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# A Comprehensive Review on Robotic Arm Design, Control, and Applications Across Multiple Domain

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***Abstract: Robotic arms have evolved rapidly over the past decade, integrating advanced control algorithms, lightweight materials, and artificial intelligence to perform diverse tasks across industries. This review paper provides a comprehensive overview of robotic arm development, including design structures, kinematic modeling, control methodologies, and multi-domain applications. By synthesizing findings from recent studies, this paper highlights innovations such as compliant joints, twin actuation systems, hybrid control mechanisms, and modular collaborative designs. Applications in industrial automation, medical surgery, space exploration, and precision agriculture are critically analyzed. Finally, challenges and research directions are discussed to promote further development in efficiency, adaptability, and intelligence of robotic arms.***
***Keywords: Robotic, Robot arm, Ansys, Robot arm design, Arm design for multiple material.***

## I. INTRODUCTION

Robotic arms represent one of the most significant innovations in automation, designed to mimic human limb functions for various complex operations. Over the years, their design has expanded beyond industrial manipulation to applications in medical, agricultural, and extraterrestrial environments. The fundamental aim of robotic arm research is to achieve higher dexterity, stiffness, and control accuracy while maintaining lightweight and energy-efficient structures. Researchers have proposed numerous design architectures, such as snake-arm robots for confined spaces [1], dual-arm collaborative robots [2], and compliant manipulators for safe human-robot interaction [3]. This paper reviews multiple studies covering mechanical design, control systems, and application diversity of robotic arms.

## II. DESIGN AND KINEMATIC MODELING OF ROBOTIC ARMS

Robotic arm design typically balances between flexibility, stiffness, and load-carrying capacity. Snake-arm robots, for instance, use compliant joints and twin actuation systems to achieve high bending capability while maintaining cable tension across various configurations [1]. A kinematic model simplifies motion analysis and ensures accurate control. Finite Element Analysis (FEA) is often applied to verify stiffness and dynamic stability. In space and underwater environments, robotic designs incorporate multiple degrees of freedom (DoF) and lightweight composite materials to enhance stability and mobility [4].

Table 1
Summary Of Robotic Arm Designs And Applications

| Type of Robotic Arm | Key Features | Application Domain | Reference |
|---|---|---|---|
| Snake-Arm Robot | Compliant joints, twin actuation, FEA validation | Medical & Industrial | [1] |
| Dual-Arm Collaborative Robot | Synchronous control, vision-based planning | Industrial Automation | [2] |
| Ship Hull Cleaning Robot (ARMROV) | Dynamic stability via Newton-Euler modeling | Marine Maintenance | [3] |
| Assistive Robotic Arm | Human-robot cooperation, intuitive control | Power Line Maintenance | [4] |
| Kiwifruit Pollination Arm | Lightweight 5R mechanism, MATLAB-SolidWorks design | Agriculture | [5] |
| Space Debris Capture Arm | Shock-absorbing system, multi-damper gripper | Space Operations | [6] |
| Hybrid EEG–EMG Control Arm | Brain-computer interface, multi-command control | Rehabilitation | [7] |

## III. CONTROL STRATEGIES AND OPTIMIZATION

Control systems in robotic arms have evolved to ensure precision, adaptability, and stability under uncertain conditions. Sliding Mode Controllers (SMC) are widely used for robust control; however, chattering issues arise due to high switching frequency. Advanced hierarchical controllers integrating differential flatness and PWM-based smoothing have successfully mitigated these effects [8]. In space robotics, Particle Swarm Optimization (PSO) algorithms and compliant control models enhance coordinated trajectory planning [9]. In agricultural and assistive robotics, embedded systems combined with feedback sensors optimize smooth joint actuation and synchronization.

## IV. APPLICATIONS OF ROBOTIC ARMS

Robotic arms have demonstrated versatility across numerous fields. Their applications can be categorized into four primary domains as follows:

### *A. Industrial and Assistive Robotics*

In industrial sectors, robotic arms perform assembly, polishing, and maintenance tasks with improved stiffness and stability. Dual-arm robots have replaced serial configurations to enhance positional accuracy. Assistive robotic arms, designed for electric power supply work, enable single operators to perform tasks that typically require two workers [10].

### *B. Medical and Surgical Robotics*

Medical robotic systems, such as the Transoral Robotic Thyroidectomy (TORT), integrate multiple arms for precise surgical operations. The additional axillary arm enhances counter-traction and specimen handling, although it increases surgical cost and potential scarring [11]. Snake-arm robots are also increasingly used in minimally invasive surgeries for reaching confined anatomical regions.

### *C. Space Robotics*

In space exploration, robotic arms are crucial for debris removal, satellite maintenance, and assembly operations. Dual-arm and multi-arm cooperative systems employ compliant control to minimize base disturbance and achieve synchronized manipulation [12]. Optimized shock-absorbing mechanisms and dynamic control models ensure structural integrity during capture of high-momentum debris [13].

### *D. Agricultural and Environmental Robotics*

In precision agriculture, robotic arms are utilized for seeding, pollination, and harvesting. Lightweight designs reduce inertia and energy consumption, while vision and AI-based control enable autonomous operation. Pollination robots designed via MATLAB-SolidWorks simulations achieved 85% efficiency, reducing labor dependency [14].

