

AUTOMATIC ROBOTIC INTERCHANGEABLE END-EFFECTOR SYSTEM (ARIES)

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Abstract

Robotic arms are increasingly used across industries such as manufacturing, healthcare, logistics, agriculture and research due to their precision, repeatability, and adaptability. However, their versatility is often limited by the need for manual intervention when changing end effectors (grippers, welders, screwdrivers, surgical tools, etc.). This creates downtime, reduces efficiency, and restricts adaptability across diverse tasks. The proposed project, introduces a universal connector system that allows robotic arms to automatically replace end effectors in real-time. With this design, the robotic arm and end effector remain seamlessly connected through a smart connector, allowing the arm to instantly switch between tools with minimal effort. This system transforms a single robotic arm into a multi-purpose all-in-one platform, suitable for applications in any field with just a change of end effector. By eliminating manual tool replacement, the proposed system reduces cycle time, minimizes human dependency, and improves overall system efficiency. The functionality and feasibility of the proposed system are validated through simulation using the Gazebo robotics simulator, enabling safe evaluation of tool-changing operations, motion control, and system performance prior to real-world implementation. Furthermore, its modular and scalable architecture allows compatibility with different robotic arm configurations and end-effector types, making it a cost-effective and future-ready solution for advanced automation environments.

1. Introduction

The progressive adoption of automated systems across manufacturing, healthcare, logistics, and research environments has underscored both the value and the limitations of contemporary robotic manipulators. While these systems excel at executing repetitive operations with high precision and consistency, their utility is

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frequently constrained by the assumption that a single arm will perform a single category of task throughout its operational lifetime. This single-purpose paradigm conflicts with the agile production demands characteristic of modern industrial frameworks, where rapid task reconfiguration is often a competitive necessity. In most existing deployments, transitioning a robotic arm from one task to another requires a technician to physically detach the current end effector and mount a replacement — a process that halts production, introduces alignment variability, and increases dependence on skilled personnel. The absence of a standardised, programmable tool-exchange interface means that each installation typically relies on custom coupling hardware, raising both integration complexity and long-term maintenance costs. The ARIES platform was conceived to address these limitations through the design and implementation of a universal connector mechanism capable of autonomously docking and releasing interchangeable end effectors. By embedding this capability within a servo-driven articulated arm and pairing it with a ROS2-based software stack, the system transforms a fundamentally single-purpose manipulator into a configurable, multi-function platform. The following sections describe the technical architecture, mathematical foundation, prototype implementation, and performance characterisation of the proposed system.

1.1 Robotic arm definition

A robotic arm is an articulated mechanical manipulator composed of a series of rigid links connected through joints, allowing controlled motion in multiple degrees of freedom. It is typically driven by actuators such as servo motors and controlled through embedded systems or computer-based algorithms. The end-effector interacts with the environment to perform tasks such as gripping, lifting, assembling, or processing objects. Robotic arms are used in health care, research and industries due to their high accuracy, repeatability, and ability to operate in complex and hazardous environments.

1.2 End Effector definition

An end effector is the terminal device or tool attached to the end of a robotic manipulator, designed to interact directly with the environment [7]. It forms the functional interface between the robotic arm and the task to be performed. By compared end effector to the human hand, it enables the robot to grasp, manipulate, assemble, inspect, or process objects within its workspace. End effectors are typically mounted on the wrist joint of the robotic arm and are mechanically and electrically integrated to ensure precise control and reliable operation. Depending on the application, the end effector may be classified into two primary categories: grippers and process tools. Grippers are used for object handling tasks such as picking, placing, holding, or transferring components. Process-type end effectors are designed to perform specific operations such as welding, drilling, painting, cutting, or fastening operations [9,13]

1.3 Scope and Motivation

Current robotic deployments in industry exhibit four recurring limitations that constrain their broader applicability. First, manual tool changes disrupt continuous operations and introduce non-trivial cycle time penalties. Second, the lack of a cross-compatible coupling standard forces task-specific hardware solutions that are difficult to adapt. Third, most commercial arms are optimized for one or two operation types, restricting their deployment to narrow use cases. Fourth, application-specific design philosophies limit the transferability of robotic platforms across sectors such as logistics, precision agriculture, and clinical environments. ARIES targets each of these constraints through a unified mechanical and software solution.

