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# Robotic arms: mechanical design, kinematic modeling, motion planning, control strategies, and industrial applications—a review

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**ABSTRACT**

Robotic arms are essential components of modern automation, enabling machines to perform repetitive, precise, and increasingly complex manipulation tasks. Their development has expanded from conventional industrial manipulators to collaborative, medical, agricultural, and soft robotic systems. This review examines the fundamental technologies underlying robotic arms, focusing on mechanical configurations, kinematic and dynamic modeling, motion planning, control strategies, sensing, and end-effector design. The literature indicates that serial manipulators remain widely used because of their flexibility and relatively large workspace, whereas parallel and continuum architectures offer specific advantages in stiffness, precision, or adaptability. Effective operation depends on accurate kinematic modeling, reliable trajectory generation, and control methods capable of handling nonlinear dynamics and external disturbances. Recent developments in machine learning, tactile sensing, compliant actuation, and collaborative robotics have further improved manipulation capabilities. Nevertheless, challenges remain in achieving robust grasping, precise positioning, safe human interaction, and reliable performance in unstructured environments. The review concludes that future robotic arms will increasingly combine intelligent perception, adaptive control, mechanical compliance, and integrated safety mechanisms to support flexible and human-centered automation.

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## 1. INTRODUCTION

Robotic arms have become important technologies in manufacturing, healthcare, agriculture, logistics, and scientific research. Their ability to manipulate objects with repeatable motion and controlled force makes them suitable for operations that require accuracy, consistency, and productivity. Conventional industrial manipulators have traditionally operated in structured environments, performing tasks such as welding, assembly, painting, and material handling. However, increasing demands for flexible production and human-centered automation have expanded research toward robots capable of handling uncertain objects and interacting safely with people [1], [2].

Despite substantial progress, developing an effective robotic arm remains a multidisciplinary engineering challenge. Mechanical structure, actuator characteristics, sensor performance, and control algorithms must work together to achieve accurate and stable movement. In particular, positioning errors, nonlinear joint dynamics, singular configurations, and uncertain environmental interactions can reduce operational performance. These problems become more significant when robotic arms are expected to manipulate unfamiliar objects or operate in dynamic environments [3], [4].

This review discusses the principal technologies and research challenges associated with robotic arms. The discussion covers mechanical architectures, kinematic and dynamic modeling, trajectory planning, control strategies, sensing, and end-effector mechanisms. Industrial, collaborative, agricultural, and

biomedical applications are also considered to connect technical developments with practical requirements. The objective is to provide a structured overview of the field and identify research directions for more capable and reliable robotic manipulation systems.

## 2. MECHANICAL ARCHITECTURE AND STRUCTURAL CONFIGURATIONS

The mechanical architecture determines the workspace, flexibility, payload capacity, stiffness, and motion characteristics of a robotic arm. A conventional robotic manipulator consists of interconnected links and joints driven by electrical, hydraulic, or pneumatic actuators. Revolute joints generate rotational movement, whereas prismatic joints produce linear displacement. The number and arrangement of joints determine the robot's degrees of freedom and its ability to position and orient an end-effector [1], [5].

Serial manipulators are widely used in industrial applications because their articulated structures provide flexible movement and relatively large workspaces. Typical configurations include Cartesian, cylindrical, SCARA, and articulated robotic arms, each offering different advantages for particular tasks. Parallel manipulators connect the moving platform to a fixed base through multiple kinematic chains, potentially providing high stiffness and positioning accuracy. Continuum manipulators use flexible structures to achieve bending and movement through confined spaces, making them attractive for specialized medical and inspection applications [6], [7].

Mechanical design also influences the dynamic performance of the system. Link mass, joint friction, transmission mechanisms, structural flexibility, and actuator placement affect acceleration, vibration, and positioning accuracy. Lightweight structures can improve energy efficiency and reduce inertia, although excessive flexibility may introduce unwanted oscillations. Therefore, mechanical design should be optimized according to payload, workspace, precision, operating speed, and environmental requirements [8].

## 3. KINEMATIC AND DYNAMIC MODELING

Kinematic modeling describes the relationship between joint variables and the position and orientation of the robotic arm's end-effector. Forward kinematics calculates the end-effector pose from known joint positions, while inverse kinematics determines the joint configurations required to reach a desired pose. These models are fundamental to robot programming, positioning, and trajectory execution. However, inverse kinematics can produce multiple solutions or become difficult near singular configurations, particularly in redundant manipulators [1], [9].

Dynamic modeling describes the relationship between forces, torques, motion, and mechanical properties. It considers link inertia, gravity, friction, actuator characteristics, and interactions with external objects. Accurate dynamic models support controller development, trajectory optimization, and compensation for disturbances. In practice, uncertainties in mechanical parameters and unmodeled effects can create differences between predicted and actual robot behavior [10].