## V. DISCUSSION AND COMPARATIVE ANALYSIS

From the reviewed literature, several trends emerge: (1) the transition from rigid to compliant and hybrid designs, (2) integration of AI and sensor feedback for adaptive control, and (3) modular multi-arm systems for collaborative operations. The combination of mechanical optimization and intelligent control significantly improves performance in dynamic and uncertain environments. However, challenges remain in real-time response accuracy, lightweight actuator development, and energy-efficient mobility across domains.

## VI. FUTURE SCOPE

Future research on robotic arms should focus on data-driven modeling, deep learning integration for motion prediction, and multi-modal sensor fusion. The adoption of digital twin technology for predictive maintenance and real-time operation is expected to revolutionize design evaluation. Lightweight materials, modular components, and adaptive stiffness mechanisms will further enhance performance in space and medical robotics.

## VII. CONCLUSION

This review consolidates developments in robotic arm design, control, and applications across multiple domains. The integration of compliant mechanisms, hierarchical control, and advanced simulations has transformed robotic arms from rigid manipulators into intelligent, flexible systems. Continued interdisciplinary research will drive innovation, making robotic arms indispensable in future industrial, medical, and extraterrestrial environments.

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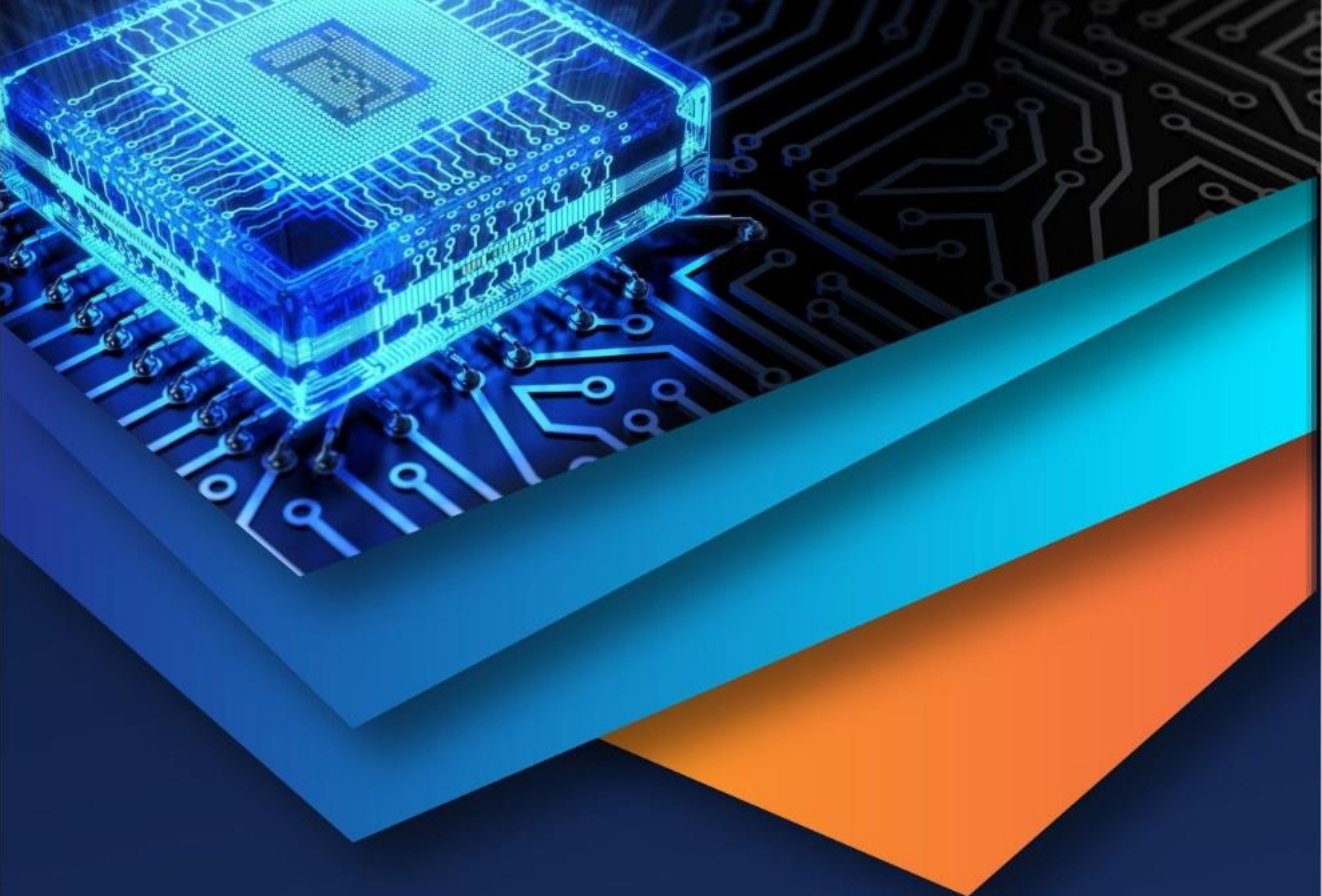


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