Journal of Artificial Intelligence and Engineering Applications

Website: https://ioinformatic.org/

15th October 2025. Vol. 5. No. 1; e-ISSN: 2808-4519

Robotic Arm for Object Stacking Based on Inverse Kinematics Method

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Abstract

This study describes the design and implementation process of a 3-DOF robotic arm designed to automatically stack objects based on coordinates using the inverse kinematics method. The system combines the use of servo motors, proximity sensors, and an Arduino Nano microcontroller to detect the presence of objects and adjust the angle of each joint, enabling precise object placement. Unlike traditional approaches that use fixed motion paths, the method proposed in this study dynamically calculates joint angles according to the height and position of the targeted stack. System testing demonstrated stable performance in stacking objects at five different coordinate points, with travel times ranging from 7.78 to 8.74 seconds and perfect placement success rates in every trial. Analysis of servo angle data indicates that the robot arm is capable of automatically adjusting its movements in response to changes in stack height, ensuring system accuracy and reliability. As such, this automation solution offers a cost-effective alternative for small-scale stacking applications that require flexibility and real-time position adjustment capabilities.

Keywords: *Robotic Arm, Inverse Kinematics, Object Stacking, Automation, Arduino.,*

1. Introduction

Advances in industrial automation have accelerated the adoption of robotics technology, particularly the use of robotic arms, to improve productivity, precision, and safety in various manufacturing processes, including automated goods stacking. Manual stacking, especially on a large scale, often requires a large workforce, is prone to errors, and is inefficient in terms of time and energy. Arm robots are a widely used solution due to their flexibility in manipulating objects in various work environments[1].

The configuration of an arm robot with three degrees of freedom (3-DOF) is considered highly effective. This is because a 3-DOF robot is capable of reaching various positions in a two- or three-dimensional workspace without requiring complex mechanisms, while remaining cost-effective and mechanically simple[2]. This flexibility allows the system to pick items from their initial position and place them in specific locations in sequence, thereby supporting the process of systematic arrangement and stacking based on height or specific position.

In order for the robot arm to reach the placement point of the object with precision, a control method is needed to accurately calculate the actuator motion parameters. One technique that is often used is inverse kinematics, which is the process of calculating the angles of the robot joints based on the target position of the end effector so that the robot arm can move towards the desired position precisely[3]. An end effector is a device attached to the end of a robot arm that performs specific tasks, such as picking up or moving objects. There are various types of end effectors, ranging from grippers to other specialised tools, depending on the application requirements[4].

In previous research by Dewi et al. (2025), inverse kinematics was combined with a fuzzy logic controller[5], thereby improving movement accuracy when handling objects in pick-and-place applications. However, no strategy was implemented for position adjustment based on stack height. In addition to motion control aspects, automatic stacking systems require environmental condition detection using sensors, such as proximity sensors, to determine the initial position of objects[6].

Based on previous studies, there has not been much research that explicitly integrates inverse kinematics methods with proximity-based sensory systems for automatic stacking of goods using 3 DOF robots. Existing research tends to focus on pick and place systems without considering the height of the stack or dynamic placement location detection. Thus, there is a need to design a system that is capable of adapting to pile conditions in real time through the combination of inverse kinematics and feedback sensors. The integration between the kinematic system and these sensors allows the robot to adapt dynamically to changes in pile configuration, as well as avoid placement errors or collisions during the process.

2. Literature Review

2.1. Robotic Arm

Arm robots are one of the most commonly used types of robotic systems in industry and automation. Robotic arms are designed to mimic human arm movements in performing various manipulation tasks, such as picking up, moving, arranging, or assembling objects in a work area. In terms of construction, robotic arms consist of several interconnected arm segments (links) connected via joints, where each joint is driven by actuators such as DC motors or servos. Each joint on a robot provides one degree of freedom (DoF), which means the ability to move in one direction or perform a specific rotation[7].

2.2. Inverse Kinematics

Inverse kinematics is a method used to determine the angle value at each joint of the manipulator arm in order to reach a specific target position[8]. When determining the final coordinates of the end-effector, inverse kinematics calculations must take into account the worspace limitations and the robot's range of motion[9]. The inverse kinematics method aims to find the parameter values that need to be given to each actuator so that the end-effector can reach the target position. Inverse kinematics facilitates motion control in robotic arms by calculating the position of the actuator based on the desired position. In addition, this algorithm also speeds up the work process because it does not require the use of trial and eror methods to determine the position and orientation of the robot[10]. Thus, the Inverse Kinematics algorithm not only improves work efficiency, but also supports positional accuracy in automation systems that require high precision.

