Design, Implementation, and Evaluation of a Robotic Arm for Centrifuge Tube Handling

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ABSTRACT

This study presents the design and implementation of a robotic arm for transferring centrifuge tubes in laboratory environments. The robotic arm is developed to enhance safety and efficiency in handling chemical or biological samples, minimizing human error and contamination risks. The system integrates mechanical, electrical, and programming components, utilizing Dynamixel smart servos, stepper motors, and an Arduino Mega microcontroller. The robot operates in both manual and automatic modes, allowing users to select the source and destination of tube transfers via a Nextion HMI interface. Experimental results demonstrate that the robotic arm can accurately transfer tubes with diameters up to 17 mm while maintaining stability and consistency. The gripper, powered by a Tower Pro MG995 servo, ensures reliable handling without damaging the tubes. The system's modular design facilitates maintenance and scalability, making it suitable for various laboratory applications. Despite its advantages, the robotic arm has limitations, including a maximum payload of 200 grams and a total weight of 30 kg. Future improvements include integrating vision sensors and artificial intelligence for advanced functionalities such as object recognition and autonomous decision-making. This research contributes to the development of automated solutions for laboratory safety and efficiency.

1. Introduction

The development of robotic technology has brought significant changes in various industrial sectors, including manufacturing, healthcare, agriculture, and laboratories. One prominent application is the use of robotic arms for automated tasks such as object movement, tool manipulation, and interaction with the environment. In this context, robotic arms are an effective solution to improve efficiency, precision, and safety in operations that require a high level of accuracy or involve risks to humans.

The laboratory is one of the environments that greatly requires automation systems to support daily activities, such as handling chemicals, biologicals, or pharmaceuticals. Manual handling of centrifuge tubes, for example, often involves the risk of human error, such as tube falls, contamination, or even exposure to hazardous materials. To overcome this challenge, several studies have proposed the use of robotic arms as an automation solution. For example, Jesus et al. (2024) [7] showed that centrifuge tube detection and manipulation can be optimized using robotic technology for the pre-analytical phase in the laboratory. This approach not only increases the speed of the process but also reduces the risk of human error.

In addition, the development of robotic control technology increasingly enables the integration of advanced features, such as computer vision, tactile sensors, and brain-computer interfaces. Abougarair et al. (2021) [1] showed that robotic arm control via brain-computer interface can be used for rehabilitation or assistance applications for individuals with physical disabilities. This technology opens up new opportunities for the development of robotic systems that are more intuitive and adaptive to user needs.

In recent years, the design and implementation of robotic arms have developed rapidly, driven by advances in mechatronics, artificial intelligence, and materials engineering. One of the main trends is the development of robotic arms with higher degrees of freedom (DOF) to increase movement flexibility. Narayan et al. (2020) [10] designed a 5-DOF robotic arm with a three-finger gripper for physical therapy applications. This design allows for high-precision object manipulation and adaptability to various object shapes.

In addition, the integration of computer vision technology is also a major focus in the development of modern robotic arms. Intisar et al. (2021) [6] proposed a robotic arm system controlled through a graphical interactive interface (GUI) with computer vision support. The system allows the user to automatically identify and manipulate objects, reducing the need for manual intervention. This approach is particularly relevant in laboratory applications, where precision and speed are critical.

Robotic arms have a wide range of applications across industries, from manufacturing to medical services. In the medical field, Girerd and Morimoto (2021) [3] designed a concentric tube-based robotic arm for minimally invasive surgical operations. This design allows for high-precision manipulation of surgical instruments in confined spaces, reducing trauma to the patient. On the other hand, Mourtzis et al. (2022) [9] explored the use of robotic arms within the Industry 5.0 framework, focusing on 3D printing for the fabrication of robotic arm transforming tools. This approach shows great potential for low-cost mass production.

In agriculture, Kumar et al. (2023) [8] developed a multifunctional robotic arm to support agricultural operations, such as harvesting, pesticide spraying, and crop monitoring. These systems are designed to improve the efficiency of agricultural operations while reducing the reliance on human labor. Similarly, Nnanna et al. (2024) [11] highlighted the use of robotic arms for repetitive pick-and-place tasks, such as handling goods in warehouses or factories.

