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ANALYSIS OF THE INFLUENCE OF SPRAY DISTANCE AND ANGLE ON COATING QUALITY IN ROBOTIC MANIPULATOR PAINTING USING MATLAB

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Abstract:

In this paper, the influence of spray distance and spray angle on coating quality during robotic manipulator painting is analyzed in the MATLAB environment. In robotic painting systems, ensuring product quality, uniform paint layer distribution, and stability of the technological process depend on the correct positioning of the spray gun relative to the surface. Particularly on complex-shaped and uneven surfaces, variations in spray distance lead to increases or decreases in coating thickness. The spray angle, in turn, determines the efficiency of paint particle deposition on the surface. In this paper, the combined effect of distance and angle is modeled using a spray cone model, coating thickness equation, and quality indicator. The relationships among distance, angle, and coating quality are evaluated using graphs in MATLAB. The results show that an optimal spray distance and a spray angle close to the surface normal improve coating quality.

Keywords: Robot manipulator, spray distance, spray angle, coating quality, MATLAB, painting process, spray cone, coating thickness.

Introduction

In modern industrial manufacturing, the use of robot manipulators enables the execution of technological processes with high precision. Robots are widely employed to perform operations that are hazardous, complex, or repetitive for humans. The painting process is one such operation, as it involves chemicals, fine particles, and harmful vapors that can negatively affect human health. Robotic painting systems reduce this risk and enable the production of a uniform coating. In such systems, the robot manipulator moves the spray gun along a predefined trajectory. However, achieving high-quality painting on uneven and complex surfaces requires more than a simple trajectory.

One of the main challenges in robotic manipulator painting is maintaining a constant distance between the spray gun and the surface being painted. If the robot does not adapt to the surface shape, the spray distance varies, resulting in non-uniform coating thickness. This issue is

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particularly evident when painting car bodies, curved metal panels, industrial equipment housings, or parts with complex geometries. Some areas of the surface may be too close to the robot end-effector, while others may be too far, causing the paint layer to form with varying thickness. Therefore, maintaining the spray distance at an optimal value is a fundamental requirement for robotic painting quality.

The spray angle is another parameter that strongly affects coating quality. Ideally, the spray gun should be oriented perpendicular to the surface normal. If the spray gun is tilted relative to the surface, paint particles are not distributed evenly, and the spray footprint becomes elongated. In such cases, the coating becomes thick on one side and thin on the other. As a result, surface quality deteriorates, paint consumption increases, and rework becomes necessary. Thus, controlling the spray angle is an important task in robot manipulator trajectory planning.

MATLAB provides a convenient environment for mathematical modeling, parameter analysis, and graphical visualization of robotic painting processes. In MATLAB, relationships among spray distance, spray angle, coating thickness, quality indicator, and surface model can be computed. Furthermore, 3D graphs, normal vectors, and optimal zone maps for uneven surfaces can be generated. In this paper, the influence of spray distance and angle on coating quality is analyzed using MATLAB. The results serve as a scientific and practical basis for optimizing robot manipulator trajectories and improving painting quality.

Research aim and objectives

The main aim of this research is to mathematically and graphically analyze the influence of spray distance and spray angle on coating quality in a robotic manipulator painting process using MATLAB. In this paper, the painting process is represented using a simplified physical model, and the relationships among the key parameters are determined. The optimal positioning of the spray gun relative to the surface, the uniformity of the paint layer, and the quality indicator are adopted as the main evaluation criteria. The task of the robot manipulator is to move the spray gun such that the paint is deposited uniformly and consistently on the surface. To achieve this, the surface geometry, spray cone, and robot motion are analyzed together. In addition, the theoretical model is implemented practically using MATLAB code.

The first objective of the research is to develop a mathematical model of the painting process. This model accounts for paint flow rate, spray distance, spray angle, robot travel speed, and spray area. The second objective is to determine how coating thickness changes when the spray distance varies. The third objective is to evaluate the decrease in coating quality when the spray angle deviates from the surface normal. The fourth objective is to visualize the combined effect of spray distance and angle using 3D graphs and contour maps. The fifth objective is to generate an adaptive trajectory for the robot end-effector based on an uneven surface model.

MATLAB was chosen as the primary computational and visualization tool in this paper. This software offers extensive capabilities for engineering modeling and facilitates work with functions, matrices, graphs, and optimization algorithms. MATLAB is particularly convenient for problems involving robot manipulators, surface models, and trajectory planning. During the research, a spray distance range of 100–350 mm and a spray angle range of 0–60° were selected. The optimal spray distance was conditionally taken as 200 mm. These values were used as representative parameters for typical industrial robotic painting systems.

