo motors and one motor for every joint. The connection between the motor and the Arduino is shown in Fig. 13. The used types of the servo motors in our work are presented in Table 4.

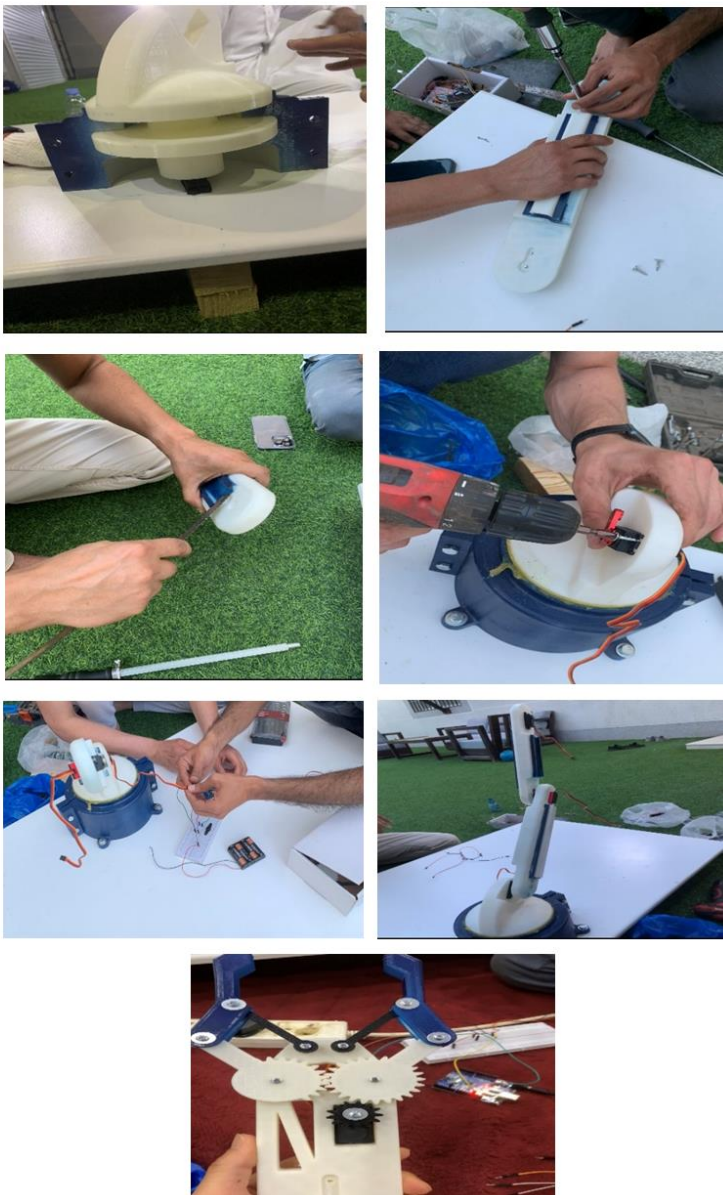


Fig. 12. Some taken photos during the assembly process of the developed 5-DOF robotic manipulator

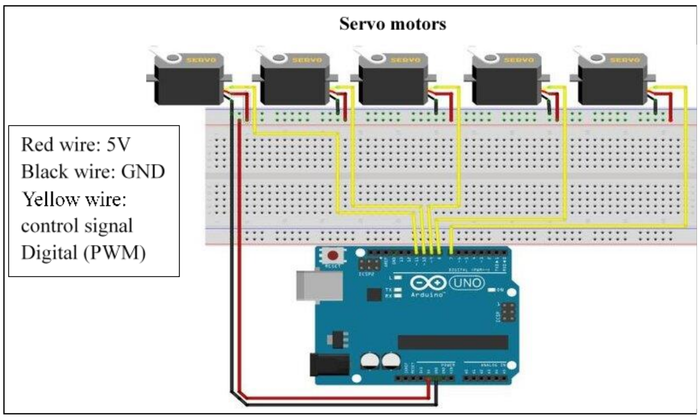


Fig. 13. The connections between the servo motor and the Arduino unit. In the Figure, five motors are used as one motor for every joint. This is an illustrative Figure showing how the servo motor is connected to Arduino Uno. In our work, the yellow wires are connected to pin 3, 5, 6, 10, and 11

Vol. 4, No. 2, 2024, pp. 893-909

Table 4. The used types of the servo motors in this work

Joint	Type of servo motor
Base	Servo 360 Degree NO.3003 12Kg
Shoulder	Servo SG90 120 Degree
Elbow	DM-S0306D Digital Servo 270 Degree
Wrist	MG90 MG90S 180 Degree
Gripper	Servo SG90 9g 120 Degree

The Valve Regulated Lead Acid battery is used for operation, and it is NP12-7Ah (12 volt, 7Ah)

To minimize the cost and the complexity, we considered a known environment surrounding the robotic manipulator. In another meaning, the main job of the robotic manipulator is to transfer a box from a known position to another known position. Therefore, no need for any external sensor. To do this job, we only depend on the programming of the motor motion via Arduino. The implemented code is presented in APPENDIX 1.

