



Research on the Development and Challenges of Robotic Arm Applications

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Abstract. A robotic arm is a device designed to emulate the functions of a human arm and execute many activities. This article carefully examines the essential principles that regulate robotic arms, including mechanical structure, motion control, and path planning. We classify modern robotic arms into three primary categories: Cartesian coordinate robotic arms, cylindrical coordinate robotic arms, and articulated robotic arms, and examine their attributes. This article examines the contemporary industrial applications of robotic arms in medical surgeries, the food sector, and the aerospace industry, emphasizing a case study on robotic cholecystectomy for gallbladder cancer treatment. It specifically tackles emerging challenges, including restricted environmental adaptability, limitations in human-robot interaction, and elevated costs. The article forecasts the developmental trends of robotic arms by examining methods of multi-technology integration and multi-robot collaboration, thereby offering insights for their future advancement. This paper systematically analyzes the key principles, classification and applications of robotic arms, and proposes future development directions in response to current technical challenges. It provides important theoretical basis and practical guidance for promoting breakthroughs in robotic arm technology in terms of intelligence, precision and collaboration, and has profound significance for promoting progress in fields such as industrial automation and minimally invasive medical treatment.

Keywords: Robotic Arms, Applications, Challenges and Development

1 Introduction

The robotic arm is a complicated system with high precision, multi-input, and multi-output and it has widely been used in contemporary society, not only in different industrial areas but also in all areas of life [1]. Originally, the robotic arms are designed to mimic the functions of the human arm to automate pick-and-place activities; however, they have since advanced to execute more intricate jobs such as medical surgeries, agriculture, manufacturing, food processing and aeronautical engineering[2-4].

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The swift advancement of computer technology and artificial intelligence is also constantly expanding the application domains of robotic arms while continually improving their performance. Related research proved the viability and efficacy of integrating high-frequency SSVEP-based BCI with computer vision-based object recognition to manipulate robotic arms, and the control method could be adapted for executing more complex tasks [5].

However, the application of robotic arms continues to encounter numerous challenges, including adaptive control in intricate situations [6], restricted capacities for connection with humans [7], energy efficiency for prolonged operations, and economic viability. For example, the da Vinci system represents a significant advancement in the use of robotic arms for minimally invasive surgery; but the absence of force feedback during procedures may elevate the risk of tissue injury, and the prohibitive cost restricts the widespread adoption of the technology [8].

This article seeks to carefully delineate the basic principles and classifications of robotic arms, examine its applications across several industries, identify the primary challenges now encountered, and anticipate future developmental trends. Through systematic literature research and technical analysis, this study will support future advancements in robotic arm technology.

2 Principles and Classification of Robotic Arms

2.1 The basic principle of the robotic arms

Mechanical Structure. The mechanical structure constitutes the essential framework of robotic arms, delineating their architectural configuration and primary components. A conventional robotic arm system comprises three fundamental components: a base, arm links, and joints. Each component is designed with remarkable durability and load-bearing capability to guarantee dependable performance under substantial load conditions [9]. Serial structure, parallel structure, and hybrid structure are the main structural configurations of robotic arms [9].

Motion Control The motion control of robotic arms is fundamental for precise trajectory tracking and stable operation. Typically, its control system relies on computers or microcontrollers that modulate the output of drive devices, such as motors and hydraulic actuators, to ensure accurate control of the robotic arm's position, velocity, and acceleration [9,10].

Motion control includes both open-loop and closed-loop control systems. In contrast to open-loop control, closed-loop control incorporates a feedback mechanism, exhibits better anti-interference capabilities, and achieves superior control precision, rendering it appropriate for high-demand situations. Contemporary robotic arm motion control generally employs sophisticated algorithms to improve performance, including PID control (Proportional-Integral-Derivative), adaptive control, and fuzzy control.

Path Planning. To enhance the control of the robotic arm and match it with human requirements, path planning is necessary to ensure the arm operates according to directives. Path planning for robotic arms typically encompasses two methods: joint space planning and Cartesian space planning.

Joint space planning entails determining the range of motion angles for each joint of the robotic arm, whereas Cartesian space planning focuses on delineating the motion trajectory of the robotic arm within three-dimensional space to enable its movement [9, 11].

2.2 Classification of robotic arms

Robotic arms can be classified according to various criteria, and when categorized by structural form, they can generally be divided into the following types.

