Review Article

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A COMPREHENSIVE REVIEW OF ROBOTIC ARMS: DESIGN, CONTROL, AND APPLICATIONS

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Abstract: In this paper to the discusses the develope of the robotic manipulator, commonly referred to as a robotic arm, which is designed to replicate gripping and movement actions. The arm consists the series of rigid the segments called links, connected in a sequence to form the complete structure. The manipulator is controlled using an Arduino UNO and is suitable for tasks in hazardous environments, such as material handling or industrial operations. To analyze the torque requirements, a prototype in the robotic arm built and tested through simulated tasks. The paper also explores potential applications of a robotic manipulator with 6 degrees of freedom, focusing on functionality the end effector as the primary interface for interaction.

Keywords: Robotic Manipulator, Arduino UNO, Degree of Freedom, End Effector, Servo motor, Kinematics, Prototype Design, Mechatronics.

Introduction: Today, robotic arms various role in industrial applications and are particularly valuable in hazardous environments. Although robotic manipulators too costly due to their high precision and accuracy, they offer substantial benefits by reducing in need for human labor and increasing industrial efficiency. Key of the performance parameters for evaluate robotic arms include backlash, payload capacity, operating speed, repeatability, structural flexibility (compliance), safety in human interaction, and overall cost. In robotics, kinematics—both forward and inverse—are essential techniques used regularly in system design and control. Forward kinematics involves calculating the position and orientation of the robot's end effector based on known joint parameters, while inverse kinematics works in reverse, determining joint angles needed to achieve a desired position and orientation. In the robotic arm is typically a programmable mechanical structure, which may function independently or as part of the more complex robotic system. Kinematics focuses on the study of movement without considering the forces behind it. When deploying such systems near humans, ensuring safety becomes a key challenge.

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Literature Review:

A. Arduino-Controlled Robotic Arm Systems: Recent advancements in embedded systems have enabled the development of low-cost, versatile robotic arms. One such system incorporates a six degrees of freedom (6-DOF) robotic manipulator, operated through an Arduino Uno microcontroller. User input is provided via potentiometers, allowing real-time manual control of the arm's movement. The robotic structure consists of four rotary joints and a terminal end effector, each driven by servomotors to achieve the desired range of motion.

B. Development of Industrial Robotic Manipulators: In industrial environments, robotic manipulators are essential for automating tasks such as picking and placing objects that are beyond an operator's physical reach However, frequent maintenance, particularly due to cable wear and friction, can lead to increased operational costs. Therefore, recent designs focus on reducing mechanical friction and enhancing durability, which helps extend maintenance intervals and lowers long-term costs.

C. Design and Implementation of Low-Cost 6-DOF Robotic Arms

Developers can implement complex control systems without the expense associated with industrial-grade solutions. The modular design approach further simplifies fabrication and assembly, enabling wide adoption in educational institutions and small-scale manufacturing setups. Research continues to focus on improving the load capacity.

D. Design and Implementation of a Lightweight Robotic Arm Using Servo Motors

This study explores the design, development, and implementation of a robotic arm capable of performing basic tasks, such as handling lightweight materials. The mechanical structure of the arm is fabricated using acrylic sheets, selected for their low cost and ease of machining. Servo motors are employed at each joint to drive the arm's movements and establish link connections between segments. These motors are integrated with built-in encoders, eliminating the need for external feedback controllers for position tracking. However, one limitation identified is the restricted rotational range of typical servo motors, which is generally less than 180º. This constraint significantly reduces the workspace and number of reachable positions for the arm. The robotic manipulator in this design supports six degrees of freedom (DOF).

Working Principle: The robotic manipulator operates by converting electrical energy into mechanical motion, enabling it to perform specific tasks. This process is facilitated through programmed control and automation, where embedded systems or microcontrollers interpret input signals and generate corresponding movements in the robotic joints and actuators. Through this integration of electronics and mechanical components, the manipulator can execute actions such as lifting, rotating, or positioning objects with precision.

A.Components

1. Servo Motor (MG995): The robotic arm utilizes three MG995 servo motors to enable its primary movements. One servo motor is mounted at the base to control rotational motion, while the other two are positioned on either side of the base plate to transmit motion through the arm's interconnected links. Each servo motor is securely fastened to the base plate to ensure stability and minimize vibrations during operation, which is crucial for maintaining precision. Servo motors like the MG995 function as rotary actuators, combining a DC motor with a position sensor to provide accurate angular motion. These motors require a dedicated controller capable of interpreting feedback signals and adjusting motor output accordingly. This closed-loop system allows for precise control over the arm's positioning, making it suitable for robotic applications where accuracy and responsiveness are essential.

2. Servo Motor (SG90**):** The SG90 micro servo SG90 motor in the widely used in robotic arms to control movements such as wrist pitch, wrist roll, and ease of control. For wrist pitch, the SG90 allows the end in the robotic arm to move up and down, simulating the natural bending motion of human wrist. In the case of wrist roll, the SG90 can provide rotational motion along the arm's longitudinal axis, although this function may require a mechanical linkage since the SG90 cannot rotate continuously. For the gripper, the SG90 is ideal for opening and closing the gripping mechanism, allowing the robot to pick up and release lightweight objects. Its 180-degree rotation range and simple PWM control make it suitable for beginners and hobbyists

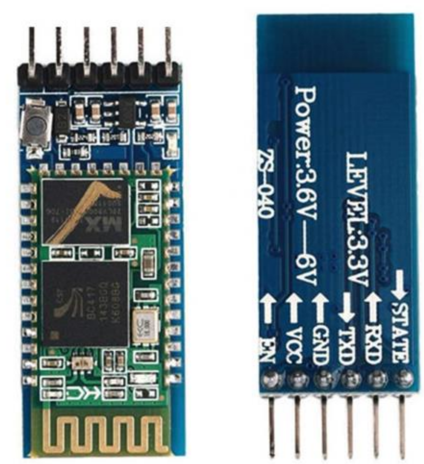
building functional yet affordable robotic systems.