Robotic arm design involves the integration of various disciplines, including mechanics, electronics, and programming. Rozas Llontop et al. (2020) [12] showed that a mechatronics approach can be used to design an anthropomorphic robotic arm mounted on a wheelchair to assist patients with spastic cerebral palsy. This design not only considers technical aspects but also ergonomics and user needs.

In addition, Surati et al. (2021) [13] compiled a comprehensive review of the development of pick-and-place robotic arms, covering various trajectory planning methods and control strategies. This study highlights the importance of optimal trajectory planning to avoid collisions and improve operational efficiency. Afrisal et al. (2020) [2] also explored trajectory planning with obstacle avoidance for a 3-DOF robotic arm in a test tube handling system. Their results showed that this approach can improve system reliability and safety.

Although robotic arms offer many advantages, there are several challenges that need to be overcome to maximize their potential. One of the main challenges is the cost of development and implementation, especially for small-scale applications such as laboratories. In addition, the complexity of designing and integrating advanced technologies, such as tactile sensors and computer vision, often requires specialized expertise and large investments. Zlokapa et al. (2022) [16] showed that an integrated design pipeline can be used to optimize the development of robotic arms with tactile sensors, thereby reducing production time and costs.

On the other hand, opportunities for innovation are still wide open. For example, Szolga and Opra (2021) [14] developed a robotic arm specifically for handling biological probe tubes, which shows great potential for laboratory applications. Similarly, Thomas et al. (2022) [15] designed a lightweight and foldable robotic arm for drones, which can be used in surveying or logistics applications.

Overall, robotic arms have proven themselves to be a very valuable technology in a variety of applications, from laboratories to manufacturing industries. Advances in the design, control, and integration of advanced technologies have opened up new opportunities to improve the efficiency, precision, and safety of operations. However, challenges such as high cost and design complexity still need to be overcome to ensure wider adoption. This study aims to contribute to the development of robotic arms for laboratory applications, focusing on centrifuge tube handling. By utilizing

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mechatronics principles and modern technology, it is hoped that this robotic arm can be a practical solution to increase productivity and safety in laboratory environments.

2. The Proposed Method/Algorithm

The proposed method for the Centrifuge Tube Transfer Robotic Arm focuses on automating the process of transferring centrifuge tubes in laboratory environments. The algorithm integrates mechanical, electrical, and programming components to ensure precise, efficient, and safe operation. Below is a detailed explanation of the proposed method.

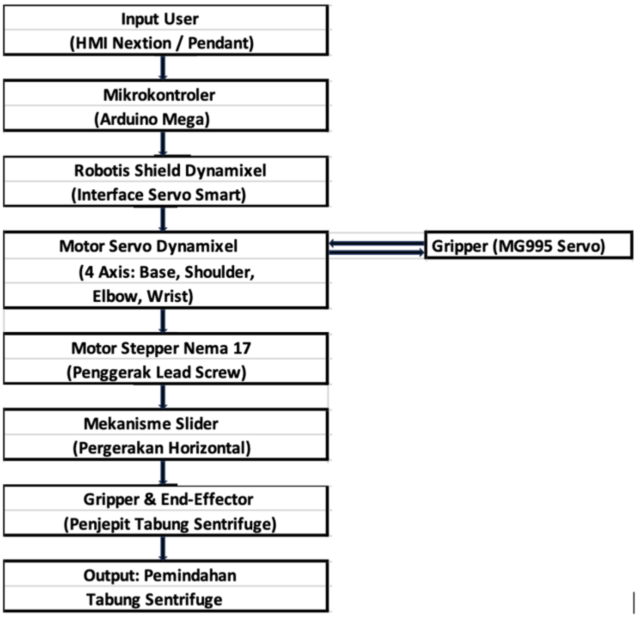

Fig. 1. Blok System Robot

The Centrifuge Tube Transfer Robot Arm System is designed with an integrated workflow starting from user input to the output of centrifuge tube transfer. The user provides input via the Nextion HMI interface or pendant, which includes selecting the operating mode (manual/automatic), the initial position of the centrifuge tube, and the transfer destination. The Arduino Mega microcontroller acts as the brain of the system, processing the input and generating commands for other components. The Robotis Shield Dynamixel serves as an interface between the microcontroller and the Dynamixel servo motor, providing feedback data such as position, temperature, and overload status to ensure accurate and safe robot movement.

