SciEn

Proceedings of 8th International Conference on Mechanical, Industrial and Energy Engineering 2024
02-04 January, 2025, Khulna, BANGLADESH

SciEn Conference Series: Engineering Vol. 3, 2025, pp 126-130 https://doi.org/10.38032/scse.2025.3.30

Design, Development and Performance Evaluation of a Vacuum type Gripper Based Pick and Place Robotic Arm

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ABSTRACT

This research paper presents the design and development of a 3 DOF Vacuum-type Gripper-based Pick and Place Robotic Arm, integrated with IoT capabilities to meet Industry 4.0 standards. The robotic arm addresses previous limitations in accuracy and precision, utilizing stepper motors instead of servo motors and operating without sensors. The arm is designed to move flat objects between locations with high precision, using a vacuum gripper and controlled by an ESP32 microcontroller. The system supports three modes: Autonomous, Web app-controlled, and Joystick-controlled. In Autonomous mode, a visual camera detection system identifies objects, and the arm automatically grasps them with its gripper. The Web app-controlled mode, hosted on an ESP32 microcontroller, allows for easy reprogramming without coding, while the Joystick mode uses a DS4 controller for manual adjustments. The robot's performance was evaluated through 50 trials at three different speeds (500mm/min, 166.67mm/min, and 100mm/min) and with various payloads (15-50g). Results showed that the robot could reliably handle objects within a 10-30g range, achieving 97% accuracy at minimum speed. Precision decreased at higher speeds but remained acceptable at moderate speeds. Overall, the use of stepper motors improved the robot's accuracy and precision. The study concludes that the robotic arm is a viable solution for automating pick-and-place tasks, enhancing productivity, safety, and cost-efficiency in industrial settings by replacing human labor in material handling. The system's adaptability and precision make it a promising tool for future industrial automation. This kind of robot will potentially reduce reliance on human labor in the material handling area.

Keywords: Pick & Place, Robotic arm, Vacuum gripper, IoT.

1. Introduction

Robots that pick and put objects can do so more quickly and precisely than humans. Most transfers are often done by hand when there are flat shaped pieces. Yet, if the operator performs these transfers frequently over an extended period of time, they will become tiresome and make mistakes [1]. The gripper may take the role of a human hand if it could be made to be able to grab objects of flat shapes and different weights. Even, the accuracy is about 70-90% [2]. If the microprocessor is programmed correctly, there will be a reduced possibility of error as it runs [3]. Hence, human errors brought on by fatigue will be reduced.

Quickness and consistency are crucial for productivity when it comes to production. Likewise, dangerous actions exist in every sector of the economy, and they are always guarded against [4]. The efficiency, profitability, and quality of the goods will all improve if pick-and-place processes can be automated utilizing a robotic arm since speed, consistency, and safety will all be optimized.

A robot that can pick up a certain object and place it in a predetermined spot is known as a pick and place robot [5-7]. This kind of robot will take the place of all human labor in the material handling area. Cycle times for the speedier activities will be shorter, which will lower operational costs as well. Industries will develop a highly repeatable pick-and-place system that is completely functional, precise, and able to react swiftly [8].

One type of robot commonly used in industry is a robotic manipulator or simply a robotic arm. It is an open or closed kinematic chain of rigid links interconnected by movable joints [9]. In some configurations, links can be considered to correspond to human anatomy as waist, upper arm, and forearm with joint at shoulder and elbow. At the end of arm, a wrist joint connects an end effect which may be a tool and its fixture or a gripper or any other device to work [10-13].

2. Objectives of the study

The main objective of this study is to construct a robot which can perform pick and place operations of flat types of objects using vacuum type gripper. Thus, this study focuses on:

1. Using Stepper motors to regulate the robotic arm's displacement so that it may pick and position objects from any source to any location.
2. Controlling the movement of the arm using ESP32 microcontroller and necessary programming
3. Assessing the robot's performance, including its precision and accuracy when handling objects of various forms.

3. Methodology:

3.1. Design and construction of the pick and place robotic arm:

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AutoCAD Fusion 360 is used to design the robotic arm. Snapshots of different parts are attached below to represent the complete design.