B. Arduino UNO

The Arduino Uno is a widely adopted microcontroller board built around the ATmega328P microchip. It includes 14 digital input/output pins—6 of which support Pulse Width Modulation (PWM)—along with 6 analog input channels, a 16 MHz quartz crystal oscillator, a USB interface, a power input jack, and a reset button. Due to its simplicity, versatility, and extensive community support, the Uno is favored by both beginners and experienced developers in the field of embedded systems and electronics.

C. HC-05 Bluetooth Module

The HC-05 Bluetooth module popular and widely used wireless communication device designed to facilitate short-range data transmission between devices, such as microcontrollers, smartphones, and computers. It operates on Bluetooth version providing a reliable and low power solution for wireless communication. The module typically supports a serial communication interface (UART), making it easy to integrate with microcontrollers and others. It uses a 3.3V to 5V operating voltage and can communicate in the over distance range from 10 meters to 100 meters, depending on environmental conditions. The module can be controlled through AT commands for setting parameters such as the device name, baud rate, and pairing option this Bluetooth module is highly favoured in robotics, home automation, and IoT applications due to its ease of use, low cost, and reliable performance. Its small size and ease of integration make it idea for the project that require simple, wireless communication without the need for complex networking protocols.



DESIGN

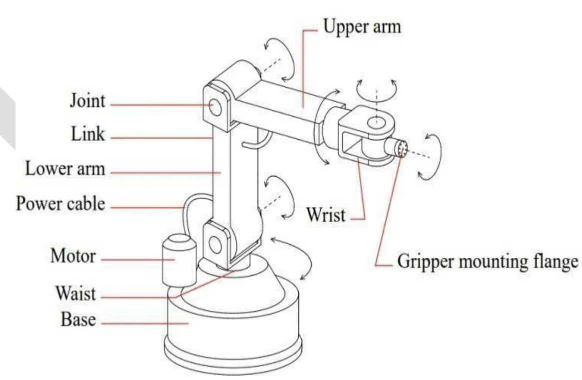
A 6 DOF robotic arm is a versatile and widely used mechanical system designed to replicate the movement and flexibility of a human arm. It consists of six independent joints, typically all rotary, that allow the arm to position and orient its end effector in three-dimensional space. These joints include a base rotation (yaw), shoulder and elbow pitch for vertical motion, and wrist pitch, roll, and yaw for fine positioning and manipulation. The arm is built using lightweight materials such as aluminum or carbon fiber to balance strength and weight. Servo motors or stepper motors, often paired with gearboxes or harmonic drives, provide the motion and torque needed at each joint. Control systems are the implement using the microcontrollers or industrial controllers that interpret motion commands and coordinate the arm's movement using algorithms for forward and inverse kinematics.

Axis and Links: The axes correspond to the joints of the robotic arm, and they define the motion capabilities of the system. Typically, a 6 DOF robotic arm will have six rotational axes, each contributing a degree of freedom. The movement along these axes is driven by motors or actuators, such as servo or stepper motors, which provide the necessary torque and precision.

Axis-

1. Base Rotation (Yaw Axis) – This axis allows the entire arm to rotate around its base, enabling the arm to face different directions.
2. Shoulder Pitch – The joint at the shoulder that enables the arm to move up and down in a vertical plane.
3. Elbow Pitch – This joint controls the bending and extension of the arm, typically allowing movement in a similar plane to the shoulder pitch.
4. Wrist Pitch – Controls the vertical orientation of the wrist, adding flexibility in positioning the end effector.
5. Wrist Roll – Allows rotation of the wrist around its axis for more precise orientation control.
6. End Effector Rotation (Wrist Yaw) – This axis controls the rotation of the tool or gripper at the end of arm for more fine-grained positioning.

Links- The links are the rigid structures that connect the joints or axes of the robotic arm, providing the necessary support and maintaining the arm's shape. These links can vary in length depending on design and purpose of robotic arm. The primary function of the links is to allow movement between the joints while maintaining the overall integrity of the arm. The design of these links is critical in determining the arm's reach and payload capacity.



Calculation

No	Function	Servo Type	Torque Needed	Reason
1	Base Rotation	MG996	98.1 N·cm	Highest load
2	Shoulder	MG996	≥ 80 N·cm	Lifting arm + loa
3	Elbow	MG996	≥ 50 N·cm	Secondary lift
4	Wrist Pitch	SG90	≤ 10 N·cm	Light motion
5	Wrist Roll	SG90	≤ 10 N·cm	Light motion
6	Gripper (Open/Clos	SG90	≤ 5 N·cm	Grip only

Result and Discussion: The 6-degree-of-freedom robotic arm was tested to see if it could successfully pick up and place a 500ml water bottle. The arm used three MG995 servo motors for the base, shoulder, and elbow joints, and three SG90 micro servos for the wrist movements and the gripper.

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Conflict of Interest: The authors affirm that there are no financial or personal relationships that could be perceived as influencing the work reported in this project. No conflicts of interest exist in connection with the research, authorship, or publication of this study.

Author Contributions

- Magar Prathmesh: Mechanical design, system integration, testing of the robotic arm, and report writing.
- Kale Suraj: Arduino programming, servo control system implementation, and performance analysis.
- Prof. Surwase S. S.: Project supervision, technical mentorship, final review, and validation of results.

All authors have read and approved the final version of the manuscript.

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