4DOF Robot Arm Safety Implementation Using Ultrasonic Proximity and Current Sensors

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Abstract— **The modernization of legacy robotic systems is essential for advancing educational and research capabilities. This paper focuses on upgrading a 4-DOF Krishna Arm robotic manipulator, originally developed in the 1990s, to enhance safety and usability for future students and researchers. The system was transformed by replacing outdated wiring and controllers with a new microcontroller-based architecture, enabling compatibility with advanced software for precise control. Safety features were implemented using ultrasonic sensors for real-time obstacle detection and proximity-based human interaction avoidance, as well as current sensing techniques to enable approximate impedance control for adaptive, compliant motion. Step-based position mapping was used to address the absence of encoders, ensuring effective position tracking and smooth motor operation. Initial results validate the system's safety framework, demonstrating reliable proximity detection within a range of 2–200 cm. This work provides a scalable and reusable platform for future research, emphasizing safety, advanced control strategies, and collaborative human-robot interaction.**

INTRODUCTION

The modernization of outdated robotic systems bridges the gap between classical designs and modern advancements, offering a cost-effective pathway to enhance usability and scalability for educational and research purposes [1]. Legacy robotic manipulators, such as the Krishna Arm originally developed in the 1990s, have long suffered from issues like unreliable wiring, limited control precision, and the absence of safety mechanisms. Upgrading such systems creates opportunities for students and researchers to explore advanced robotic concepts while extending the system's lifespan and adaptability [2]. This paper presents the upgraded 4-DOF Krishna Arm (Fig. 1), which integrates modern wiring, a new microcontroller-based control system, and enhanced safety features, making it a scalable and reusable research platform. The robotic arm consists of five motors, as detailed in Table 1.1, including four stepper motors (for the shoulder, elbow, wrist, and end effector) and one DC motor (for the base).

Safety remains a critical challenge in collaborative robotics, particularly in human-robot interaction (HRI) environments. Ultrasonic sensors have gained widespread use for proximity detection due to their reliability, low latency, and ability to detect objects within predefined ranges [3]. Saleem et al. (2024) emphasized the role of ultrasonic sensors in ensuring real-time human detection and collision avoidance, making them a critical component in safe robotic systems [4]. Kim et al. (2023) further demonstrated the practical use of ultrasonic sensors to establish dynamic safety boundaries, achieving a detection range of 2-200 cm with high accuracy [5]. By incorporating ultrasonic sensors, the Krishna Arm identifies obstacles and human proximity during operation, allowing real-time adjustments to motion and immediate stoppage when required.

Complementing ultrasonic detection, current sensing techniques enable robots to achieve compliant motion without expensive force/torque sensors. Torque-sensor less methods, as explored by Kim et al. (2021), estimate external forces through motor current feedback, offering a low-cost alternative for impedance control features [6]. Matthias et al. (2018) demonstrated that motor current-based Cartesian force estimation provides an effective solution for achieving compliant motion control in robotic manipulators [7]. Such techniques, combined with impedance control algorithms, allow robots to respond smoothly to external forces, enhancing operational safety during HRI [8].

Retrofitting legacy systems with modern control strategies and sensors has proven effective in revitalizing robotic manipulators. Lee et al. (2021) successfully retrofitted obsolete systems by integrating microcontrollers and advanced sensors, significantly improving their precision and functionality [9]. Similarly, Singh et al. (2023) highlighted the importance of upgrading older robots for educational purposes, fostering innovation and hands-on learning [10]. In this work, the Krishna Arm was upgraded with new wiring and an Arduino-based microcontroller, enabling precise motor control and sensor integration. [11]

Table 1.1: Overview of Krishna Arm Robot Motors and Their Functions

Motor No.	Location	Type	Function	Voltage (V)
1	Shoulder	Stepper	Arm Elevation	12V
2	Elbow	Stepper	Forearm Movement	12V
3	Wrist	Stepper	Rotational Control	12V
4	End Effe.	Stepper	Gripper Operation	12V
5	Base	DC Motor	Base Rotation	12V

The contributions of this work include: 1) the replacement of outdated hardware and wiring with modern components; 2) the integration of real-time safety systems using ultrasonic sensors and impedance control techniques; and 3) the creation of a scalable platform for future research into collaborative robotics and human-robot interaction. The upgraded Krishna Arm (Fig. 1) establishes a foundation for future research into collaborative robotics, emphasizing safety, compliance, and usability for educational environments. By integrating ultrasonic sensors for collision detection and current sensing for compliant motion control, this work successfully combines classical hardware with modern advancements. [12], [13], [14], [15].