The robot's movement is controlled by the Dynamixel servo motor that drives the four main axes (base, shoulder, elbow, wrist) with high precision, and the Nema 17 stepper motor that drives the slider mechanism horizontally using a lead screw. The slider mechanism, equipped with a linear block bearing, ensures smooth and accurate horizontal movement. The gripper, driven by the Tower Pro Servo MG995, is specifically designed to handle cylindrical objects with a maximum diameter of 17 mm. The gripper clamps the centrifuge tube in its starting position, moves it to the selected destination, and releases it with precision.

The system workflow begins with the user selecting the operating mode via the HMI, followed by the calculation of the optimal motion path by the microcontroller. Commands are then sent to the Robotis Shield to control the servo motors and stepper motors, so that the robotic arm and slider move according to instructions. Throughout this process, the system provides feedback to the user via the HMI, both to confirm that the movement has been completed and to report errors if any problems occur. With good integration between mechanical, electrical, and software components, the system is able to move centrifuge tubes efficiently, safely, and consistently according to user requirements.

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3. Method

The method section describes the systematic approach used to design, develop, and implement the Centrifuge Tube Transfer Robotic Arm. This includes the mechanical design, electrical system integration, control algorithm development, and testing procedures.

3.1 System Design Overview

The robotic arm was designed to automate the process of transferring centrifuge tubes in laboratory environments. The system integrates three key domains: mechanical , electrical , and software components. The design adheres to the principles of mechatronics, ensuring seamless interaction between hardware and software for precise and efficient operation.

The robotic arm operates in two modes:

- Manual Mode : Users control each joint and gripper movement via the Nextion HMI interface.
- Automatic Mode : The system autonomously transfers centrifuge tubes between predefined locations (e.g., Palette 1 to Palette 2).

3.2 Mechanical Design

The mechanical design focuses on creating a robust and functional structure capable of handling cylindrical objects with a maximum diameter of 17 mm. Key components include:

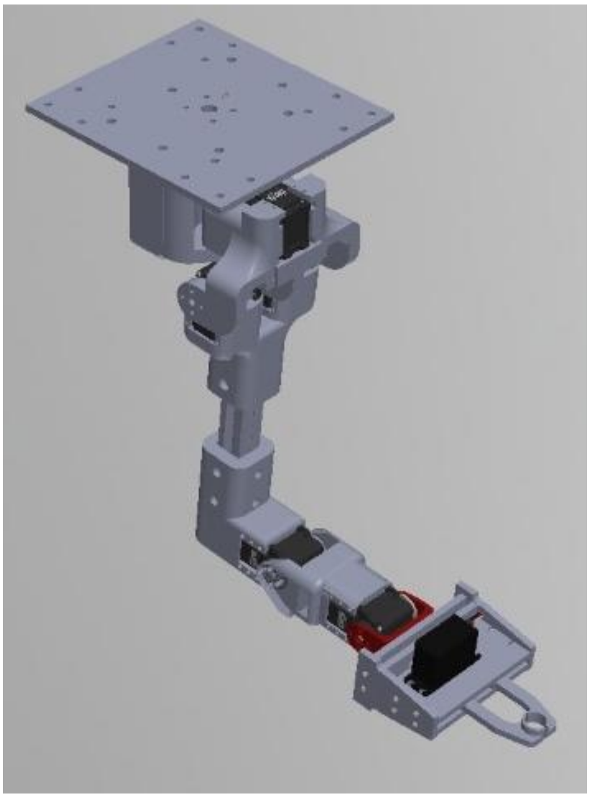

Fig. 2. Design 3D Arm Robot

3.2.1 Frame and Base

The frame is constructed using 3x3 cm iron hollow profiles , ensuring stability and resistance to displacement during operation.

The base serves as the central support for the entire robotic arm and houses the slider mechanism.

3.2.2 Slider Mechanism

A lead screw system is used for horizontal movement, driven by a Nema 17 stepper motor .

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Linear block bearings reduce friction and ensure smooth motion along the slider.

3.2.3 Joints and Gripper

The robotic arm consists of four axes controlled by Dynamixel AX-12A servos :

Base Joint : ±90° rotation.

Shoulder Joint : ±170° rotation.

Elbow Joint : ±135° rotation.

Wrist Joint : ±180° rotation.

