

The Current Status, Challenges, and Future Development Directions of Drone Robotic Arm Technology

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Abstract. With the development of material science, control technology, and other fields, significant progress has been made in unmanned aerial vehicle (UAV) and robotic arm technologies. As a cutting-edge field where the two technologies converge, the UAV robotic arm system has become a current research hotspot. By integrating the aerial maneuverability of UAVs with the physical interaction capabilities of robotic arms, this system has significantly expanded the applications of UAVs in infrastructure inspection, logistics transportation, and other fields. This article reviews the current core technologies of the system, such as robotic arm technology and perception technology, and specifically analyzes their applications in production. At the same time, this article also deeply analyzes the technical challenges currently faced by the system and proposes future development directions, such as the integration of intelligent perception and control, to promote the further development of this technology. This work aims to provide a theoretical reference and technical foundation for future research and practical deployment of UAV–robotic arm systems.

Keywords: Unmanned Aerial Vehicle (UAV) manipulator system, multimodal perception, specific applications, development trends.

1. Introduction

In recent years, with breakthroughs in key technologies and the reduction of manufacturing costs, the application of drones in both military and civilian contexts has become increasingly widespread, attracting extensive research interest from the academic community. Driven by the wave of artificial intelligence development and advances in precision drive technology, robotic arm technology has also made significant progress. By integrating the operational capabilities of robotic arms with the mobility of drones, the drone-robotic arm system has emerged. Traditional drones are primarily used in observational fields such as aerial photography, and their effectiveness in areas like logistics, delivery, assembly, and maintenance is limited. Equipping drones with robotic arms can significantly enhance their physical interaction capabilities, greatly expanding the scope of their applications. This paper aims to systematically review the current technological status, application scenarios, and challenges of Unmanned Aerial Vehicle (UAV) robotic arm systems, and to prospect their future development directions, providing a reference for research and engineering practice in this field.

2. The Current State of Drone Robotic Arm Technology

2.1. Robotic Arm Technology

2.1.1 Flexible robotic arm technology

Soft robotic arms are typically made from highly flexible materials, such as silicone rubber and thermoplastic polyurethane, and achieve motion through pneumatic actuation, shape memory alloys (SMA), or dielectric elastomer actuators (DEA)[1]. Soft robotic arms, with their high degree of freedom and excellent continuous deformation capabilities, are particularly well-suited for operations in confined environments. The soft structure of these arms also allows for more efficient utilization of the drone's space, effectively alleviating issues related to the storage of the robotic arms.

In the study of line-driven robotic arms, Burgner-Kahrs and others utilized distal motors to actuate tendon-driven multi-segment rigid or semi-rigid link structures made of superelastic nickel-titanium

alloy wires or high-modulus polyethylene fibers, achieving continuous bending motions similar to those of an elephant's trunk [2]. This design positions the drive unit at the base station, significantly reducing the weight at the end, making it particularly suitable for drone platforms with limited payload capacity. In addition, the linearly actuated continuum robotic arm designed by Deng et al. weighs only 850 grams and can carry a maximum payload of 3.2 kilograms, successfully performing bolt-tightening and cable-grasping operations in power inspections [3]. If successfully applied to drone-mounted robotic arm systems, it would markedly reduce the workload of inspection personnel in the field of power inspections.

2.1.2 Rigid robotic arm

Traditional rigid robotic arms possess high stiffness characteristics, which provide them with strong end-effector capabilities. Thanks to these advantages, they have been widely applied in fields such as intelligent manufacturing. The new generation of rigid robotic arms, while maintaining structural rigidity and high positioning accuracy, significantly reduces its own weight by using new materials such as carbon fiber, thereby achieving better compatibility with UAV platforms. However, these robotic arms lack flexibility and exhibit poor adaptability to complex, unstructured environments. When integrated into UAV robotic arm systems, their own weight and inertia can severely affect the UAV's endurance and stability.