Cartesian Robot. Named after the Cartesian coordinate system they operate within, Cartesian robots move along three linear axes—X, Y, and Z—allowing for precise and controlled movements in three-dimensional space, in figure 1 [12].

Cartesian robots include linear actuators, tracks, and a stiff framework. Their simple architecture, excellent scalability, and straightforward maintenance make them a compelling option for extensive applications [12]. Cartesian robots can be adapted to various end effectors and tools, making them suitable for different tasks, including handling, loading, packaging, welding, and other basic yet relatively precise jobs.

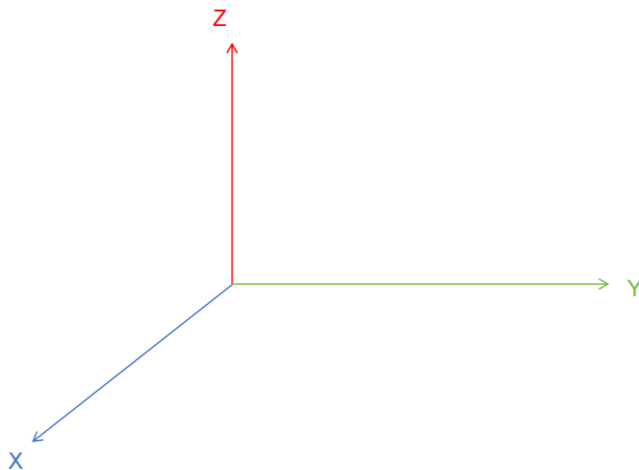


Fig. 1. Cartesian Coordinate System (Picture credit: Original)

Cylindrical Robot. Cylindrical robot is a robot that is constructed using the cylindrical coordinate system [9]. Its movement is comprised of numerous linear

joints and rotational joints. The horizontal direction and angle of the robotic arm are determined by the rotational joints, which rotate around a vertical axis. The linear joints enable the robotic arm to extend and retract in both horizontal and vertical dimensions, thereby altering its working range. Cylindrical robot is capable of rapidly encircling the work area as a result of the radial expansion and rotation of cylindrical coordinates. This makes it appropriate for the uniform spraying of cylindrical workpieces and the selecting and stacking of materials on the production line [13]. Cylindrical coordinate robots exhibit excellent rigidity, substantial load-bearing capability, and optimal space usage, rendering them ideal for operations in warehouse centers.

Articulated Robot. The design inspiration for articulated robotic arms comes from the human arm, elephant trunks, and octopus tentacles [14]. It boasts a structure that is highly articulated, which allows for a significant amount of DOFs [14]. The flexibility of the entire structural device and the variety of duties that the mechanical device can perform are both influenced by the degree of freedom of the robotic arm. Articulated robots possess a great degree of freedom and exceptional flexibility, enabling them to negotiate obstacles, execute jobs at various angles, and demonstrate significant adaptability to their environment.

Articulated robots are extensively employed in industries including aerospace, military, healthcare, and manufacturing, where they are capable of completing tasks in intricate workspaces. For instance, they may be implemented for endoscopy or cholecystectomy [15].

3 Applications of Robotic Arms

3.1 Medical surgeries

The application of robotic arms in medical surgeries is becoming more ubiquitous, particularly in laparoscopic and gynecological surgeries, as a result of the rapid development of robotic technology. Over the past decade, the incidence of patients undergoing robotic-assisted radical cholecystectomy for gallbladder cancer has surged. A study aggregated all pertinent articles from PubMed, Web of Science, and Scopus from their inception until February 2023, followed by screening and statistical analysis. The findings indicated that, in comparison to open cholecystectomy, robotic cholecystectomy for gallbladder cancer patients significantly diminishes estimated blood loss, with a mean difference (MD) of -175.43, substantially reduces hospital stay, with an overall MD of -2.26, and presents a lower complication rate, with an odds ratio (OR) of 0.49 [16].

A separate study presented a comparison of the effectiveness of robot-assisted hysterectomy with open surgery. There were significant differences in intraoperative blood loss and time spent in hospital stay between the two groups, with the robot-assisted group exhibiting superior outcomes. No intraoperative injuries were recorded

in the robot-assisted surgery cohort [3]. Robotic arms clearly possess substantial advantages in the domain of medical surgery.