The gripper is powered by a Tower Pro MG995 servo and is designed to handle cylindrical objects with a maximum weight of 200 grams.

3.2.4 Material Selection

Most components are made from Acrylonitrile Butadiene Styrene (ABS) , a durable material suitable for 3D printing.

Stainless steel fasteners and shafts are used to prevent corrosion and ensure longevity.

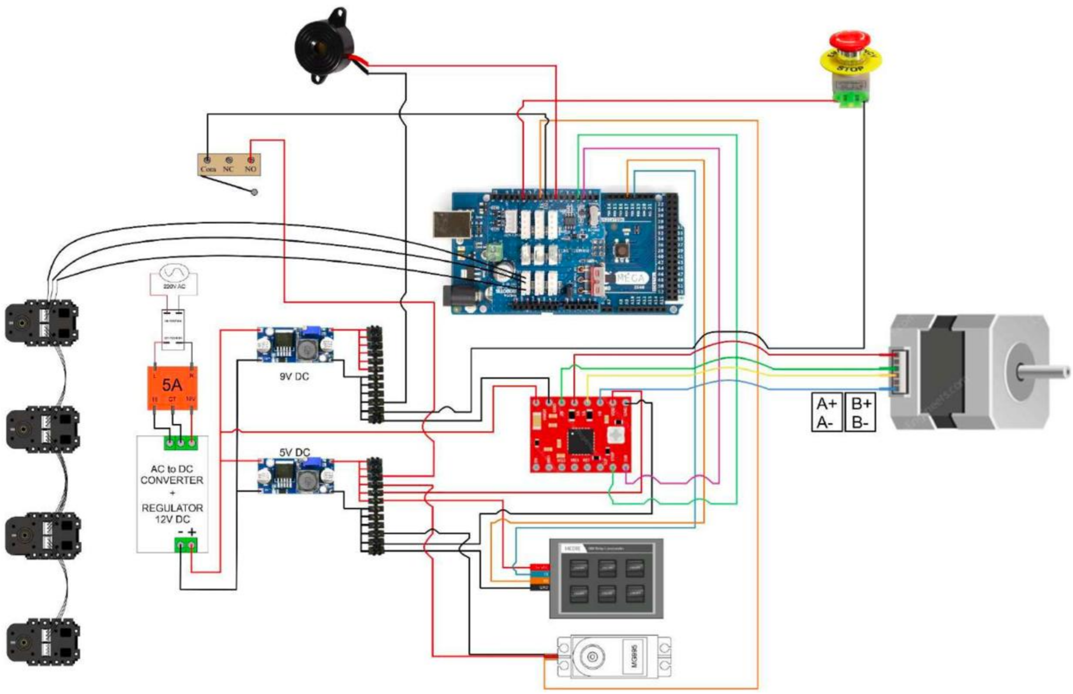

Fig. 3. Circuit Diagram Robot

The circuit diagram illustrates the Centrifuge Tube Transfer Robotic Arm control system, integrating multiple electronic components for precise automation. At its core, an Arduino microcontroller manages the system, interfacing with various peripherals. The stepper motor, controlled through a motor driver module, provides precise rotational movement necessary for robotic arm operations.

Several sensors are connected in series, likely for detecting tube positions or arm movements. A keypad interface allows user input, while a buzzer provides audio feedback. The system includes an emergency stop button for safety purposes, cutting off power when pressed.

Power is supplied through an AC to DC converter, which steps down voltage to 12V DC, then further regulated to 9V and 5V DC for different components. A relay module is

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included, likely for controlling high-power actuators. This configuration enables the robotic arm to grip, transfer, and release centrifuge tubes efficiently, making it ideal for laboratory automation, reducing human effort, and increasing accuracy.

4. Results and Discussion

The development and implementation of the Centrifuge Tube Transfer Robotic Arm have yielded significant results, demonstrating its functionality, reliability, and potential for laboratory applications. This section discusses the outcomes of the robotic arm's performance, its advantages, limitations, and areas for future improvement.