The results of this research can be used in the development of robotic painting systems, the organization of laboratory work, and the generation of simulation results for scientific papers. Although the model does not capture all of the complex physical features of a real painting process, it is sufficient to explain the key technological relationships. Using this approach, a student or researcher can clearly see through graphs how spray distance and angle affect coating quality. In future stages, the model can be extended to include robot manipulator kinematics, sensor feedback, and an aerodynamic model of real paint particles. This model can also serve as a basis for developing adaptive control algorithms. Ultimately, the robot manipulator will be able to paint complex surfaces with higher quality and efficiency.

Mathematical Model of the Painting Process

In a robotic manipulator painting process, the paint particles emitted from the spray gun typically spread onto the surface in a conical shape. As the distance between the spray gun and the surface increases, the area covered by paint also expands, which reduces the amount of paint deposited per unit area. If the distance decreases, the paint accumulates in a smaller area, and the coating may become excessively thick. Therefore, coating thickness is considered an inverse function of spray distance. In the mathematical model, this relationship is expressed through the spray area.

The main parameters are the paint flow rate Q, adhesion coefficient η, robot speed v, spray angle θ, and the spray area $A(d)$. The coating thickness is expressed using the following simplified formula:

$$h = \frac{Q \cdot \eta \cdot \cos(\theta)}{v \cdot A(d)}$$

where h is the coating thickness, Q is the paint flow rate, η is the adhesion coefficient, θ is the spray angle, v is the robot end-effector speed, and $A(d)$ is the spray area dependent on distance. This equation is convenient for explaining the overall nature of the painting process, clearly showing how distance and angle affect coating quality.

The spray area is determined based on a conical spray model. If the half-opening angle of the spray cone is α, the radius of the spray footprint on the surface is found as follows:

$$r = d \cdot \tan(\alpha)$$

$$A(d) = \pi r^2$$

These expressions show that the spray area is proportional to the square of the distance. That is, if the distance doubles, the spray area can increase nearly fourfold. Therefore, even a small change in spray distance significantly affects the coating thickness. This demonstrates the need for high-precision control of the robot manipulator trajectory.

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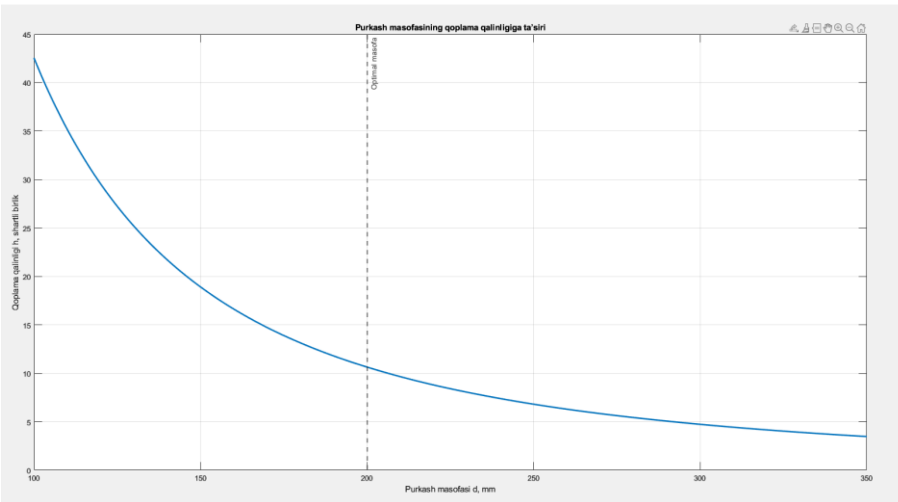
A quality indicator model was also introduced to evaluate coating quality. This model accounts for deviation from the optimal distance and increase in spray angle:

$$S = \exp\left(-k_1\left(d - d_{opt}\right)^2\right) \cdot \cos^n(\theta)$$

where S is the coating quality indicator, d_{opt} is the optimal spray distance, k_1 is the distance sensitivity coefficient, and n represents the degree of sensitivity to angle. If the spray distance is close to the optimal value and the spray angle is small, the quality indicator is high. Conversely, if the distance deviates from the optimal value or the angle increases, the quality decreases. This model is very convenient for graphical analysis in MATLAB.