2. EXISTING WORK

The current use of robotic arms in industries is limited by inefficiencies and adaptability issues. While they improve productivity, their effectiveness is reduced due to challenges in tool changing and versatility [3,4]. **Operational Downtime:** Robotic arms require manual intervention for tool changes, which disrupts workflow and causes significant downtime, reducing efficiency in continuous operations[8]. **Lack of Universal Connector:** There is no standardized system for automatic tool switching, making current solutions task-specific and dependent on custom connectors[13]. **Single-Purpose Limitation:** Most robotic arms are designed for one or two dedicated tasks, limiting their ability to perform varied operations such as gripping, welding, or screwing[5]. **Limited Industrial Applicability:** Existing robotic systems are often built for specific industries, restricting their broader use in fields like logistics, agriculture, or healthcare[6].

3. LITERATURE SURVEY

Research into robotic manipulator design and tool-changing mechanisms has advanced substantially over the past decade, though significant gaps remain in the integration of programmable positional control with low-cost, modular end-effector exchange systems.

1.1 Kinematic Modelling and Control Strategies

Investigations into PID-based and model-driven control strategies have demonstrated measurable improvements in the positioning accuracy and dynamic stability of articulated robotic arms. Zhang and Liu [1] presented a benchmark framework for a 7-DOF manipulator operating under ROS and Gazebo, establishing baseline performance metrics applicable to medium-payload educational platforms. Cheng, Liao, and Lan [10] developed a four-degree-of-freedom pick-and-place configuration demonstrating sub-millimeter repeatability under structured load conditions, a result attributable to the mechanical rigidity of the parallel-linkage architecture they employed.

1.2 Automatic Tool-Change Mechanisms

Ambrosio and Karamanoglu [13] proposed an “automatic tool changer for an articulated industrial arm”, demonstrating that spring-based locking mechanisms can provide adequate coupling force for moderate-payload operations while remaining mechanically simple. Their work identified alignment precision during the docking phase as the critical determinant of exchange reliability. Zeng, Chuang, and Chen [7] extended this concept to microsurgical robotics, where the tolerance requirements are substantially more stringent, and demonstrated that sensor-assisted alignment significantly reduces engagement error. However, the sensor overhead they introduced raises per-unit cost beyond the reach of educational or small-scale industrial deployments. Mourtzis, Angelopoulos, and Papadokostakis [3] examined tool-changing under Industry 5.0 conditions, proposing a 3D-printed changer prototype validated through finite element analysis. Their findings confirm that additive manufacturing is a viable fabrication route for low-force coupling hardware, an observation that directly informs the ARIES fabrication strategy.

1.3 Multi-Purpose and Educational Robotic Platforms

Mandeep et al. [5] demonstrated a multi-purpose pick-and-place arm designed around a Raspberry Pi controller, showing that open-source hardware can support acceptable task-switching performance when software coordination is carefully managed. The AR3 open-source arm, evaluated at the CSIR Learning Factory [1], provided evidence that machined and 3D-printed hybrid construction achieves functional parity with commercial alternatives for educational automation tasks. Luan, Hu, and Wang [9] contributed “a quick-change end-effector control architecture for lightweight arms used in assembly tasks”, highlighting the role of software-level sequencing in achieving smooth, jerk-free tool transitions.

Collectively, the surveyed literature identifies a gap between high-precision industrial tool changers, which are cost-intensive and mechanically complex and low-cost educational systems that lack any automated exchange capability. ARIES is positioned to bridge this gap by delivering reliable autonomous tool changing within a cost-constrained, open-hardware framework.

4. SYSTEM ARCHITECTURE

The ARIES platform comprises four tightly integrated subsystems: (1) the mechanical arm structure, (2) the universal connector and docking mechanism, (3) the embedded control electronics, and (4) the software execution framework [6]. Fig. 1 illustrates the overall system block diagram.