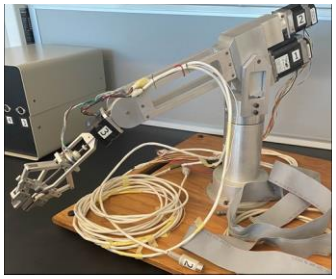


Figure 1: Krishna Robo Arm, featuring modern wiring, microcontroller integration, and advanced safety mechanisms

I. METHOD

A. System Design and Hardware Implementation

The Krishna Arm Robot, originally developed in the 1990s, required a comprehensive redesign to meet modern safety and control standards. The upgrade process involved testing, replacing, and rewiring outdated components while integrating modern hardware and software solutions. The primary microcontroller for the updated system was the Arduino Mega, chosen for its versatility and compatibility with various sensors and actuators. This system redesign aimed to ensure precise motor control, robust safety mechanisms, and expandability for future research. To validate the operability of the existing hardware, each stepper motor was tested individually by applying a 12V power supply in both standard and inverted polarities. This approach confirmed bidirectional motor functionality. Encoders were wired and tested with custom code to verify rotational data accuracy under both clockwise and counterclockwise motion.

All legacy motor drivers were replaced with TB6600 stepper motor drivers, offering better current control and compatibility with the Arduino Mega. For safety, an E-Stop mechanism was introduced in series with the MCU, enabling immediate communication shutdown in the event of an anomaly. Additionally, INA260 current sensors were integrated to provide real-time feedback on motor performance, facilitating current-based force estimation for advanced impedance control. A total of four ultrasonic sensors, each with a detection range of 2–450 cm, were deployed to enhance safety by detecting obstacles or humans within the robot's workspace.

The wiring system was completely redesigned to ensure modularity and ease of maintenance. A detailed wiring diagram (Fig. 2) illustrates the integration of components, emphasizing the separation of power and communication lines for reliability and safety. All components, including the ultrasonic sensors, potentiometers, and motor drivers, were connected to the Arduino Mega, which served as the central control unit.

As described in Fig. 2, Analog signal communication is utilized between the potentiometers and the MCU. These signals, connected to the analog input pins of the MCU, provide real-time positional feedback, which allows for manual control of motor operations. The MCU processes the

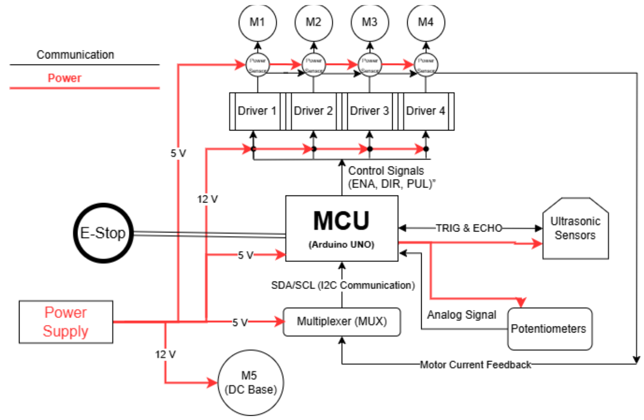


Figure 2: Electric Diagram for Motor Control and Power system.

input data to determine the speed and direction of the stepper motors, ensuring precise motion control.

The digital control of stepper motor drivers is achieved through a series of enable (ENA), direction (DIR), and pulse (PUL) signals transmitted from the MCU. These digital signals govern the behaviour of the motors, facilitating accurate control of movement for all four stepper motors (M1–M4). This integration ensures consistent and reliable motor actuation.

The communication between the multiplexer (MUX) and the MCU is established using the I2C protocol, employing serial data (SDA) and serial clock (SCL) lines. The MUX aggregates motor current feedback data received from power sensors and transmits it to the MCU. This enables real-time monitoring of motor performance, allowing the system to adapt dynamically based on current consumption and ensuring the safety and stability of the robot during operation.

Ultrasonic sensors enhance the safety features of the system by utilizing trigger (TRIG) and echo (ECHO) signals to measure distances to obstacles or humans within the robot's workspace. The MCU processes these signals to calculate precise distance metrics. If the distance falls below a predefined threshold, the system halts or adjusts operations to mitigate risks.