2.3. Arduino Nano

The Arduino Nano development board is one of the smallest boards in the Arduino family in terms of dimensions, making it ideal for applications that require compact devices. Technically, the Arduino Nano uses an Atmega328P microcontroller based on the Atmel AVR architecture. This board provides 12 digital input/output pins (D2 to D13), 8 analogue input pins (A0 to A7), and a pair of TTL serial RX/TX ports. Additionally, there are 6 PWM pins (D3, D5, D6, D9, D10, D11). The Arduino Nano can be powered via the USB port, an external 5 V to 12 V DC power source, or a 9 V battery. For memory capacity, the board is equipped with 32 KB flash memory, 2 KB SRAM, and 1 KB EEPROM.

2.4. Servo Motor MG995

A servo motor is a small DC motor equipped with a gear system and potentiometer, allowing the servo to be positioned as desired. Basically, servo motors use a closed loop system, whereby the position of the motor is sent back to the control circuit inside the servo motor to ensure its position is accurate. Unlike DC motors that rotate continuously, servo motors move only to a certain angle and stop at that position. These motors are typically used to move robot parts that require precise angular movement, such as robot arms, grippers for picking up objects, or leg movements when walking[11]. Servo motors are generally operated with PWM (Pulse Width Modulation) signals. In this system, the width of the pulse given will determine the angle of rotation of the motor, allowing for accurate and stable position control.

2.5. Proximity Sensor

A proximity sensor is an electronic component that can detect the presence of an object within its range without direct contact thereby minimising mechanical wear. This sensor works by converting the movement of an object into an electrical signal. The detection range of a proximity sensor varies depending on the type of sensor used, such as light-based sensors, sound-based sensors, infrared (IR) sensors, or even electromagnetic field sensors. Proximity sensors are widely used in various sectors such as industrial automation, security systems, and consumer electronics due to their ability to detect objects quickly and accurately without physical contact. This makes them highly effective in ensuring precision and safety in a wide range of applications, from industrial process control to features in smart devices.

2.6. Solenoid

A solenoid is an electromagnetic device that converts electrical energy into kinetic energy. Generally, solenoids produce movement in the form of a push or pull. Simply put, a solenoid consists of a coil of wire wound around a cylindrical tube, with a plunger as the actuator that can move freely, such as moving in and out of the coil body. The actuator in a solenoid is a mechanical component that plays a role in controlling a mechanism[12]. Solenoids are often used in applications such as electric door locks, automotive starter systems, and pneumatic or hydraulic valve controllers, where fast linear motion with precise control is required. Solenoid operation enables fast and measured mechanical displacement to effectively regulate these functions.

2.7. Relay

A relay is an electromechanical device that functions as an automatic switch in various electronic and electrical applications. The operation of a relay is based on the principle of electromagnetism, where when an electric current flows through the coil, the resulting magnetic field moves the switch contacts to change position, from the open state (Normally Open/NO) to closed, or vice versa. With this mechanism, relays enable the control of high-voltage circuits or high-current circuits using low-voltage control signals[13]. Relays are widely used in automation systems, motor controllers, and protection circuits due to their ability to separate control signals from power circuits, thereby ensuring safety and preventing electrical interference. This function makes relays essential in maintaining the stability and operational safety of electronic devices.

3. System Design

The system design in this study includes mechanical, electronic, and control logic designs for a 3-DOF robotic arm created to automatically move and stack objects. This system consists of three interconnected main subsystems, namely the mechanical system, the electronic system, and the software system (control). From a mechanical perspective, the robotic arm has three degrees of freedom (3-DOF), enabling both horizontal and vertical movements. Each joint is controlled by an MG995 servo motor mounted on a lightweight yet robust frame structure. Proximity sensors are installed in the detection area to detect the presence of objects to be moved. The integration of these subsystems allows the robotic arm to perform tasks with a high degree of precision and repeatability, making it suitable for automated object handling in structured environments such as production lines or sorting stations.