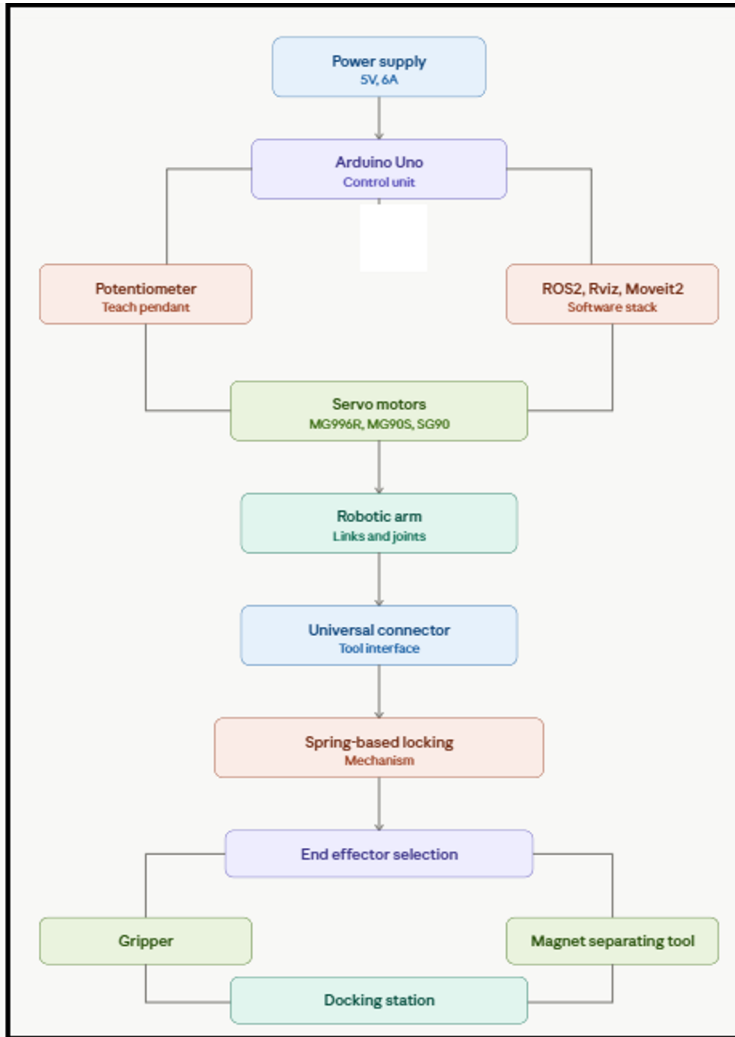


Fig. 1. ARIESSystem Block Diagram

4.1 Mechanical Structure

The arm structure consists of four primary degrees of freedom: base rotation about the vertical axis, shoulder elevation, elbow flexion, and wrist pitch orientation. This configuration provides sufficient workspace coverage for the docking and task-execution operations required by the target application set. Structural components are fabricated from lightweight aluminium profiles and 3D-printed polymer brackets, a combination that balances rigidity against fabrication cost and mass. The docking station is a fixed platform mounted within the reachable workspace envelope of the arm. It accommodates multiple end effectors at pre-surveyed, calibrated positions, each defined in the robot's base frame coordinate system. This pre-registration ensures that the arm can approach each tool station along a repeatable, collision-free trajectory without requiring real-time sensing during the approach phase.

4.2 Actuator Selection

The robotic arm utilizes a combination of servo motors selected based on torque and application requirements [8]. High-torque servo motors (MG996R) are used at the base and primary joints to handle load-bearing operations and provide sufficient strength for lifting and positioning. Lightweight servo motors (MG90S and SG90) are employed at distal joints and in the tool-changing mechanism to reduce the load on the main actuators while maintaining precise control. The distribution of actuators ensures efficient power utilization, improved motion accuracy, and reduced mechanical stress on the system.

4.3 Controller Platform

The embedded control layer is implemented on an Arduino Uno, utilising the ATmega328P microcontroller's hardware PWM channels to generate independently controllable drive signals for each servo. Joint angle commands are computed by the upstream motion planner and transmitted to the Arduino via serial communication, where they are converted into PWM duty cycles and dispatched to the corresponding servos at a control update rate of 50 Hz. A potentiometer-based teach pendant provides a manual override interface for joint-by-joint commissioning and emergency positioning.

4.4 Software Framework

The software framework integrates ROS2, RViz, and MoveIt2 to enhance system capabilities. ROS2 provides communication and control between system components, while RViz enables real-time visualization of robotic movements [1,2]. MoveIt2 is used for motion planning and trajectory generation, ensuring smooth and collision-free operation of the robotic arm.

5. METHODOLOGY

5.1 Modelling and Design

The development of the robotic arm system begins with the design of its mechanical structure using CAD-based modelling techniques [11,12]. The arm links, joint configurations, and end-effector interface are designed to achieve optimal reachability, stability, and efficient motion within the workspace. Special emphasis is placed on ensuring proper alignment between the robotic arm and the docking station to enable reliable tool attachment and detachment. The design also considers weight distribution and structural rigidity to enhance system performance and durability.