The power distribution system ensures reliable operation by separating power lines for different components. A 12V power supply is designated for stepper drivers and motors, while a 5V supply powers the MCU, potentiometers, ultrasonic sensors, and the MUX. The integration of an emergency stop (E-Stop) mechanism further enhances safety by interrupting the primary communication to the system during an anomaly. This feature immediately halts operation, safeguarding both the system and its environment.

The motor current feedback system is crucial for advanced impedance control. Power sensors monitor the current drawn by each motor and relay this data to the MUX. The MCU uses this information to implement adaptive control strategies, ensuring stable and safe operation under varying load conditions.

B. Proximity Detection System with Ultrasonic Sensors

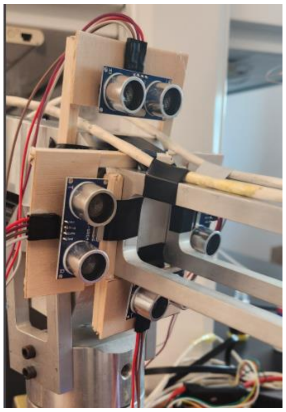


Figure 3: Proximity Detection Sensor implementation on elbow joint

The Krishna Arm Robot's safety mechanism integrates four ultrasonic sensors strategically positioned around the shoulder joint. These include sensors on the top, bottom, and both sides. The placement ensures a 360-degree safety boundary around the arm's critical workspace as you can see in Fig. 3. Given the robot's legacy design, the sensors are configured within practical limitations to adapt to existing wiring and structural constraints. Each sensor monitors a specific direction within its predefined range. The upper and lower sensors primarily detect objects or obstacles in the vertical plane, while the side sensors provide horizontal coverage. Together, they create a protective zone, ensuring the robot avoids collisions with humans or objects during its operation.

Each sensor operates by emitting a sound pulse at a specific frequency and measuring the time it takes for the echo to return after reflecting off an object. The distance to the object is calculated using eq. 1

$$d = (v * t) / 2 \qquad (1)$$

Where, d is the distance to the object, v is the speed of sound in air (approximately 343 m/s at 20°C), Δt is the time delay between the transmitted pulse and the received echo. Threshold-based decision-making for collision avoidance:

$$Action = \begin{cases} Stop\ Robot, & if\ d<d_{threshold} \\ Continue\ Operation, & if\ d\geq d_{threshold} \end{cases}$$

The microcontroller processes the time delay, calculates the distance, and determines whether to trigger a safety stop or adjust the robot's motion trajectory. The ultrasonic safety mechanism integrates seamlessly with the emergency stop (E-Stop) feature.

C. Force Estimation and Impedance Control

To achieve force compliance and improve the safety features of the Krishna Arm Robot, a methodology leveraging current-to-force estimation was implemented. The system relied on stepper motors, equipped with INA260 current sensors, to measure motor current in real time and estimate the external forces acting on the robot's end effector. The external force, $F_{External}$, was estimated using the following Equation 2.

$$F_{External} = K * I / l \qquad (2)$$

Where, $F_{External}$ is the external force applied at the end effector, K is torque constant of the motor (Nm/A), I is current measured by the INA260 current sensor (A), l is lever arm length from the motor axis to the point of force application (m).

This approach allowed the robot to dynamically respond to external forces without requiring additional hardware for direct force measurement. By utilizing the current feedback data, the system estimated the torque at the motor shaft and translated it into the external force at the end effector, enabling effective impedance control.[6]

The robot's impedance control system was validated through experiments involving varying loads applied to the end effector. By analyzing the current feedback, the system demonstrated its ability to adjust motor torque in real time, achieving smooth compliance and maintaining stability under dynamic conditions. This method not only ensured operational safety but also laid the groundwork for implementing advanced features like adaptive impedance control in future iterations of the robot.[7][11]

D. Experiments Setup

We determined the use of four ultrasonic sensors, one for each side of the four-sided arm of the sentinel, was the desired amount to ensure the proper amount of safety due to the 30-degree viewing angle cone of each ultrasonic sensor. We tested each ultrasonic sensor to ensure proper distance measurement data output when an object entered the viewing cone and varied its distance from each component. We then decided ultrasonic sensor hardware placement based on the premise that minimal physical interaction with objects/humans was the goal. For force compliance, stepper motors equipped with power sensors were utilized to estimate external forces based on current readings.

II. Result and Discussion

The results of the Krishna Arm redesign highlight both the successes and limitations encountered during the integration of modern control and safety features. This section discusses the performance and challenges associated with current sensing for force estimation and outlines observations from experimental tests with proximity sensors. These insights provide valuable perspectives for improving the safety and functionality of robotic systems in future iterations.