2.2. Perception Technology

2.2.1 Visual perception system

Visual perception typically employs deep learning-based multi-source information fusion algorithms to enhance the ability to perceive key features of the target. The CMAC network proposed by Li and others utilizes both color (RGB) and depth (HHA) information sources to achieve a more accurate understanding of scenes in images, thereby enabling the model to overcome the limitations caused by relying on a single data type, such as the sensitivity of RGB images to lighting and the lack of texture in depth images, ultimately resulting in more robust and precise comprehension capabilities [4, 5].

2.2.2 Self-state awareness

When working in confined spaces, the perception of its own pose and the state estimation of a flexible robotic arm are particularly important for the safety and reliability of its operations. In response to this need, researchers have developed a sensor system based on fiber Bragg gratings (FBG). This system embeds a fiber array within the robotic arm to measure the bending, twisting, and strain states of the continuum robotic arm in real time, providing feedback for shape reconstruction and force control based on the collected data [6]. However, when using this sensing system in long-distance, dynamic environments, or in the presence of signal noise, data errors accumulate with the length of the sensor, resulting in inaccurate shape reconstruction. To address this issue, Y. Lu and colleagues proposed a general framework based on graph optimization. The precision of the robotic arm equipped with the optimized system has been greatly improved, making it suitable for medical fields such as endoscopy. If this system is applied to UAV robotic arm systems, it will significantly enhance accuracy and reliability in confined operations. This effectively broadens the system's application in areas such as earthquake relief and geological exploration.

2.2.3 Environmental perception and understanding

In order to enhance the system's perception and understanding of the environment, researchers employed the method of constructing maps. Classic map models such as point cloud maps, grid maps, and ESDF maps provide different forms of spatial representation for environmental perception. Among them, ESDF maps support gradient-based trajectory optimization through Euclidean distance and gradient information, aiding drones in achieving safe obstacle avoidance. Semantic maps, by integrating environmental semantic labels, enable drones to understand the properties of different objects and obstacles, thereby providing a higher level of environmental cognition for autonomous

navigation in complex environments such as urban areas [7]. Applying such technology to drone robotic arm systems can significantly enhance the drone's operational capabilities in both known and unknown environments. By understanding and perceiving the environment, the system can autonomously select appropriate routes based on environmental features during tasks such as search and rescue or monitoring, thereby effectively reducing the operator's burden.

3. Application Scenarios of Drone Robotic Arm Systems

3.1. Inspection and Maintenance of Electric Power Facilities

Electric power inspection is a key component in ensuring the safe and stable operation of the power grid. Wind turbines, however, are often exposed to harsh environments such as wind, sand, rain, and snow, which increases both the frequency and difficulty of inspection and maintenance. Relying entirely on manual labor for work at high altitudes poses significant risks, efficiency issues, and high costs. The application of UAV robotic arm systems provides an innovative solution to these challenges.

Drones equipped with high-definition cameras can autonomously patrol and collect high-resolution images and video data for transmission. Image automatic registration technology based on convolutional neural networks (CNNs) can deeply extract image features and match feature point pairs through Euclidean distance. By further employing geometric similarity techniques to effectively eliminate mismatched points, high-precision automatic registration of multi-source inspection images is ultimately achieved based on an affine transformation model [8]. Under the condition of a 45° rotation of the fan blades, this method achieves a Dice value of 0.947, and the average pixel discrepancy (APD) is only 1.36 pixels under scaling conditions, significantly improving the precision of blade image alignment and defect localization [9]. After obtaining the precise locations of defects through accurate image data, robotic arms equipped with devices such as laser scanners or ultrasonic probes can conduct detailed inspections of suspected defective areas, thereby accurately pinpointing concealed damages such as surface material detachment or internal cracks in power generation equipment.

In addition, the robotic arm can be equipped with cleaning nozzles or spraying devices to carry out automated cleaning of blade surfaces and the repair spraying of protective coatings on the leading edges. This operational mode achieves an integration of "inspection and maintenance," allowing for the early detection of blade damage and timely intervention, effectively preventing the expansion of defects. This can reduce the manpower required for blade maintenance and minimize power generation losses caused by downtime maintenance, significantly enhancing the intelligence level and economic efficiency of wind farm operations [9].