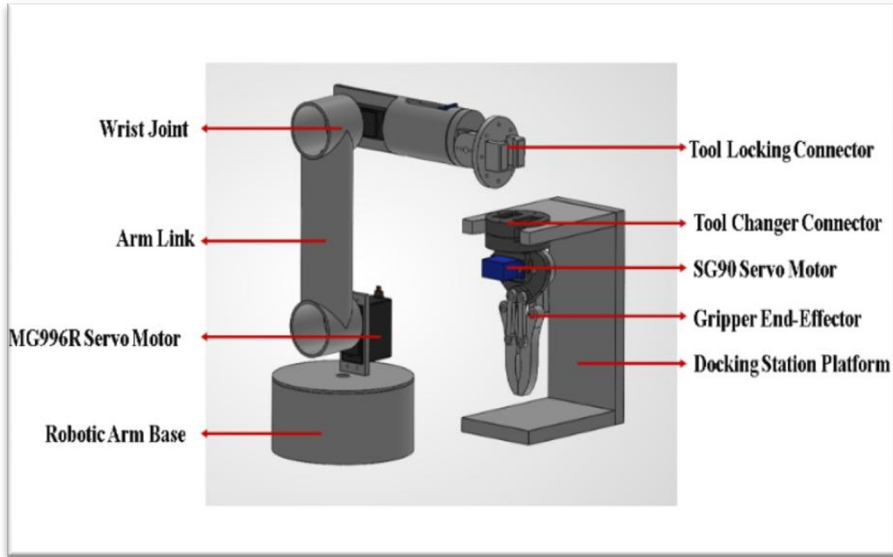


Fig. 2. ARIES - 3D Model of Project

5.2 System Integration

System integration encompasses the electrical interconnection of all active components — the microcontroller, servo motors, power supply, and manual control interface — into a unified, functional circuit. The complete schematic is illustrated in Fig. 3. The Arduino Uno serves as the central node of the circuit, with its ATmega328P microcontroller. All servo signal lines are driven at 5 V logic level, consistent with the PWM input specifications of the MG996R, MG90S, and SG90 motors employed across the arm.

Power distribution follows a two-rail architecture. A regulated 5 V, 6 A supply feeds the servo motor rail directly, bypassing the Arduino's onboard voltage regulator to avoid overloading it under the combined stall-current draw of six simultaneously active servos. The Arduino itself is powered separately via its USB interface or a dedicated 7–12 V barrel input, ensuring that transient current spikes on the servo rail do not induce voltage droop on the microcontroller supply and cause spurious resets during operation. All ground references are tied to a common bus to eliminate potential differences between the two rails that could corrupt PWM signal integrity.

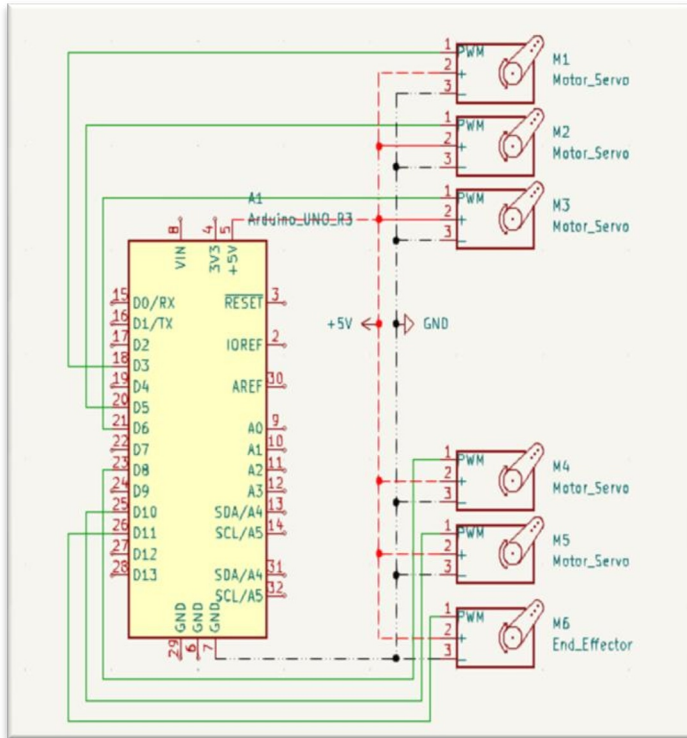


Fig. 3. ARIES Circuit Diagram

5.3 Prototype Development

A modular robotic prototype as shown in Fig. 4 is developed to validate mechanical stability and interchangeability of tools [11]. The docking station is precisely aligned to allow smooth attachment and detachment of end effectors. The system is designed to support multiple industrial tools such as:

5.3.1 Mechanical Gripper

The mechanical gripper is designed as a primary end-effector for object handling applications [5]. It operates using a servo-driven mechanism that controls the opening and closing of the gripping jaws. The gripper is capable of holding objects of varying sizes and shapes within its operating range. Its design ensures sufficient gripping force to prevent slippage while maintaining controlled motion to avoid damage to the object. The lightweight construction of the gripper minimizes additional load on the robotic arm, thereby improving overall efficiency and stability during operation.

5.3.2 Magnetic Separator

The secondary end effector employs a neodymium permanent magnet to handle ferromagnetic workpieces. A fixed magnet is mounted within a polymer housing that interfaces with the universal connector; a small SG90 servo actuates a magnetic shielding plate to enable controlled engagement and release of the workpiece without physical contact between the gripper mechanism and the part surface. This contactless handling approach reduces surface marking risk and simplifies the release sequence for flat metallic components.



Fig. 4. Robotic arm with both Mechanical gripper and Magnetic separator

6. RESULTS AND DISCUSSION

The robotic arm system proved itself in practice, handling tool changes automatically—no need for anyone to step in. Each time the arm switched tools, the mechanism aligned perfectly with the docking station, locking the end-effector firmly in place. This precision removed any doubts about its ability to engage and secure attachments reliably in real-world use. Looking at the arm’s movement, the servo motors played a big role. They steered the joints with impressive accuracy, so the arm’s motion wasn’t just fluid but also predictable and deliberate, even across a wide range of movements [10]. Repeated trials backed this up: the system delivered the same consistent performance every time, with no failures cropping up during tests. This level of reliability shows that the underlying engineering—from both hardware and control software—hits the mark when it comes to repeatable, robust results. When it came to handling weight, the arm didn’t flinch under moderate loads. Pushing the payload higher did lead to a slight bump in positioning error, as expected with most electromechanical systems. Still, the system held its ground and didn’t stray beyond its defined accuracy limits. Even as the demands increased, its stability persisted, illustrating a well-balanced design between speed, strength, and precision.

6.1 PAYLOAD TESTING

The Fig.5 illustrates the relationship between payload and positional error of the robotic arm system. It can be observed that as the payload increases, the positional error also increases gradually. At lower loads (0–150 grams), the system maintains high accuracy with minimal deviation. However, as the load increases beyond 300 grams, a rise in error is observed due to servo limitations.

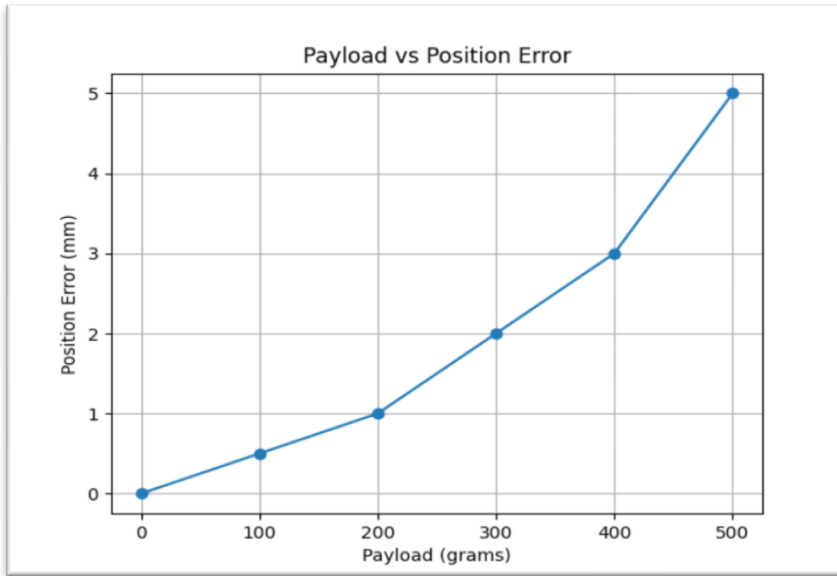


Fig. 5. Payload vs position Error graph

6.2 TOOL CHANGING MECHANISM

The tool-changing mechanism is an important feature of the robotic system, enabling automatic attachment and detachment of end-effectors without manual intervention [13]. The sequence of operations is illustrated in the Fig. 6(a)(b)(c) which shows the step-by-step process of tool engagement and release using the docking station.