- **Base Arm:**
The stable platform to which an industrial robotic arm is attached. the base coordinate system (sometimes referred to as "**World Coordinate System"**) defines a common reference point for a cell or application.
- **Base Movement Gear:**
Base Arm is attached to base movement gear. This gear helps to rotate the base arm around 360 degrees.
- **Humerus:**
This controls the horizontal movement of the robot. This movement is along the Y-axis.
- **Radius:**
This controls the vertical movement of the robot. This movement is along the Z-axis.
- **Support Link:**
This link supports the humerus and radius. It works as a joint also.
- **Tri link:**
This link provides three links. humerus, radius and support link are connected through Tri-link.
- **Gripper:**
The vacuum type gripper is attached with the trilink of the robot, and it is the most important part for this robot. Silicon suction cup is used for the robot.

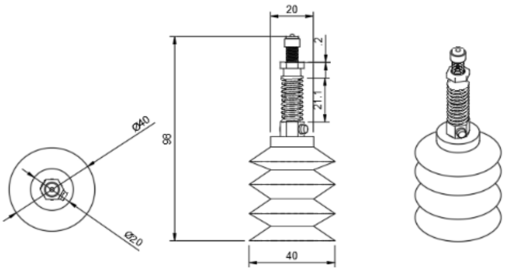

Figure 1: Gripper

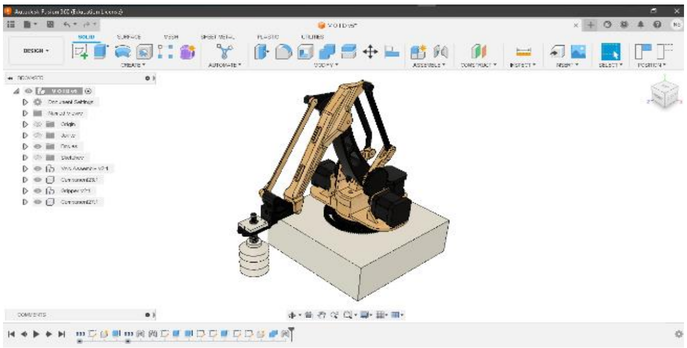

Figure 2: Designing of the pick and place robotic arm in Autodesk

Figure 3: The complete rendered view of the pick and place robotic arm

3.5. Description of electrical and electronic elements of robotic arm and their functions:

- **ESP32 microcontroller:** The ESP32 microcontroller low-power system with integrated Wi-Fi and dual-mode Bluetooth
- **NEMA-17 Stepper Motor:** The stepper motors move in precisely repeatable steps; hence they are the motors of choice for the machines requiring precise position control. The nema17 4.2 kg-cm stepper motor can provide 4.2 kg-cm of torque at 1.7A current per phase.
- **A4988 Step stick Stepper Motor Driver Module:** This breakout board for allegro's a4988 micro stepping bipolar stepper motor driver features adjustable current limiting, overcurrent, and over-temperature protection, and five different micro step resolutions (down to 1/16-step).
- **NPN transistor**: It's a Bc337 transistor.
- **Vacuum pump:** This Vacuum pump can adopt high quality steel and industrial plastic, sturdy and durable.
- **Solenoid Valve:** A tiny 12V DC 2-position 3-way small mini electric solenoid valve for control the gas flow in and out.

3.5. Theories related to robotic motion and load calculation:

Given are joint relations (rotations, translations) for the robot arm. The orientation and position of the end-effector will be evaluated.

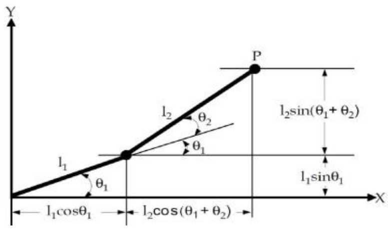

Figure 4: Forward kinematic explanation of the robotic arm

Figure-4 shows and explains the forward kinematics of our pick and place robotic arm. It can be determined that the position of the end effector of the arm in world space by defining a vector for link-1 and another for link-2.

$$r1 = [l1cos\theta_1, l1sin\theta_1)$$

$$r2 = [l2cos(\theta_1+\theta_2), l2sin\theta_1 + \theta_2]$$

Vector addition of () and () yields the coordinates *x* and *y* of the end of arm (point *x*, *y*) in world space,