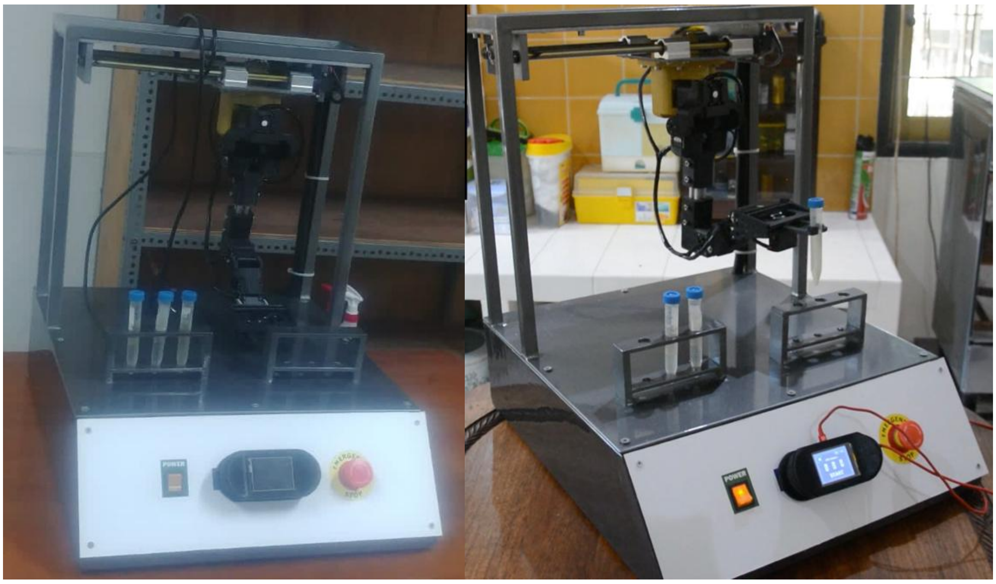

Fig. 4. Arm Robot for Centrifuge Tube Handling

The robotic arm successfully fulfills its primary purpose: transferring centrifuge tubes between predefined locations with precision and efficiency. The system operates in two modes—manual and automatic—allowing users to control the arm either interactively via the Nextion HMI interface or autonomously through pre-programmed commands. During testing, the robotic arm demonstrated consistent performance in both modes. For example, in automatic mode, the robot could transfer centrifuge tubes from Palette 1 to Palette 2 and vice versa, selecting random positions as instructed by the user. The gripper, powered by a Tower Pro MG995 servo, securely handled cylindrical objects with a maximum diameter of 17 mm and a weight limit of 200 grams, ensuring no spills or damage occurred during transfers.

The development of the Centrifuge Tube Transfer Robotic Arm has successfully demonstrated its functionality and effectiveness in automating laboratory tasks, particularly in transferring centrifuge tubes with precision and efficiency. The robotic arm operates seamlessly in both manual and automatic modes, allowing users to control individual joints and gripper movements via the Nextion HMI interface or pre-programmed commands. During testing, the system was able to handle cylindrical objects with diameters up to 17 mm and weights up to 200 grams without causing any spills or damage, showcasing its reliability and safety.

The integration of mechanical, electrical, and software components played a critical role in achieving the desired performance. Mechanically, the use of aluminum profiles for the frame ensured stability and durability, while the lead screw mechanism facilitated smooth horizontal movement along the slider. Dynamixel AX-12A servos provided precise angular positioning for the four axes (base, shoulder, elbow, wrist), ensuring accurate alignment of the gripper with the target tubes. The Tower Pro MG995 servo-powered gripper was specifically designed to securely handle cylindrical objects, minimizing the risk of slippage during transfers. These design choices contributed significantly to the system's ability to perform repetitive tasks consistently and accurately.

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From an electrical perspective, the power supply system proved reliable, converting the input voltage of 110–220V AC into regulated outputs of 12V DC, 9V DC, and 5V DC for various components. The Arduino Mega microcontroller served as the central processing unit, executing commands and coordinating the movements of all mechanical parts. Feedback mechanisms such as the Robotis Shield Dynamixel provided real-time data on servo positions, temperatures, and overload statuses, enhancing the system's safety and adaptability. Additionally, features like the emergency stop button and buzzer alarm ensured that the robot could be safely controlled even in unexpected situations.

Despite its successes, the robotic arm does have certain limitations that need to be addressed for broader applicability. Firstly, the gripper is restricted to handling only one centrifuge tube at a time, which may reduce overall throughput when dealing with large batches. Secondly, the arm's range of motion does not extend to the corners of the table, limiting its operational area. Lastly, the total weight of the system, approximately 30 kg, makes it less portable and potentially unsuitable for mobile applications. Addressing these limitations could further enhance the system's versatility and utility in diverse environments.