Fig. 6 (a). Before connection

Initially, the robotic arm moves towards the docking station and performs precise alignment between the tool locking connector and the selected end-effector. This alignment ensures that the connector properly fits into the tool interface without misplacement. In the next stage, the arm moves forward to achieve mechanical engagement [7], where the connector makes contact with the end-effector.

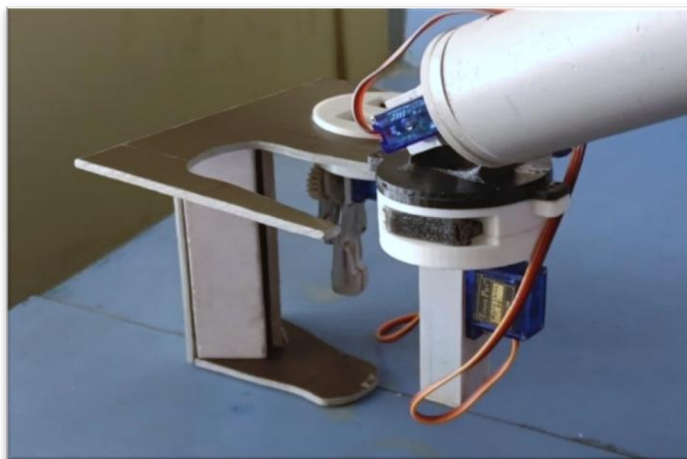
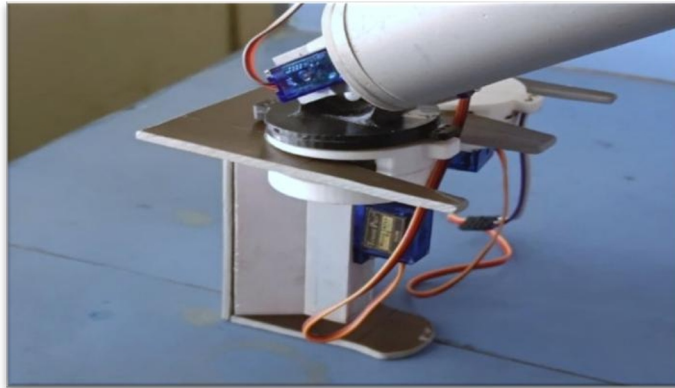


Fig. 6(b). Engagement & Locking; **Fig. 6(c).** Ready for operation

Once engaged, a spring is enclosed to secure the end-effector firmly. This locking ensures that the tool remains stable during operation and prevents any unwanted displacement. After successful attachment, the robotic arm lifts the tool from the docking station and proceeds to perform the assigned task.

After completing the assigned operation, the robotic arm moves back toward the docking station to return the active end-effector. The arm performs precise alignment with the designated slot to ensure correct positioning. Once aligned, the locking mechanism is released, allowing the connector to safely disengage from the tool. The end-effector is then placed back into its docking position, and the robotic arm returns to its predefined home position, ready for the next operation.

7. CONCLUSION

The project successfully developed a robotic arm with an automatic end-effector docking mechanism that allows tools to be attached and detached without manual intervention. The system uses a universal connector and spring-based locking mechanism to ensure secure tool attachment. The experimental results demonstrate that the proposed design enables reliable operation, reduced tool changing time, and improved flexibility of robotic systems. The use of servo-based control and a simple mechanical structure makes the system cost-effective and suitable for educational and small-scale industrial applications.

8. FUTURE ADVANCEMENT

The ARIES system sets the foundation for versatile robotic automation, but further advancements can expand its capabilities and adaptability for next-generation applications.

Future versions can integrate AI to predict and automatically select the right end effector based on the task, improving efficiency and decision-making. Incorporating wireless energy transfer and data communication will eliminate physical connectors, reducing wear and extending system lifespan. Developing compact and lightweight universal connectors will enable usage in mobile robots, drones, and collaborative robots. Integrating haptic and force-feedback sensors can allow safer and more precise tool handling in delicate operations like surgery or electronics. Connecting the system to cloud platforms and IoT networks will enable remote monitoring, predictive maintenance, and global scalability.

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