$$X = l1\ cos\theta_1 + l2cos(\theta_1 + \theta_2)$$

$$Y = l1\ sin\theta_1 + l2\ sin(\theta_1 + \theta_2)$$

3.5. Working area:

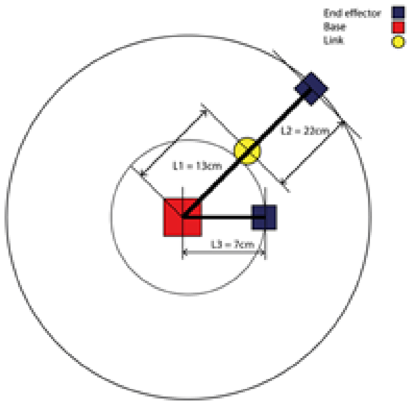

Figure 5: Maximum and minimum working area

For maximum area calculation:
For the robotic arm,
$\theta_1 = 0^\circ, \theta_2 = 0^\circ$
L1= 13 cm, L2= 22 cm
Therefore, X=35 cm, Y=0 cm
Figure-5 also shows the maximum working area of the robot which is about 35 cm along the X-axis.

For minimum area calculation:
In the robotic arm,
$\theta_1 = 45^\circ, \theta_2 = 90^\circ$ L3 = 7 cm
Therefore, X=7 cm, Y=0 cm
Figure-5 shows the minimum working area of our robot which is about 7 cm along the X-axis.
To see the maximum working radius, two links parallel to the ground are being placed and the circular area where the radius of the circle indicates the maximum distance from where the end-effector can reach along x-axis. Since the maximum rotation of the motor at the base is 360 degrees. Through forward and backward kinematics, the movement of the end effector at a given location can be determined by mutual rotation of the joint and vise-versa.

3.6. Torque and payload for our robotic arm

Stall torque is the torque load that causes a stepper motor to "stall" or stop rotating.
A stall torque of 4.2 kg-cm means that the stepper motor will stop rotating when it is trying to move a 4.2 kg weight at a radial distance of 1.0 cm.
In the 2nd joint the maximum torque is needed. So, we just calculate the payload with respect to joint2,
Here, we use NEMA-17 stepper motor. As the specification of the model, we found that the stall torque at 2.6 V is 4.2 kg-cm. Our maximum distance of payload from joint2 is 35cm.
The maximum payload become,
(4.2)/35 = 0.12 kg = 120gm (Neglecting the link weight)

3.7. Circuit diagram for the robotic arm

This represents the circuit diagram for our Pick and Place Robotic Arm, the parts involved are briefly indicated.

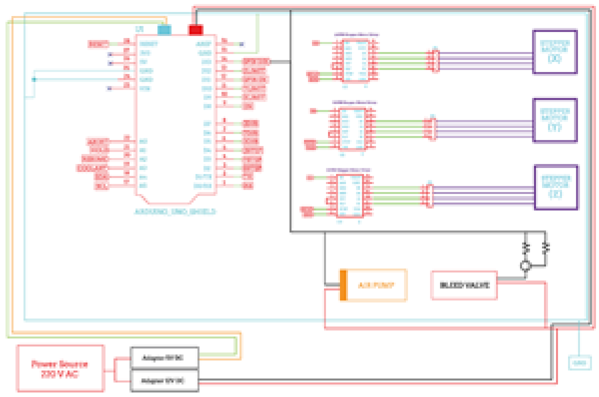

Figure 6: Electrical circuit design of the pick and place robotic arm

3.8. Torque and payload for our robotic arm

Below figure presents the original view of our experimental setup of the robotic arm. There is a picking and placing position and the payloads that are working as loads. The Flat type objects that we have used is 90X90mm and 2 mm width and weight of approx. 15gm.

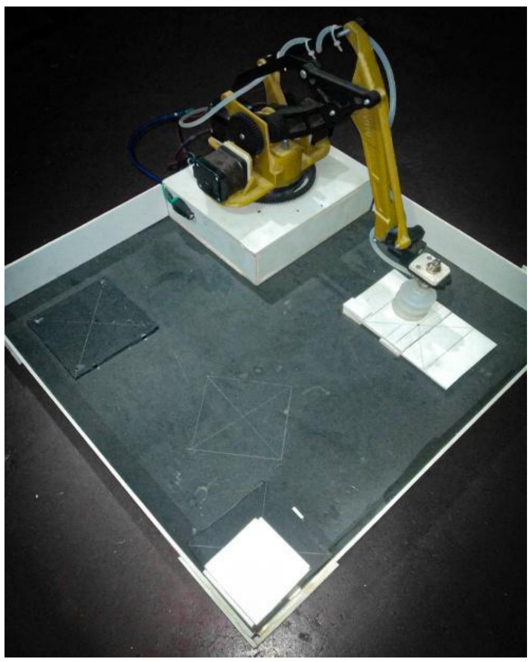

Figure 7: Experimental setup of the pick and place robotic arm

Figure 8: Flat Type of object used weighted 15 gm each

3. Results & Discussion

The experiment is done in 3 different speed ranges along with 4 different weights.