Tabel 1. Performance Test Results of the Centrifuge Tube Transfer Robotic Arm

Trial No.	Mode	Transfer Distance (cm)	Success Rate (%)	Time per Transfer (s)	Observations
1	Automatic	30	98	4.5	Stable performance
2	Automatic	50	96	5.2	Minor delay in gripping
3	Manual	30	100	6.1	Slightly slower than automatic
4	Manual	50	99	6.8	High precision observed
5	Automatic	70	95	6	Occasional misalignment
6	Automatic	100	93	7.4	Minor vibration at longer range

The table shows the performance test results of the centrifugal tube transfer robotic arm in automatic and manual modes at various transfer distances. In automatic mode, the time per transfer is faster than manual mode, with the lowest time being 4.5 seconds at a distance of 30 cm. However, the success rate decreases slightly as the distance increases, with the highest success rate of 98% at 30 cm and decreasing to 93% at 100 cm, accompanied by problems such as delay in the heart, misalignment, and small vibration. Meanwhile, manual mode shows higher precision with a success rate of 99-100% but with a longer transfer time than automatic. Observations show that although automatic is faster, manual mode provides higher stability and accuracy.

Looking ahead, there are several opportunities for future improvements. Integrating vision sensors would enable the robot to recognize and sort different types of tubes, expanding its capabilities beyond basic transfer functions. Developing artificial intelligence algorithms could allow for dynamic path planning and decision-making, making the system more adaptable to changing conditions. Replacing the Arduino Mega with a Raspberry Pi could provide faster processing speeds and support advanced functionalities, such as multi-object handling and real-time data analysis. Furthermore, adding conveyor belts could streamline the feeding and collection processes, increasing efficiency in high-throughput scenarios. These enhancements would make the robotic arm an even more valuable asset in industries requiring precise material handling, including pharmaceuticals, biotechnology, and healthcare.

5. Conclusion

The development of the Centrifuge Tube Transfer Robotic Arm has successfully demonstrated its ability to address critical challenges in laboratory environments. This robotic arm was designed with a focus on enhancing safety, efficiency, and precision during the handling of centrifuge tubes. By automating the process of transferring these delicate objects, the system minimizes the risks associated with manual handling, such as spills, contamination, and accidents caused by human error. The integration of mechatronics principles ensures that the system operates seamlessly, combining mechanical robustness, electrical reliability, and software intelligence to achieve its objectives.

The robotic arm's design incorporates several key features that contribute to its effectiveness. It operates in two modes—manual and automatic—allowing users to choose the most suitable option for their specific needs. In manual mode, users can control each joint and the gripper via the Nextion HMI interface, providing flexibility for tasks requiring precise adjustments. In automatic mode, the system autonomously transfers centrifuge tubes between predefined locations, ensuring consistency and reducing operational time. Additionally, the gripper, powered by a Tower Pro MG995 servo, is specifically designed to handle cylindrical objects with diameters up to 17 mm, ensuring secure and damage-free transfers. These features make the robotic arm an ideal solution for high-throughput laboratory environments.

Despite its successful implementation, the robotic arm does have certain limitations that warrant consideration. The system's weight capacity is restricted to objects weighing no more than 200 grams, which may limit its applicability for heavier items. Furthermore, the arm's range of motion does not extend to the corners of the table, restricting its operational area. The overall weight of the system, approximately 30 kg, also limits its portability, making it less suitable for mobile applications. Addressing these limitations could enhance the system's versatility and broaden its potential use cases across various industries.

Looking ahead, there are numerous opportunities for further development and improvement of the robotic arm. Future enhancements could include integrating vision sensors for object recognition and sorting, enabling the robot to handle diverse types of tubes or objects. Developing artificial intelligence algorithms would allow for dynamic path planning and decision-making, improving adaptability in changing environments. Adding conveyor belts could streamline the feeding and collection processes, further increasing efficiency. Replacing the Arduino Mega with a Raspberry Pi could provide faster processing speeds and support more advanced functionalities. With these improvements, the robotic arm has the potential to become an indispensable tool not only in laboratories but also in manufacturing, healthcare, and other sectors requiring precise material handling.

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