3.1. Block Diagram

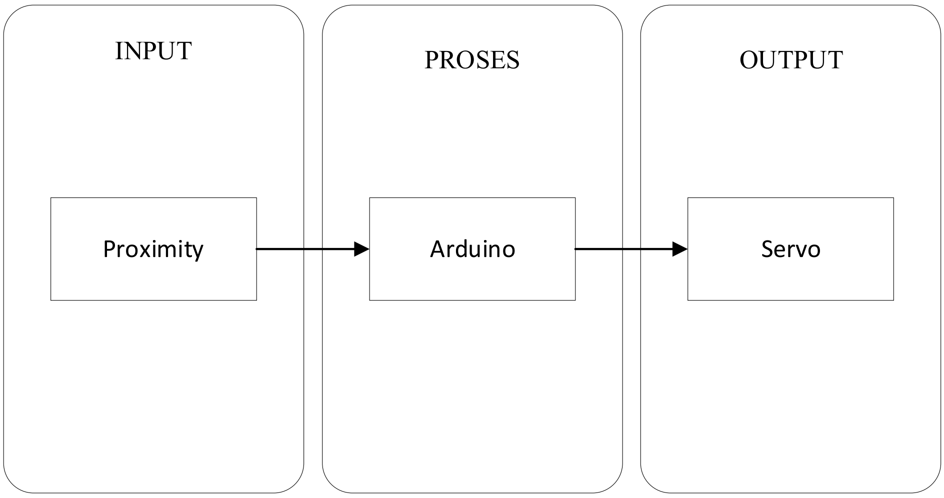

Fig. 1: Block Diagram

In designing this system, component selection is the first step in describing the relationships between the main components in the designed robotic arm. This diagram aims to provide an overview of how data and signals are transmitted between components in the system. In this system, several components are used, including a power supply and a proximity sensor that functions as a detector for the presence of objects in the input path. When the sensor detects an object, a signal is sent to the Arduino Uno microcontroller for processing. The block diagram of this system is designed to ensure that the integration between components runs synchronously and efficiently, from object detection to the process of stacking goods.

3.2. Wiring

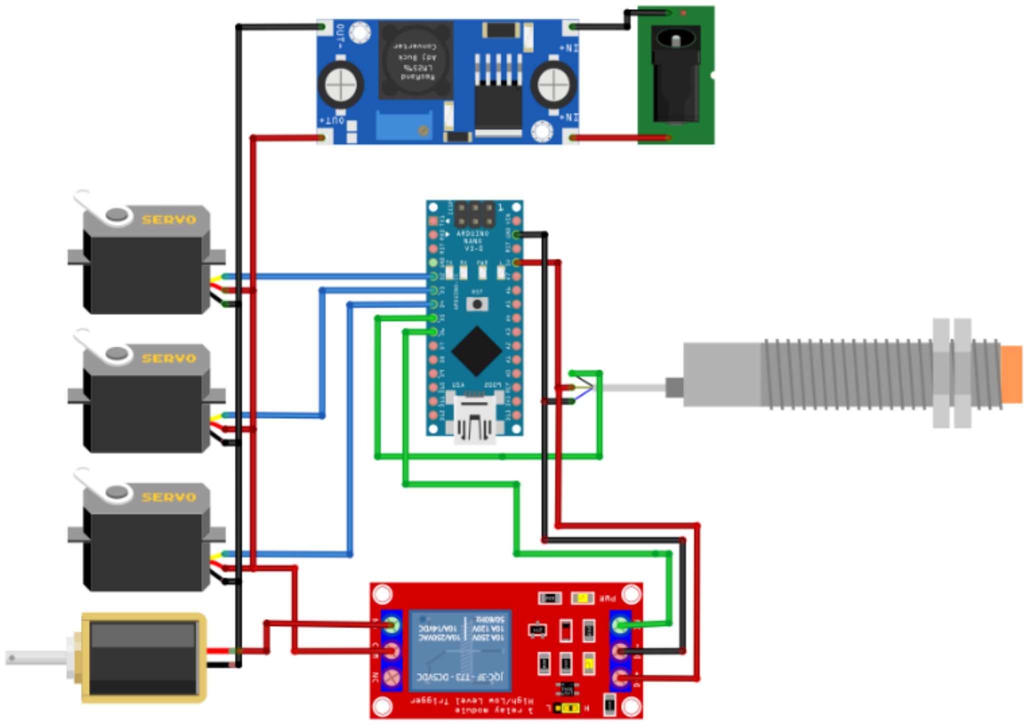

Fig. 2: Wiring Diagram Robotic Arm

The hardware circuit design for this system can be seen in the diagram, which aims to integrate all components into the main system. The first step is to connect the Arduino Nano to a 5-volt power source, consisting of a power supply and a step-down module. Next, the proximity sensor is connected to the Arduino's digital pins, with the configuration VCC (5V), GND, and Signal to pin D5.

The servo motor outputs are connected to the VCC and GND of the step-down module, and the servo signal pins 1-3 are connected to the PWM pins D2, D3, and D4. The solenoid is connected to the NO contact of the relay as an automatic switch, then the relay is connected to pin D6 as the relay coil trigger, and the relay power supply is connected to the VCC and GND of the Arduino Nano. The design process of this circuit ensures that each component operates optimally in executing the control system based on the designed method.