Table 1: Data table for different speed and different weight

Speed		Weight	Std. Value
Maximum	500mm/min	15 30 40 50	7.5
Moderate	166.67mm/min	15 30 40 50	22.5
Minimum	100mm/min	15 30 40 50	37.5

Table-1 shows that the experiment is done at three different speeds starting with maximum speed with 500mm/min, moderate speed at 166.67mm/min and minimum speed at 100mm/min. Again, in each speed range the experiment is done with four different weights which are 15gm, 30gm, 40gm and 50gm. In maximum speed with 15 and 30gm weight, the data is collected for 50 trials, for moderate speed with 15, 30 and 40 gm the data is collected for 50 trials and for minimum speed range with 15, 30, 40 and 50 gm the experiment is done with 50 trials and the data is being collected. The standard value indicates how much time it takes to complete a single pick and place operation. At maximum speed it is given as 7.5 seconds, at moderate speed it is given as 22.5 seconds and at minimum speed it is set at 37.5 seconds.

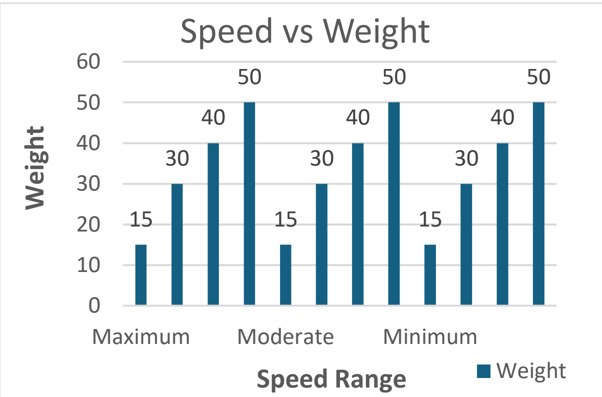

Figure 9: Speed vs weight graph

The movement time at different speeds and with different weights is being plotted in SPSS and can be summarized in the following table with the necessary value.

Table 2: Summary table for normality test

Normality Test							
Speed Range	Weight	Pick	Place	Std P Value	Estimated P value	Z value	
						Skewness	Kurtosis
Maximum	15	Success	Success	0.05	0.300	0.26	-0.73
	30	Success	Success		0.215	0.51	-1.4
	40	Failed	Failed		N/A	N/A	N/A
	50	Failed	Failed		N/A	N/A	N/A
Moderate	15	Success	Success		0.318	0.89	1.25
	30	Success	Success		0.269	0.55	-1.33
	40	Success	Success		0.420	-0.65	-1.65
	50	Failed	Failed		N/A	N/A	N/A
Minimum	15	Success	Success		0.123	0.06	-1.32
	30	Success	Success		0.269	0.56	-1.33
	40	Success	Success		0.431	-1.65	-1.3
	50	Success	Success		0.210	-0.66	-1.77

Table-2 shows that P and Z value maintains the required condition and from the appendix section B, the "SPSS" and "Minitab" analysis result shows that the data maintains bell shape curve. So, it can be said that all of the collected data maintains the conditions to be normal.