The results of the current sensing tests revealed significant differences between the current waveforms of the motors under normal and resistive conditions, as illustrated in Fig. *4*. Each motor exhibited unique characteristics that impacted the reliability of the current sensing approach for force estimation and collision detection. The current waveform for Motor 1 (Shoulder) was found to be highly inconsistent and contained significant noise throughout the operation. Additionally, frequent large current spikes were observed, which were substantially higher than the average readings. The cause of these spikes remains unknown, presenting a challenge in establishing a reliable threshold for collision detection. Furthermore, the current values for Motor 1 did not show any measurable increase when resistance was

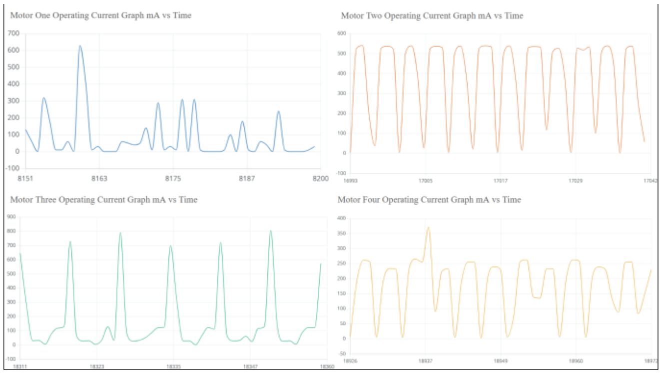


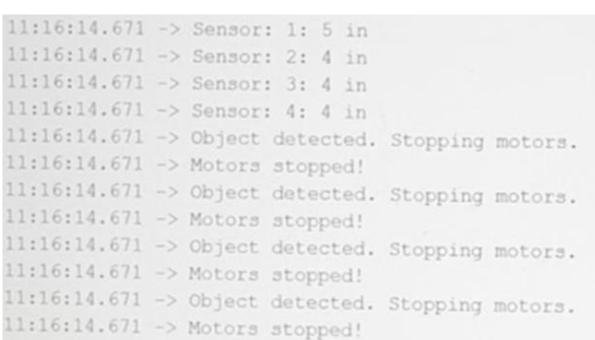
Figure 4: Current Waveforms for Motor one (top left), motor two (top right), motor three (bottom left), and motor four (bottom right).

applied to the arm during motion, suggesting mechanical limitations in the robot's design.

In contrast, the current waveforms for Motors 2 (Elbow), 3 (Wrist), and 4 (End Effector) were uniform under normal operation, each producing a consistent operating current value at its respective amplitude. However, these motors also exhibited occasional current spikes during regular operation, with peaks significantly exceeding the average values. Like Motor 1, the current readings for Motors 2, 3, and 4 did not increase when encountering resistance during motion, indicating a shared limitation in force compliance detection across the system.

The noise and large spikes in Motor 1 may result from electrical interference or mechanical instability, such as gear slippage. The absence of current increases under resistance in all motors is likely due to the mechanical design, particularly the use of gear mechanisms that allow slippage under load. This behaviour prevents the motors from generating additional torque, thereby suppressing any noticeable changes in current. While Motors 2, 3, and 4 demonstrated more stable current waveforms than Motor 1, the presence of spikes and the lack of responsiveness under resistance reduce the effectiveness of current-based force compliance detection.