3.3. Flowchart

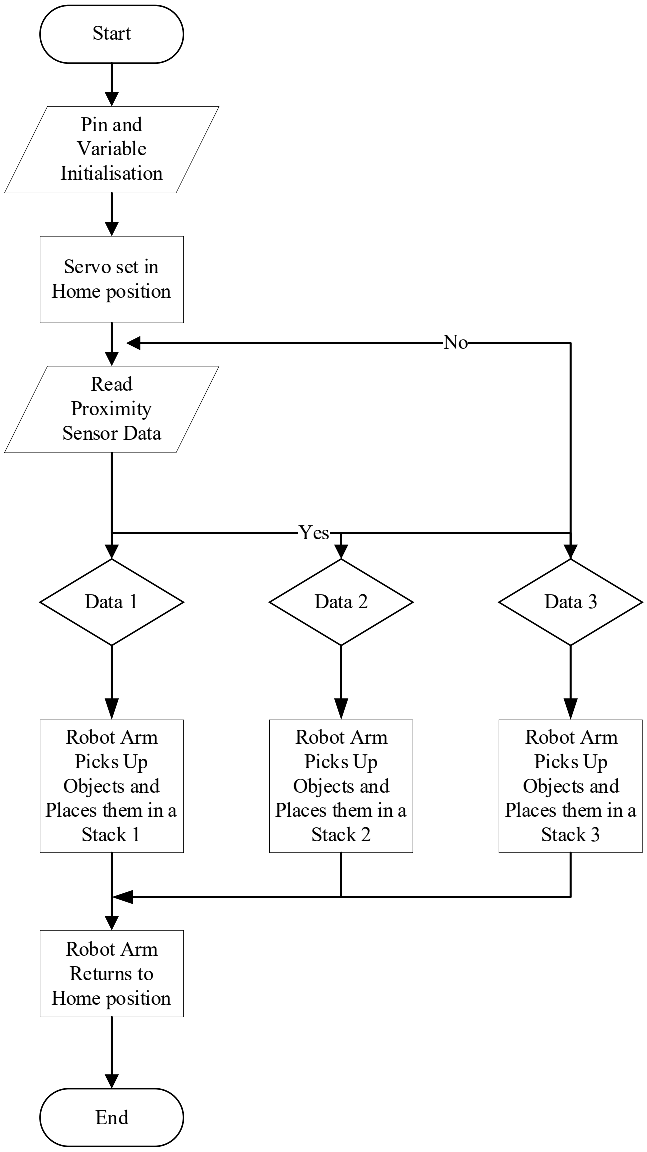

Fig. 3: Flowchart Robotic Arm

The flowchart above explains how the system works, starting with initialising variables, the servo motor directing the robot arm to its home position, and the Arduino microcontroller processing data read by the proximity sensor in the form of object data. Based on the data read, if the data is 1, the robot arm picks up the object and places it on the first pile. If the data is 2, the object is placed on the second pile, and if the data is 3, the object is placed on the third pile. After the three-item stacking cycle, the robot arm returns to its initial position, and the system stops.

3.4. Inverse Kinematics Method

The design of an arm robot using the inverse kinematics method aims to find the angle of each joint required by the end-effector to reach the desired point. Formulas are used to find the values of $\theta 1$, $\theta 2$, $\theta 3$. The coordinates (x, y, z) and link lengths (L1, L2, L3) must be known before calculating the third θ value.
The formula for finding the value of θ can be seen in the equation (1)

$$\theta_1 = atan2\,(y, x) \tag{1}$$

Description.
x = coordinate values x
y = coordinate values y

In equation (1) with input values for coordinates x and y, the value of $\theta 1$ will be obtained.
After finding the value of $\theta 1$, the next step is to find $\theta 2$ and $\theta 3$, which requires the values of $c3$ and $s3$. The values of $c3$ and $s3$ are auxiliary variables used to solve the formulas for $\theta 2$ and $\theta 3$.
The formulas for finding the values of $c3$ and $s3$ are:

$$c3 = \frac{(x^2+y^2+(z-L1)^2-L2^2-L3^2)}{(2\times L2\times L3)} \tag{2}$$

$$s3 = \sqrt{1-c3^2} \tag{3}$$

Description.

x = coordinate values x — L1 = length of the first link
y = coodinate values y — L2 = length of the second link
z = coodinate values z — L3 = length of the third link

Next, find the value using the formula in equation (4).

$$\theta_3 = atan2\ (s3, c3) \tag{4}$$

In equation (4), by inserting the values of variables s3 and c3, we obtain the value of $\theta 3$.
After finding the value of $\theta 3$, we then find the value of $\theta 2$ using the formula in equation (5).

$$\theta_2 = atan2\left((L3\times s3), (L2 + (L3\times c3))\right) \tag{5}$$

Description.
L2 = length of the second link
L3 = length of the third link

In equation (5), by inserting the values of L2, L3, c3, and s3, the value of $\theta 2$ will be obtained.