Calibration is therefore important for improving positioning performance. Manufacturing tolerances, joint offsets, structural deformation, and assembly errors can cause deviations between theoretical models and physical robot configurations. Calibration procedures use measurements from external sensors or reference positions to identify and compensate for these deviations. Reliable kinematic and dynamic models provide the foundation for accurate motion planning and stable control [9], [10]

## 4. MOTION PLANNING AND TRAJECTORY GENERATION

Motion planning determines how a robotic arm moves from an initial configuration to a desired target while satisfying mechanical and environmental constraints. A valid trajectory should avoid obstacles, respect joint limits, and maintain appropriate velocity and acceleration profiles. Planning can be performed in Cartesian space or joint space, depending on the application and the desired movement characteristics. The choice of planning method influences computational requirements, smoothness, and the ability to respond to environmental changes [11], [12].

Conventional planning methods include polynomial interpolation, spline trajectories, potential-field methods, and sampling-based algorithms. Polynomial and spline approaches can generate smooth trajectories for structured tasks, while potential-field methods provide a relatively intuitive approach to obstacle avoidance. However, potential-field algorithms may become trapped in local minima or generate undesirable paths in complex environments. Improved planning strategies therefore incorporate dynamic target points, optimization, and additional collision-avoidance mechanisms [11].

Learning-based approaches have also become increasingly relevant to robotic manipulation. Machine learning can help robots recognize objects, estimate grasp configurations, and adapt their actions

using previous experience. Kleeberger *et al.* [4] reviewed learning-based robotic grasping and highlighted differences between model-based and model-free approaches, including their respective strengths in object placement and generalization. Nevertheless, learning-based systems require suitable training data, reliable perception, and validation on physical robots before they can be deployed in safety-critical applications.

## 5. CONTROL STRATEGIES FOR ROBOTIC ARMS

Control systems translate planned movements into actuator commands while maintaining the required position, velocity, or interaction force. Conventional proportional-integral-derivative control remains widely used because of its relatively simple implementation and practical effectiveness in many industrial applications. Model-based control methods use information about robot dynamics to compensate for nonlinear effects and improve tracking performance. Adaptive and robust control approaches are particularly useful when the system experiences parameter uncertainties, external disturbances, or changing operating conditions [9], [10].

Impedance control and admittance control are important when robotic arms interact physically with objects or humans. These approaches regulate the relationship between motion and interaction force rather than relying exclusively on position tracking. Variable impedance control allows the robot to modify its apparent stiffness and damping according to task requirements. Abu-Dakka and Saveriano [13] reviewed variable impedance control and learning, identifying the importance of adaptive interaction behavior for manipulation and physical human–robot interaction.

The selection of a control strategy should reflect the required accuracy, operating speed, computational resources, and interaction conditions. Position control is suitable for many repetitive industrial tasks, while force and impedance control are more appropriate for contact-rich operations. Hybrid approaches can combine position regulation with force regulation to improve performance during assembly, grasping, and physical interaction. Consequently, robust robotic-arm control requires coordination between mechanical design, sensing, trajectory planning, and feedback algorithms.

## 6. END-EFFECTORS, SENSING, AND ROBOTIC GRASPING

The end-effector is the component that directly interacts with objects and determines the practical manipulation capabilities of a robotic arm. Common end-effectors include parallel-jaw grippers, vacuum suction devices, magnetic grippers, and multi-fingered robotic hands. Their selection depends on object geometry, material, weight, surface condition, and task requirements. Agricultural and industrial applications often require specialized grippers capable of handling objects with different shapes and mechanical properties [14].

Reliable grasping also requires information about the object and its environment. Cameras, depth sensors, force sensors, tactile sensors, and proximity sensors provide information for object localization and interaction monitoring. Wang et al. reviewed sensing and grasping approaches for objects with uncertain geometric and physical properties, emphasizing the difficulty of handling unfamiliar objects. Their review highlights the importance of combining visual perception, physical-property estimation, and learning-based grasping methods [15].

Soft and compliant grippers provide an alternative to rigid end-effectors when handling delicate or irregular objects. Their flexible structures can adapt to object shapes and reduce the risk of damaging fragile materials. Continuum and soft robotic designs also offer opportunities for manipulation in confined environments and biomedical applications [6], [16]. However, compliant mechanisms may introduce challenges in modeling, force estimation, sensing, and precise positioning.

## 7. APPLICATIONS AND COMPARATIVE ASSESSMENT

Robotic arms are used in a wide range of applications, although the technical requirements differ considerably between sectors. Industrial manipulators emphasize repeatability, payload capacity, speed, and integration with production equipment. Collaborative robots require additional attention to collision detection, compliant behavior, and safe interaction with human operators. Medical and rehabilitation systems place greater emphasis on controlled motion, patient safety, ergonomic design, and accurate physical interaction [3], [12], [17].