3.2 Food industries

The expansion of the global population has led to an increased demand for food and an augmented land area necessary for agriculture. The automation of the food processing sector is partially mitigating these challenges. Innovations in the food business have led to the deployment of several types of robots for diverse applications. SCARA robots exist, exhibiting movements analogous to that of a human arm. Their rapid and repetitive actions render them very appropriate for food handling, packing, and sorting tasks [4].

The dairy sector uses automatic milking systems (AMS) featuring five robotic arms that execute functions including teat cleaning and the attachment of milking machines. This device can milk around 100 cows per hour, markedly enhancing milking efficiency and reducing labor expenses [4].

3.3 Aeronautical engineering

The exceptional precision, reliability, and adaptability of robotic arms to harsh settings facilitate their extensive utilization in the aerospace sector. Given the intricate and inhospitable conditions of other planets, which render them unfit for human labor, robotic arms must be installed aboard alien spacecraft to aid humans in planetary exploration. A study titled "Rover-71" developed a probe capable of enduring the severe Martian conditions, outfitted with a robotic arm for duties including object manipulation [16,17]. Furthermore, to enhance the installation, docking, and maintenance of spacecraft, space-based robotic arms have been integrated into the space station, assisting humans in doing chores more safely and efficiently in a microgravity environment[18].

4 The Challenges and Development of Robotic Arms

4.1 The challenges of robotic arms

Robotic arms are extensively utilized in industrial manufacturing, medical surgery, food processing, aerospace, and several other sectors; yet their advancement continues to encounter numerous hurdles and obstacles.

In intricate and fluctuating situations, robotic arms have significant challenges in attaining precise adaptive control. In agricultural operations, robotic arms frequently must adjust in real-time to alterations induced by various uncontrollable natural elements, which might result in inaccuracies in evaluating the agricultural environment, thereby leading to erroneous operations [6].

Robotic arms have limitations in areas of human-computer interaction. Regarding informational input, they primarily furnish people with predominantly unisensory data. For instance, when physicians utilize the Da Vinci system for surgical

procedures, they are deprived of genuine tactile feedback and must depend solely on visual information to execute the surgery [8].

Moreover, there are concerns over elevated latency and diminished precision in information exchange. Individuals utilizing brain-computer interfaces to manipulate robotic arms are limited to executing basic pick-and-place tasks, and achieving intricate movements remains a problem.

In some domains, the application of robotic arms remains constrained by elevated expenses. Agricultural robots require multiple sensors and high-performance CPUs to adapt to fluctuating conditions, hence escalating investment costs. Despite the Da Vinci system's ability to deliver substantial outcomes in minimally invasive surgery, its adoption is limited by the exorbitant expenses associated with the equipment and the extensive training required for medical personnel, resulting in usage by only a select number of hospitals [8].

4.2 Projection of development trends

As time progresses, technological integration is emerging as a prevailing trend. Robotic arms will integrate with diverse technologies, including artificial intelligence, deep learning, and computer vision, to mutually enhance their environmental perception and adaptability. A study integrated brain-computer interface (BCI) with computer vision technologies to manipulate robotic arms [5]. This strategy enhanced the accuracy and speed of picking and placing activities compared to solo BCI control, illustrating the potential and benefits of merging robotic arms with additional technologies [5].

Simultaneously, multi-robot collaboration will assume an increasingly significant role across multiple fields. Multi-robot collaboration can improve operational efficiency and reduce work cycles by coordinating various robots to execute distinct jobs [19]. Integrating deep reinforcement learning (DRL) with multi-robot collaboration can enhance task decision-making capabilities, effectively address path planning and task allocation challenges in intricate environments, and further augment efficiency [19].

5 Conclusion

This article delineates the fundamental principles and classifications of robotic arms, examining their applications across several industries with particular examples. Furthermore, it examines the primary problems encountered by robotic arm applications and contemplates potential developmental trajectories.

Robotic arms, as mechanical devices that replicate human arm functionality, are progressively broadening their applications, extending from conventional industrial sectors to encompass medical operations, agriculture, food processing, and aerospace. In the medical domain, surgical robots facilitate reduced hemorrhaging and smaller incisions, advancing minimally invasive surgical techniques; in the food processing industry, robotic arms autonomously execute food packaging, improving operational

efficiency; in the aerospace sector, robotic arms supplant human labor in extraterrestrial exploration and spacecraft installation and maintenance, ensuring the safety of astronauts.