Modeling the influence of spray distance on coating thickness in MATLAB

Spray distance is one of the most important technological parameters in robotic painting. If the robot manipulator cannot maintain a constant distance between the spray gun and the surface, the paint layer will not be uniform. When the distance decreases, paint accumulates in a smaller area, and the coating becomes thicker. When the distance increases, the spray cone expands, and the paint spreads over a larger area, leading to a decrease in coating thickness. Therefore, modeling the relationship between distance and thickness in MATLAB is of great importance. The following MATLAB code calculates the influence of spray distance on coating thickness. The code inputs the paint flow rate, adhesion coefficient, robot speed, and spray cone angle. The spray distance is varied from 100 mm to 350 mm. For each distance, the radius and area of the spray footprint are calculated. The coating thickness is then determined according to the formula. The result is visualized as a graph.



The graph shows that when the spray distance is small, the coating thickness is high. In this case, paint particles fall onto a narrow area and form a thick layer. Although such a coating might appear high-quality, in practice, paint consumption increases and the risk of dripping rises. As the distance increases, coating thickness decreases. Near the optimal distance, the

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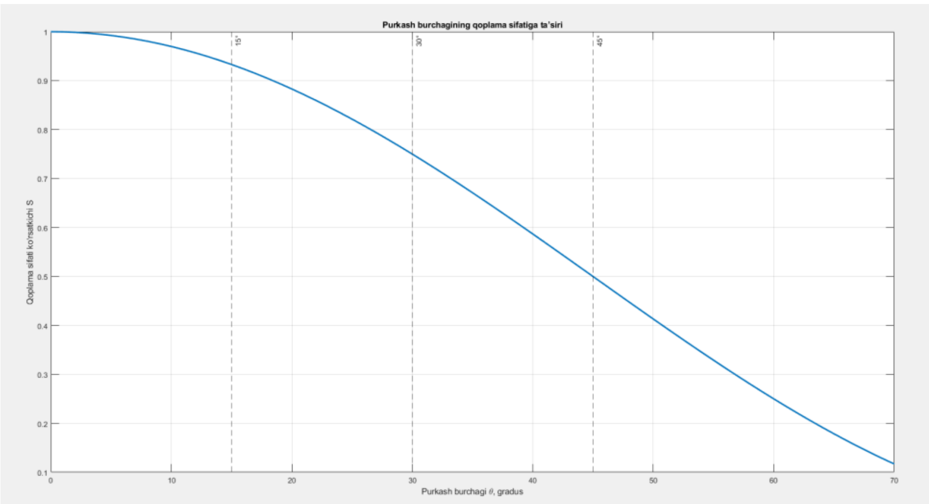
coating thickness meets technological requirements and remains stable. Therefore, the robot manipulator should maintain the distance close to the optimal value as it moves along the surface.
From a practical point of view, the optimal spray distance depends on the paint type, spray pressure, nozzle diameter, surface material, and travel speed. In this paper, 200 mm is taken as the conditional optimal distance. If real industrial experience is available, the d_{opt} value in the model can be adjusted accordingly. The MATLAB code allows the user to experiment with different parameters, helping to select optimal settings before actual production. Thus, modeling the spray distance is an effective method for predicting painting quality.

Modeling the influence of spray angle on coating quality in MATLAB.

The spray angle in robotic painting is defined relative to the surface normal. Ideally, the spray gun should be oriented perpendicular to the surface to be painted. In this case, paint particles are deposited most efficiently and uniformly. If the spray gun is tilted relative to the surface, the paint footprint becomes elongated like an ellipse. Consequently, the coating may be thick on one side and thin on the other. Therefore, controlling the spray angle is a necessary condition for high-quality painting.
As the angle increases, the effective amount of paint deposited on the surface decreases. This can be expressed mathematically by $cos(\theta)$. When $\theta=0°$, $cos(\theta)=1$, and paint is deposited with maximum efficiency. When the angle reaches 30^0 or 45^0, the effective coating decreases. If the angle becomes very large, some paint particles do not properly adhere to the surface, and the quality indicator drops sharply.
The following MATLAB code graphically illustrates the effect of spray angle on coating quality. Here, the quality indicator is assumed to be of the form $cos^n(\theta)$, where the coefficient n represents the sensitivity to angle. If n is chosen large, a small change in angle strongly affects quality. In the model, the angle is varied from 0^0 to
70^0. The graph shows within which angle range high quality is maintained.