Agricultural robotic arms illustrate the challenges of operating outside highly structured industrial environments. They may need to identify fruits, estimate their position, and adjust grasping forces according to object properties. Zhang *et al.* [14] reviewed robotic grippers, grasping, and control strategies in agricultural applications, highlighting the importance of combining suitable end-effector designs with sensing

and control methods. Similarly, continuum and soft manipulators offer potential benefits for biomedical procedures and applications that require compliant interaction [6], [16].

Table 1 summarizes the principal robotic-arm architectures and their typical characteristics. It compares the structural advantages, limitations, and representative applications of each configuration. The comparison demonstrates that no single architecture is optimal for every manipulation task. Selection should instead be based on workspace requirements, payload, stiffness, precision, environmental constraints, and interaction safety.

Table 1. Comparison of robotic arm architectures

| Architecture | Main characteristics | Advantages | Limitations | Typical applications |
|---|---|---|---|---|
| Cartesian | Linear motion along orthogonal axes | Simple control and high positioning accuracy | Limited flexibility in complex workspaces | CNC handling and pick-and-place |
| SCARA | Selective compliance with rotary joints | Fast planar movement and efficient assembly | Limited orientation flexibility | Electronics assembly |
| Articulated serial | Multiple interconnected rotary joints | Flexible movement and large workspace | Complex kinematics and accumulated joint errors | Welding, painting, and material handling |
| Parallel | Multiple kinematic chains support a moving platform | High stiffness and potential precision | Restricted workspace and complex structure | Precision positioning and specialized manufacturing |
| Continuum/soft | Flexible or continuously bending structure | Adaptability and compliant interaction | Complex modeling and control | Medical procedures and confined-space manipulation |

The architectures in Table 1 demonstrate how mechanical configuration determines the capabilities and limitations of robotic arms. Serial articulated robots are suitable for versatile industrial tasks, while Cartesian and SCARA configurations are effective in applications with more predictable motion requirements. Parallel manipulators provide advantages in stiffness and precision, whereas continuum and soft structures are useful where flexibility and compliance are essential. These differences reinforce the need to match robot architecture with the intended application rather than selecting a design solely according to nominal degrees of freedom.

## 8. HUMAN–ROBOT COLLABORATION AND SAFETY

Human–robot collaboration is an important development in modern manufacturing because it allows robots and people to share tasks and workspaces. Collaborative robotic arms can support assembly, inspection, material handling, and repetitive operations that benefit from combining human judgment with robotic consistency. Matheson *et al.* [3] reviewed collaborative robotics in manufacturing and identified technical and organizational factors that influence practical deployment. Effective collaboration requires appropriate robot design, task planning, risk assessment, and reliable monitoring of the surrounding environment.

Safety cannot be achieved through mechanical design alone. Sensors, collision detection, force limitation, speed monitoring, and emergency-stop mechanisms contribute to safe operation. Compliant control can reduce interaction forces, but it must be combined with appropriate workspace design and risk-management procedures. The requirements become more demanding when robots operate near people or perform tasks involving direct physical contact [3], [13], [17].

## 9. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Several research challenges continue to limit the wider deployment of robotic arms in unstructured environments. These include reliable manipulation of unfamiliar objects, accurate perception under occlusion, efficient motion planning, and adaptation to changing physical conditions. Flexible and soft robotic structures introduce additional difficulties because their deformation complicates kinematic modeling and feedback control. Research into learning-based manipulation, sensor fusion, and compliant mechanisms may help address these limitations [4], [6], [15].

Future robotic arms are likely to integrate perception, planning, control, and safety within more unified architectures. Machine learning can improve object recognition and grasp selection, while model-based methods can provide predictable motion and physical constraints. Collaborative systems will also require better ways to interpret human intentions and coordinate shared tasks. Progress will depend on evaluating complete robotic systems under realistic operating conditions rather than assessing individual algorithms only in simulation [2], [3], [17], [18].

## 10. CONCLUSION

Robotic arms are versatile mechatronic systems whose performance depends on the interaction of mechanical architecture, kinematic and dynamic modeling, motion planning, control, sensing, and end-effector design. Serial, parallel, and continuum configurations offer different capabilities for industrial, biomedical, agricultural, and collaborative applications. Accurate modeling and robust control remain essential for achieving reliable positioning and effective manipulation. At the same time, advances in perception, learning-based grasping, and compliant actuation are expanding the range of objects and environments that robotic arms can handle.

Despite these developments, challenges remain in achieving precise movement, robust grasping, safe human interaction, and reliable operation under uncertainty. Future systems should combine intelligent perception with adaptive control, appropriate mechanical compliance, and integrated safety mechanisms. Their development will require stronger connections between theoretical models, physical experiments, and application-specific requirements. Overall, robotic arms are expected to remain a central technology in the evolution of flexible automation and intelligent manufacturing.

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