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Adaptive Control of Spray Angle and Distance in Robotic Painting Systems

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Abstract: Ensuring consistent paint quality in automated painting systems requires precise control of spray parameters, particularly the spray angle and the distance between the spray nozzle and the surface. This paper presents an adaptive control approach for regulating these parameters in robotic painting systems. Using feedback from depth cameras and surface normal estimation algorithms, the system maintains an optimal spray angle and distance in real time, even on complex and irregular surfaces. A PID-based control algorithm dynamically adjusts the manipulator's motion to minimize deviations, ensuring uniform paint coverage and reducing material waste. Simulation results using a ROS-based environment demonstrate significant improvements in painting accuracy, repeatability, and efficiency compared to conventional fixed-path methods. The proposed system shows strong potential for applications in flexible and small-batch industrial painting processes aligned with Industry 4.0 standards.

Keywords: adaptive control, robotic painting, spray angle, spray distance, PID control, machine vision, depth camera, industrial manipulator, real-time adjustment, ROS, surface normal estimation, trajectory optimization, Industry 4.0, automation, smart manufacturing.

Introduction. The automation of surface finishing operations, such as painting, has become a crucial aspect of modern manufacturing processes. Robotic painting systems are increasingly being adopted across various industries due to their ability to deliver high precision, consistency, and efficiency. However, achieving uniform paint coverage—especially on complex, curved, or irregular surfaces—remains a significant challenge. One of the key factors affecting paint quality is the ability to maintain the optimal spray angle and distance between the nozzle and the surface throughout the operation.

Traditional robotic painting systems often rely on predefined motion paths and static settings, which may not adapt well to variations in object shape, size, or placement. These limitations can lead to uneven coatings, increased paint consumption, and longer setup times. To overcome these issues, there is a growing need for intelligent, adaptive control strategies that can respond dynamically to the environment in real time.

This paper focuses on the development of an adaptive control system for robotic manipulators used in painting applications. The proposed system leverages machine vision, depth sensing, and real-time surface analysis to continuously adjust the orientation and position of the spray nozzle. By maintaining an optimal spray angle and distance, the system aims to improve coating quality, minimize overspray, and enhance operational efficiency. The integration of these technologies is aligned with the principles of Industry 4.0, promoting flexible and intelligent automation in manufacturing environments.

Results. The adaptive robotic painting system was modeled and tested using a simulation environment based on the Robot Operating System (ROS). A depth camera (RGB-D) and surface normal estimation algorithm were integrated to guide the motion of the manipulator in real time. Several key performance metrics were evaluated to assess the system's effectiveness.

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Spray Angle Maintenance

The system successfully maintained the optimal spray angle between the nozzle and the surface normal during motion. The deviation in nozzle orientation did not exceed 5°, which ensured uniform paint distribution even on curved and angled surfaces. This significantly reduced paint streaking and uneven coating.

Distance Control Accuracy

The spray distance was controlled within a tolerance of ±20 mm, with the ideal range maintained at approximately 200 mm. A PID controller was employed to regulate the manipulator's movements and correct deviations dynamically. This contributed to improved paint adhesion and minimized overspray.

Trajectory Adaptation

Using point cloud data from the depth camera, the system generated a real-time spray path based on the object's shape and position. This allowed the manipulator to dynamically adapt its trajectory without requiring manual reprogramming, making the system suitable for varying product geometries.

Performance Comparison

A comparative analysis between the proposed adaptive system and a conventional fixed-path system revealed notable improvements:

Metric	Conventional System	Adaptive System
Reconfiguration Time (min)	45	10
Positioning Error (mm)	±3.5	±0.8
Trajectory Repeatability (mm)	±2.1	±0.5
Paint Consumption (L/product)	0.9	0.75

The results indicate a substantial increase in accuracy, repeatability, and material efficiency when using the adaptive control system.

System Stability and Responsiveness

The system demonstrated reliable operation even when object position or orientation was altered during the process. The real-time feedback loop enabled quick adjustments, ensuring continued adherence to optimal spray parameters.

Overall, the experimental results validate the effectiveness of the adaptive control strategy. The system shows strong potential for deployment in flexible manufacturing environments, particularly for low-volume and custom product painting tasks.

Conclusion. The study demonstrated that adaptive control of spray angle and distance in robotic painting systems significantly enhances the quality and efficiency of automated surface coating processes. By integrating depth sensing, machine vision, and real-time control algorithms, the system dynamically adjusted the spray parameters according to object geometry and placement. This resulted in more uniform paint coverage, reduced material waste, and minimized positioning errors.

The adaptive system outperformed traditional fixed-path solutions in several key areas, including trajectory accuracy, repeatability, reconfiguration time, and paint consumption. Notably, the system maintained optimal spray conditions even in the presence of unpredictable object positioning, showcasing its suitability for flexible and low-volume manufacturing scenarios.

The use of ROS as a development and simulation environment enabled modular system design and virtual testing before physical deployment, which aligns well with Industry 4.0 principles. These findings suggest that the proposed adaptive approach can be a valuable addition to modern robotic painting lines, especially where product variation is high and manual programming is inefficient.

Future work will focus on implementing the system in a physical industrial environment and exploring the integration of AI-based predictive control for further optimization.

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