3.2. Logistics and Distribution

The drone robotic arm system, leveraging its aerial maneuverability, can hover outside windows to deliver meals or packages to residents in high-rise buildings and gently place items on balcony tables using its robotic arm. Delivering goods accurately to the doorstep not only saves users' time but also effectively prevents goods from being taken by mistake, significantly enhancing the user experience. Based on this concept, Kannan and others have studied precise delivery technologies for autonomous drones, targeting doorstep and courtyard drops. This technology has already achieved centimeter-level accuracy in cargo placement through the integration of visual and positioning systems. In addition, in the delivery of emergency supplies, robotic arms can also perform complex actions such as delivering through windows or turning door handles, greatly expanding the application scope of drones in emergency rescue [10]. The development of these technologies and application scenarios fully demonstrates that UAV robotic arm systems are driving logistics distribution systems towards greater intelligence, precision, and humanization.

4. Technical Challenges and Directions for Future Improvements

4.1. Key Technical Challenges

When operating in low-altitude unstructured environments, the perception system of the UAV robotic arm is easily affected by complex lighting, dynamic obstacles, and its own motion, leading to a decline in perception reliability. Furthermore, there exists a strong dynamic coupling between the robotic arm and the UAV platform, where the UAV's hovering vibrations and the reaction forces from the robotic arm's movements mutually influence each other, further increasing the difficulty of achieving millimeter-level precise operations.

The balance between endurance and payload is also a key bottleneck limiting the operational capability of drone manipulator systems. Enhancing payload capacity requires equipping the drone with more powerful and heavier motors, while the increased weight of the body consequently reduces the system's endurance. At the same time, the weight of the robotic arm mounted on the aircraft occupies the drone's payload capacity, further reducing the system's effective payload during operation. If the goal is to simultaneously increase payload capacity and endurance, the aircraft body would need to be equipped with a higher-capacity battery, which would further increase the overall system weight and reduce maneuverability. Achieving a balance among endurance, payload, and maneuverability has become the key challenge currently faced by researchers.

Executing tasks in residential areas places extremely high demands on the reliability and safety of drones. However, current collision detection algorithms exhibit a high false alarm rate in complex environments, making them unable to support the large-scale deployment of drones in urban areas, which significantly hinders the advancement of drone logistics.

4.2. Future Directions for Improvement

It is necessary to further develop multimodal fusion perception technology, integrating visual, force, tactile, and depth information to enhance the system's sensing capabilities in complex environments. At the same time, leveraging high-precision control technology can effectively improve the stability of the UAV platform during operations, thereby supporting the precise operation of robotic arms.

To address the balance among endurance, load capacity, and maneuverability, high-energy-density batteries, such as graphene composite lithium batteries, can be utilized to enhance overall endurance without increasing the total weight. Meanwhile, manufacturing robotic arms from lightweight materials can improve the load-to-weight ratio. Once wireless power supply technology matures, it can also be relied upon to further reduce the self-weight and enhance load capacity.

Regarding issues of reliability and safety, leveraging artificial intelligence technologies for rapid iteration of control and perception algorithms can effectively promote the development of collision detection algorithms. Moreover, establishing physical experimental sites can provide experimental support for assessing system capabilities.

5. Conclusion

Drone robotic arm technology combines the aerial maneuverability of drones with the precise operation of robotic arms, enabling drones to transition from pure perception to physical interaction, thereby expanding the application of drone systems in three-dimensional operations. This article systematically reviews the current advancements in robotic arm technology, perception technology, and control technology, and demonstrates the application of unmanned aerial vehicle robotic arm systems in fields such as power inspection. Although this system possesses broad application prospects, the numerous challenges it faces should not be overlooked. Difficulties such as the trade-off between endurance and load, insufficient perception accuracy, and system reliability still await breakthroughs by future researchers.

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