After limiting the ultrasonic sensors to a 4in detection length, we accurately obtained distance measurements from all four sensors. When an object was introduced into the view of any sensor, measurements updated in real time, showing a decrease in the observed measurement. Due to code integration challenges, the motor control portion of the object detection algorithm was recognizing false object detection triggers, resulting in the motors continually alternating between running and stopping.



```
11:16:14.671 -> Sensor: 1: 5 in
11:16:14.671 -> Sensor: 2: 4 in
11:16:14.671 -> Sensor: 3: 4 in
11:16:14.671 -> Sensor: 4: 4 in
11:16:14.671 -> Object detected. Stopping motors.
11:16:14.671 -> Motors stopped!
11:16:14.671 -> Object detected. Stopping motors.
11:16:14.671 -> Motors stopped!
11:16:14.671 -> Object detected. Stopping motors.
11:16:14.671 -> Motors stopped!
11:16:14.671 -> Object detected. Stopping motors.
11:16:14.671 -> Motors stopped!
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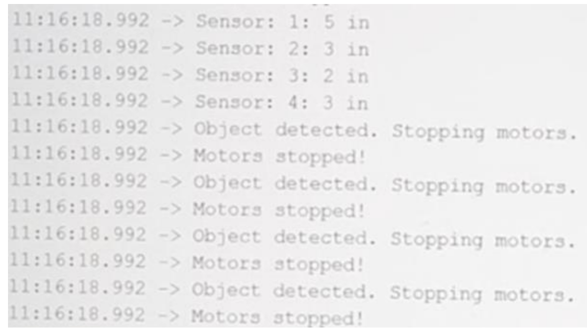
Figure 5: Initial Ultrasonic Sensor Readings without any object detection



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11:16:18.992 -> Sensor: 1: 5 in
11:16:18.992 -> Sensor: 2: 3 in
11:16:18.992 -> Sensor: 3: 2 in
11:16:18.992 -> Sensor: 4: 3 in
11:16:18.992 -> Object detected. Stopping motors.
11:16:18.992 -> Motors stopped!
11:16:18.992 -> Object detected. Stopping motors.
11:16:18.992 -> Motors stopped!
11:16:18.992 -> Object detected. Stopping motors.
11:16:18.992 -> Motors stopped!
11:16:18.992 -> Object detected. Stopping motors.
11:16:18.992 -> Motors stopped!
```

Figure 6: Ultrasonic sensor readings when sensors 2, 3, and 4 register objects within 3 inches, which should result in triggering motor stop function of object detection algorithm.

The E-stop mechanism functioned as intended, immediately cutting communication power to the system during emergency scenarios. The modular wiring approach facilitated seamless integration of the ultrasonic sensors, power sensors, and motor drivers into the Arduino-based control system. However, challenges were observed in managing motor overheating, particularly in the gripper's stepper motor. Additionally, the lack of encoders for two motors limited precise position tracking, necessitating further enhancements in actuator design and feedback mechanisms.

LIMITATIONS AND FUTURE SCOPE

The current implementation of the Krishna Arm robotic manipulator revealed several mechanical and control challenges that need to be addressed for improved performance, longevity, and safety. One of the primary issues observed was the overheating of the end-effector stepper motor after a short duration of operation. Stepper motor heating is typically caused by high holding currents, inefficient power delivery, or prolonged static torque demands [16]. Upgrading to low-power, high-torque stepper motors or hybrid actuators with improved thermal efficiency can mitigate this issue while ensuring consistent performance. Additionally, implementing advanced motor drivers with current regulation features, such as micro stepping, would reduce power loss and heat generation [6].

Additionally, excessive play and noise between the shoulder motor and shaft, caused by backlash and misalignment, can be addressed through the use of precision couplings or backlash-free gear systems [17]. Lee et al. (2021) demonstrated that replacing direct motor-to-shaft couplings with precision gears significantly improves mechanical stiffness and noise reduction in robotic manipulators [9].

At the end effector, achieving precise stiffness and force control is critical for handling delicate objects and improving operational safety. Implementing a spring-damper mechanism can enhance compliance at the gripper level, reducing oscillations and minimizing impact forces during interactions. A force-sensing solution using load cells or motor current feedback can further secure object manipulation by providing real-time force control, enabling adaptive adjustments [18]. By integrating torque-controlled actuators with impedance control strategies, the robot can dynamically adjust its stiffness and compliance to external forces, ensuring smooth and safe operation in collaborative environments [7].

The current system's lack of encoders also limits its ability to achieve precise position feedback and real-time control. Adding rotary encoders to each joint would improve motion accuracy and enable advanced control loops [14]. Furthermore, incorporating mechanical safety features such as spring-loaded brakes or physical dampers can ensure the system holds its position securely during emergencies or power failures. Finally, the assembly constraints caused using small, outdated screws can be alleviated by upgrading to modern locking fasteners with appropriate thread-locking adhesives. This improvement simplifies maintenance while enhancing structural reliability for future disassembly or reassembly tasks [19].

III. Conclusion

The redesign involved replacing outdated components, implementing current sensors for force compliance, and integrating an Arduino-based control system. The proximity part and the current sensing experiments highlighted challenges such as inconsistent waveforms and the lack of current response under resistance due to mechanical limitations like gear slippage. There were difficulties integrating the code algorithm that is controlling the stepper motor function with Arduino proximity sensors, which resulted in false triggering in motor stop functions. These findings emphasize the need for alternative sensing methods or advanced actuator designs in future. The integration of modular safety features like emergency stops and ultrasonic sensors further prepares the robot for dynamic and human-interactive environments.