Nonetheless, the further advancement of robotic arms encounters numerous obstacles, such as the refinement of adaptive control in intricate situations, the augmentation of accuracy and stability in human-robot interactions, and the substantial expenses associated. In the future, the amalgamation of robotic arms with artificial intelligence, deep learning, and computer vision technologies, alongside advancements in multi-robot collaboration, will enable research to address these difficulties.

References

1. Liu, Y., Yang, L., Sun, Y.: Overview of the Development of Origami-inspired Robot Arms, 2022 International Conference on Sensing, Measurement & Data Analytics in the era of Artificial Intelligence (ICSMD), 2022, pp. 1–6
2. Singh, T., Krushnasamy, V.S., Zubeat, S., et al.: Hand Gesture Controlled Robotic Arm, Zenodo, 2022
3. Yim, G.W., et al.: Role of Robot-Assisted Surgery in Cervical Cancer, *International Journal of Gynecological Cancer*, 21(1), 173–181(2011)
4. R, R., P, R.R., C, S., et al.: Role of Robotics and Automation in Food Industries: An Overview, 2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA), 2023, pp. 1–5
5. Chen, X., Zhao, B., Wang, Y., et al.: Combination of high-frequency SSVEP-based BCI and computer vision for controlling a robotic arm, *Journal of Neural Engineering*, 16(2), 026012(2019)
6. Jin, T., Han, X.: Robotic arms in precision agriculture: A comprehensive review of the technologies, applications, challenges, and future prospects, *Computers and Electronics in Agriculture*, 221, 108938(2024)
7. Singh, V., Singh, S.: Object picking using robotic arm mounted with a camera for detection using image processing, *AJCT*, 3(3), 2018.
8. Fujiwara, K., Fukuhara, T., Niimi, K., et al.: Load evaluation of the da Vinci surgical system for transoral robotic surgery, *Journal of Robotic Surgery*, 9(4), 315–319(2015)
9. Wang, X., Mai, K.: Research on the application and development of robotic arms in engineering machinery, *Mechanical and Electrical Product Development and Innovation*, 37(5), 65–68(2024)
10. Zheng, T., Simpson-Porco, J.W., Mallada, E.: Closed-loop motion planning for differentially flat systems: A time-varying optimization framework, arXiv, 2023
11. Lai, X., Liu, Y., Luo, W., et al.: Research of the Combined Trajectory Planning of Descartes Space and Joint Space, *Jixie Chuandong*, 41, 142–145(2017)
12. Pasha, S., Upadhye, A.R., Abrar, M., et al.: To Develop Cartesian Robot Intelligent System, Zenodo, 2024
13. Salazar Logroño, F.W., Fernández Soria, Á.P., Silva Conde, Á.A., et al.: Palletizing and classification system through artificial vision implementing a web environment for the management of an alarm system, *ODIGOS JOURNAL*, 4(2), 73–95(2023)
14. Dumitru, S., Copilusi, C., Dumitru, N., et al.: A Dynamic Analysis of a Poly-Articulated Robot, *Computation*, 12(8), 156(2024)

15. Shenoy, R., Mederos, M.A., Ye, L., et al.: Intraoperative and postoperative outcomes of robot-assisted cholecystectomy: a systematic review, *Systematic Reviews*, 10(1), 2021.
16. Aleid, M.S., Almohayya, L.A., Alkhars, A.M.A., et al.: Comparison between Robotic and Open Surgery in Gallbladder Cancer Removal: A Systematic Review and Meta-analysis, *Journal of Advanced Trends in Medical Research*, 1(2), 426–432(2024)
17. Rahman, M.E., Olee, A.H., Ahmmed, B., et al.: Electro-Mechanical Design Analysis and Implementation of an Indigenous Mars Rover, 2024 IEEE Region 10 Symposium (TENSYMP), 2024, pp. 1–6
18. Bakirci, M., Demiray, A.: Enhancing Attitude Control in Space Stations Through Integrated Robotic Systems, 2024 International Russian Automation Conference (RusAutoCon), 2024, pp. 144–149
19. Li, Z., Shi, N., Zhao, L., et al.: Deep reinforcement learning path planning and task allocation for multi-robot collaboration, *Alexandria Engineering Journal*, 109, 408–423(2024)

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