4. Results and Discussion

In this testing of the 3 DOF robotic arm that has been designed and implemented. The testing was conducted to evaluate the system's performance in performing its main function, which is to automatically stack items at specific coordinates using the inverse kinematics method. The testing covered aspects such as the time taken to reach the coordinates, the angular accuracy of each servo, and the success of the stacking process based on the height of the stack. All testing aimed to measure the overall effectiveness, accuracy, and reliability of the system.

Table 1: Stack of 1 Item

No	Accumulation point	Coodinates target (x, y, z)	Traveling time (s)	Placment status
1	Stack A	(15, 20, 28)	7.94	Success
2	Stack B	(0, 0, 12)	8.26	Success
3	Stack C	(-10, 24, 18)	7.78	Success
4	Stack D	(-20, 15, 10)	8.26	Success
5	Stack E	(25, -5, 5)	8.47	Success

Table 2: Stack of 2 Item

No	Accumulation point	Coodinates target (x, y, z)	Traveling time (s)	Placment status
1	Stack A	(15, 20, 33)	8.12	Success
2	Stack B	(0, 0, 17)	8.41	Success
3	Stack C	(-10, 24, 23)	7.91	Success
4	Stack D	(-20, 15, 15)	8.74	Success
5	Stack E	(25, -5, 10)	8.65	Success

Table 3: Testing the accuracy of the rotation angle Stack 1

No	Accumulation point	Coodinates (x, y, z)	Servo 1 (°)	Servo 2 (°)	Servo 3 (°)
1	Stack A	(15, 20, 28)	127	51	89
2	Stack B	(0, 0, 12)	90	68	97
3	Stack C	(-10, 24, 18)	112	59	84
4	Stack D	(-20, 15, 10)	131	73	110
5	Stack E	(25, -5, 5)	45	34	72

Table 4: Testing the accuracy of the rotation angle Stack 2

No	Accumulation point	Coodinates (x, y, z)	Servo 1 (°)	Servo 2 (°)	Servo 3 (°)
1	Stack A	(15, 20, 33)	127	56	98
2	Stack B	(0, 0, 17)	90	73	102
3	Stack C	(-10, 24, 23)	112	64	89
4	Stack D	(-20, 15, 15)	131	78	115
5	Stack E	(25, -5, 10)	45	39	77

Based on the data in Tables 1 and 2, the 3 DOF robotic arm successfully performed the process of stacking goods at five different coordinate points with two placements at each location. Each stacking operation was successfully carried out at the specified coordinates, with the accumulated stack height reaching 10 cm (two items) per point. The travel time from the initial position to each coordinate ranged from 7.78 to 8.74 seconds, indicating stable movement and relatively consistent speed.

The servo angle data log shows that the angle of Servo 1 (horizontal rotation) remains constant for each identical stacking location, both during the first and second placements. This is as expected because the X and Y positions of the coordinates do not change. On the other hand, the angles of Servo 2 (shoulder) and Servo 3 (elbow) increase at each second stacking at the same point, adjusting to the increasing Z value (height). This increase in angle reflects the system's response to the increasing stack height.

5. Conclusion

Based on the results of the design and testing conducted on the 3 DOF robotic arm system for stacking goods based on coordinates, it can be concluded that this system has operated in accordance with its intended purpose. The robot is capable of stacking goods automatically without explicitly applying inverse kinematics, but rather using a direct angle adjustment approach based on coordinates and height. Testing shows that the time required for the robot to reach the stacking point ranges from 7.78 to 8.74 seconds. This time range is quite stable and indicates that the system has reliable speed and movement accuracy.

The entire stacking process at five different locations was successfully completed without errors, with each location stacked twice to reach a height of 10 cm. From the analysis of the servo angle log, it was found that the angle of Servo 1 (base section) remains constant at the same stacking point, while Servo 2 and Servo 3 change in response to increases in the Z-coordinate value. This proves that the system can automatically adjust to changes in stack height with precise angle settings. Overall, the developed 3-DOF robotic arm is capable of performing the stacking process effectively, accurately, and consistently. This system has the potential to be applied in small-scale production lines or simple goods storage systems that require coordinate-based automation.

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