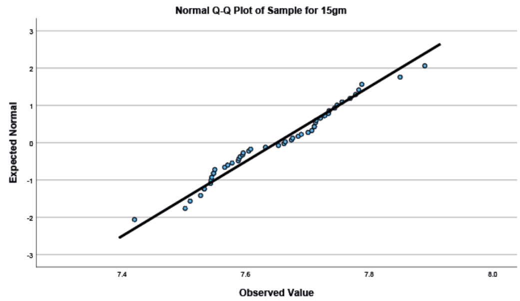

Fig:10: Normal QQ Plot for Sample 15 gm

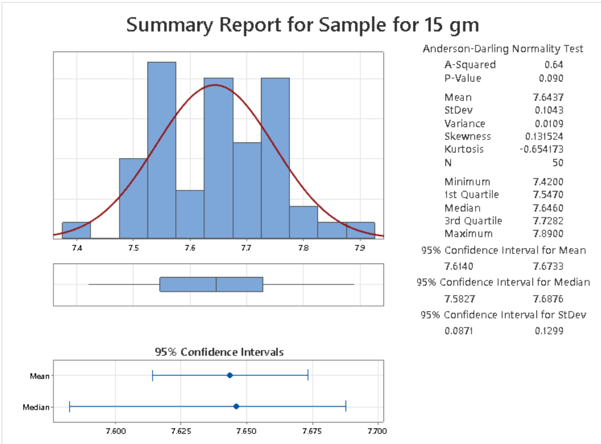

Fig:11: Summary Report for Sample 15 gm

Table 3: Summary table for accuracy and precision

Speed Range	Weight	Pick	Place	Precision	Standard Value	Mean (s)	Error	Accuracy
Maximum	15	Success	Success	100%	7.5	7.64	1.88%	98.12%
	30	Success	Success	100%		7.70	2.60%	97.40%
	40	Failed	Failed	0%		7.72	2.85%	97.15%
	50	Failed	Failed	0%		7.69	2.42%	97.58%
Moderate	15	Success	Success	100%	22.5	22.93	1.86%	98.14%
	30	Success	Success	100%		23.10	2.60%	97.40%
	40	Success	Success	100%		23.13	2.74%	97.26%
	50	Failed	Failed	0%		23.11	2.64%	97.36%
Minimum	15	Success	Success	100%	37.5	38.17	1.77%	98.23%
	30	Success	Success	100%		38.50	2.60%	97.40%
	40	Success	Success	100%		38.70	3.10%	96.90%
	50	Success	Success	100%		38.62	2.89%	97.11%

Table-3 shows that at maximum speed the robot can uplift approx. 30gm weight with the level of accuracy of 97%. The table also indicates that at moderate speed range the robot can withstand at 40gm weight with the accuracy of 97%. Lastly at minimum speed the robot performed very well as it carried out all the weighted specimens from 15-50gm with the accuracy of 97%.

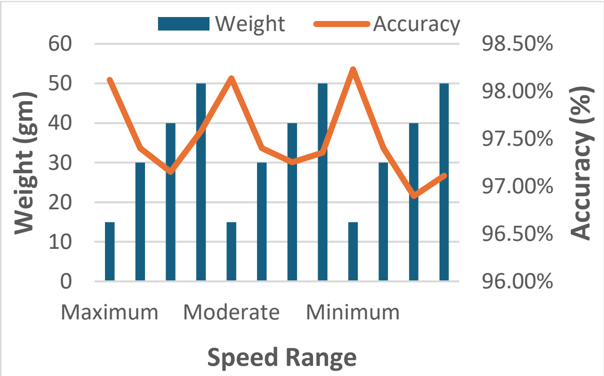

Figure 12: Speed vs accuracy graph

Figure-12 summarizes that the robot performed accurately at every speed range. It also shows that the accuracy of the robot slightly decreased with the weight of 30gm at maximum, moderate and minimum speed range. But lastly at 40gm weight it again increased and kept a mean of 97% accuracy throughout this performance test.

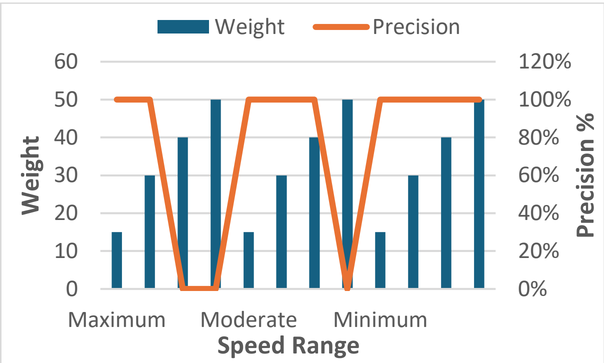

Figure 13: Speed vs precision graph

Figure-13 summarizes that the robot performed quite precisely at every speed range. It shows that the precision of the robot decreased at 50% with maximum speed. It also shows that at moderate speed range the precision increased and became 75% total. And lastly at minimum speed it kept its precision perfectly. Lastly it can be said that the robot kept its precision at 75% throughout this performance test.

4. Conclusion:

This study investigates the design and development of a pick and place robotic arm and tries to optimize the design and development in terms of motor, gripping method, gripping object type and use of sensors. Therefore, from the results and discussion, the following conclusions can be drawn:

- Use of stepper motor is a quite good decision as it increases the accuracy and precision of the robot as the robot moves following the steps.
- Using ESP32 microcontroller as the micro-controller of the movement of the arm is done and the robot is following the program accurately in different parameters.
- The accuracy and precision can vary according to the load, speed or both parameters at a time of the object.

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