4.3. Experiments with the Manipulator

The main task of the manufactured manipulator is to simulate a real industrial task which is transferring material from place to another place. In this work, the manipulator is intended to transfer three boxes from one known place to another known place. The weight of each box is 30 grams. Indeed, this process is done to check the repeatability of the manufactured robotic manipulator. Fig. 14 shows some taken photos during the transfer of the first box (box 1) by the manipulator. The manipulator does the following steps during this task:

Fig. 14. Taken photos during the experiments done with the developed robot. These are seven followed steps by the robot to move the first box from a known position to another known position

- In step 1, the manipulator moves from its home/initial position to be close to box 1.
- In step 2, the manipulator moves down and catches the box with its gripper.
- In step 3, the manipulator moves up after catching the box.
- In step 4, the manipulator moves to the second known position where the box should be.
- In step 5, the manipulator moves down to be in the second known position where the box should be.
- In step 6, the manipulator leaves the box at the second known position and then moves up.
- In step 7, the manipulator moves again and is to be close to the second box (box 2).
- These steps are repeated to transfer box 2 and box 3.

By transferring the boxes from one place to another place, the manipulator proves that it works effectively and successfully in its task.

A video for the experiments during the transfer of the three boxes by the developed manipulator is attached to this paper.

5. Conclusion and Future Work

In this paper, the design and the implementation of a 5-DOF manipulator is presented. Solidworks software is used for the design process of the manipulator parts. Then, the designed parts are manufactured using a 3D printer which shows accurate and efficient manufacturing. For the motion of the robot, servo motors are selected. Compared with DC and stepper motors, servo motors are connected directly with the control unit and easily programmed. The Arduino Uno platform is used for controlling the motion of the servo motors which are found at each joint of the manipulator. For checking the effectiveness and the success of the developed manipulator, pick and place experiments are conducted. The mani proves that can transfer objects of weight 30 grams effectively. For some future work, the following points will be considered.

- Solving the problems of the friction that is still found during the motion of the manipulator.
- Operating the manipulator using the mobile phone via Bluetooth or Wi-Fi.
- Using external sensors to work with unknown environments surrounding the robotic manipulator.
- Using machine learning and artificial intelligence algorithms to further enhance the autonomy of the robotic manipulator and capabilities of decision-making.
- Extending the current work and design and manufacturing a 7-DOF manipulator.

Supplementary Materials: Videos for the 3D printing technology for manufacturing the parts of the manipulator and some experiments with the manufactured manipulator are attached to this paper.

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Appendix 1: the Implemented Code for the Motors' Motion of the Manipulator Using Arduino

The code runs from left to right and it is only one column but here we put it in four columns just to show in a short place/space.

```
#include <Servo.h>
Servo base;
Servo shoulder;
Servo elbow;
Servo wrist;
Servo gripper;
void setup()
{
base.attach(3);
shoulder.attach(5);
elbow.attach(6);
wrist.attach(10);
gripper.attach(11);
// Home Position
base.write(53);
shoulder.write(120);
elbow.write(170);
wrist.write(120);
gripper.write(110);
delay(3000);
}
void loop()
{
//box 1
 base.write(65);
   delay(2000);
 wrist.write(60);
   delay(2000);
elbow.write(170);
   delay(2000);
shoulder.write(100);
   delay(2000);
 gripper.write(15);
   delay(2000);
//box 1
 shoulder.write(130);
   delay(2000);
  base.write(0);
     delay(2000);
  shoulder.write(100);
     delay(2000);
  gripper.write(110);
     delay(2000);
  shoulder.write(130);
     delay(2000);
//box 2
base.write(75);
    delay(2000);
wrist.write(60);
    delay(2000);
elbow.write(160);
    delay(2000);
shoulder.write(95);
    delay(2000);
gripper.write(15);
    delay(2000);
//box 2
 shoulder.write(130);
    delay(2000);
  base.write(10);
     delay(2000);
  shoulder.write(95);
     delay(2000);
  gripper.write(110);
     delay(2000);
  shoulder.write(130);
     delay(2000);
//box 3
 base.write(85);
     delay(2000);
 wrist.write(60);
    delay(2000);
 elbow.write(150);
    delay(2000);
 shoulder.write(90);
     delay(2000);
 gripper.write(15);
    delay(2000);
//box 3
 shoulder.write(130);
    delay(2000);
  base.write(20);
     delay(2000);
  shoulder.write(90);
     delay(2000);
  gripper.write(110);
     delay(2000);
  shoulder.write(130);
     delay(2000);
}
```

List of Abbreviations

Abbreviation	Meaning
DOF	Degree of freedom
3D Printing	Three-dimensional printing
SCARA	Selective Compliance Articulated Robotic Arm
RRR Manipulator	Manipulator with revolute-revolute-revolute joints The first three joints of the manipulator are revolute
RRP Manipulator	Manipulator with revolute-revolute-prismatic joints
RPP Manipulator	Manipulator with revolute-prismatic-prismatic joints
PPP Manipulator	Manipulator with prismatic-prismatic-prismatic joints
DC	Direct Current

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