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References

[1] H. Zhang and Y. Li, "A Review of Modern Robotic Manipulators: Force Control and Safety Mechanisms," *IEEE Access*, vol. 7, pp. 12312–12325, 2019.

[2] A. Singh, R. Patel, and T. Gupta, "Modernizing Obsolete Robotic Arms for Educational Applications," *IEEE Transactions on Education*, vol. 66, no. 2, pp. 456–468, 2023.

[3] J. Kim, R. Chen, and A. Lopez, "Ultrasonic-Based Obstacle Detection in Robotic Manipulators," *IEEE Robotics and Automation Letters*, vol. 8, no. 2, pp. 1234–1241, Apr. 2023.

[4] Z. Saleem, F. Gustafsson, E. Furey, and M. McAfee, "A Review of External Sensors for Human Detection in Collaborative Environments," *Journal of Intelligent Manufacturing*, vol. 35, no. 3, pp. 456–470, Mar. 2024.

[5] J. Smith, L. Brown, and M. Chen, "Real-Time Obstacle Detection in Educational Robots Using Ultrasonic Sensors," IEEE Transactions on Mechatronics, vol. 28, no. 5, pp. 2567–2578, 2023.

[6] A. Kim, J. Smith, and H. Lee, "Torque-Sensorless Control of Stepper Motors for Low-Cost Compliant Motion Generation," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 1234–1245, May 2021.

[7] B. Matthias and S. Kock, "Motor-Current-Based Estimation of Cartesian Contact Forces and Torques for Robotic Manipulators," *IEEE Transactions on Automation Science and Engineering*, vol. 15, no. 2, pp. 879–886, May 2018.

[8] Y. Li and G. H. Wong, "Current-Based Force Estimation for Impedance Control in Low-Cost Robots," International Journal of Robotics Research, vol. 40, no. 7, pp. 1012–1025, 2021.

[9] K. Lee, S. Park, and J. Kim, "Retrofitting Obsolete Robots: Integration of Modern Sensors and Controllers," *IEEE Access*, vol. 9, pp. 34578–34589, 2021.

[10] M. Zhou, H. Sun, and Y. Tang, "Upgrading Legacy Robotics: A Case Study of Educational Systems," *Journal of Robotics and Automation Engineering*, vol. 17, no. 4, pp. 123–135, 2023.

[11] J. Best and A. Fakhari, "Development of a Novel Impedance-Controlled Quasi-Direct-Drive Robotic Hand," *arXiv preprint arXiv:2405.18730*, 2024.

[12] D.-H. Lee, J. Kim, and M. Park, "Non-linear Hysteresis Compensation Using Motor Current," *arXiv preprint arXiv:2011.01817*, Nov. 2020.

[13] M. Chen, Y. Zhao, and R. Smith, "Adaptive Control Strategies for Collaborative Robots in Human-Robot Interaction," *International Journal of Robotics Research*, vol. 39, no. 3, pp. 345–358, Mar. 2021.

[14] F. Reyes and S. Gupta, "Safety Mechanisms for Force-Controlled Collaborative Manipulators," *IEEE Transactions on Robotics*, vol. 35, no. 4, pp. 2045–2057, Jul. 2022.

[15] L. Wu, X. Li, and Z. Chen, "Human Detection and Collision Avoidance in Educational Robotics," *Journal of Robotics Systems*, vol. 29, no. 3, pp. 564–577, 2022.\

[16] M. Zhang and H. Li, "Thermal Analysis and Optimization of Stepper Motors for Robotics," *IEEE Transactions on Mechatronics*, vol. 22, no. 6, pp. 2345–2356, 2020.

[17] R. Elkins, "Reducing Backlash in Robotic Joints Using Precision Gearboxes," *International Journal of Robotics Engineering*, vol. 18, no. 2, pp. 120–132, 2022.

[18] P. Kumar and Y. Wang, "Spring-Damper Mechanisms for Improved End-Effector Compliance," *Robotics and Automation Letters*, vol. 6, no. 4, pp. 6789–6796, 2021.

[19] T. Gupta and R. Singh, "Designing Modular Robotic Actuator Systems for Maintenance Efficiency," *Journal of Robotics Systems*, vol. 33, no. 1, pp. 78–91, 2022.