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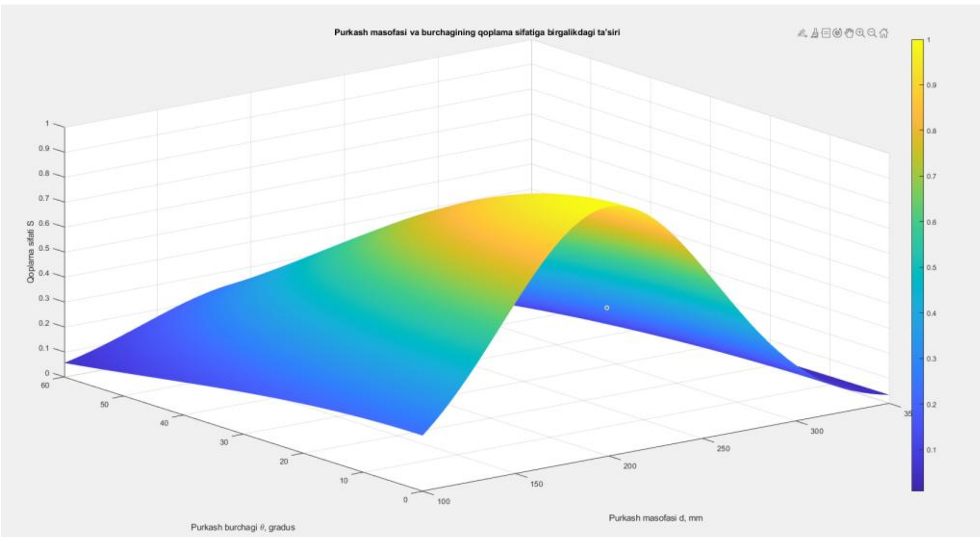
The results show that when the spray angle is between 0^0 and -15^0, coating quality remains high. Between 20^0 and 30^0, quality begins to slowly decrease, but this range may still be acceptable under some technological conditions. Beyond 30^0, the quality indicator decreases significantly. At 45^0 and larger angles, coating quality is poor, and the paint is not uniformly distributed over the surface. This confirms the necessity of adapting the robot manipulator trajectory to the surface normal vectors. Thus, the spray angle should be kept as small as possible during the painting process.

Analysis of the combined effect of spray distance and angle.

In a real painting process, spray distance and spray angle change simultaneously, not independently. As the robot manipulator moves along an uneven surface, the distance may increase at some points, while the angle may increase at others. If only distance is controlled but the angle is neglected, coating quality may still degrade. Similarly, if the angle is correct but the distance deviates from the optimal value, the coating thickness will not meet requirements. Therefore, both parameters must be analyzed together. Such an approach enables a comprehensive evaluation of the robotic painting process.

In this section, the quality indicator is considered as a joint function of distance and angle. When the distance deviates from the optimal value, the quality decreases exponentially. When the angle increases, the quality decreases according to $cos_n(\theta)$. These two effects were expressed in multiplicative form. Consequently, a quality map for robotic painting was generated. This map shows for which distance and angle values high quality can be achieved.

The following MATLAB code displays the combined effect of distance and angle as a *3D* graph. The *x*-axis represents the spray distance, the *y*-axis the spray angle, and the *z*-axis the quality indicator. The quality indicator is evaluated on a scale from 0 to 1, where a value of 1 represents the highest quality and values near 0 represent poor quality. This model is convenient for selecting optimal parameters when planning robot manipulator trajectories.



The results show that the highest quality is observed near *d*=200 mm and at angles close to $\theta=0^0$. As the distance moves away from 200 mm, the quality surface begins to decline. An increase in angle also reduces quality. Particularly when both the distance is far from optimal and the angle is large, coating quality deteriorates sharply. This demonstrates that on uneven surfaces, the robot manipulator must be controlled not only in position but also in orientation. Therefore, for high-quality painting, both the position and orientation of the robot end-effector must be optimized together.

Conclusion.

In this paper, the influence of spray distance and spray angle on coating quality in a robotic manipulator painting process was analyzed in the MATLAB environment. Calculations were performed using a spray cone model, coating thickness equation, and quality indicator. It was found that coating thickness decreases as spray distance increases, while the coating becomes excessively thick when the distance is too small. It was also shown that as the angle increases, the effective deposition of paint on the surface decreases. MATLAB graphs enabled clear visualization and analysis of these processes. Consequently, the need to select an optimal spray distance and angle range was substantiated.

According to the results, for high-quality painting, the robot spray gun must be positioned at an optimal distance from the surface and at an angle close to the surface normal. Under the model conditions, a spray distance in the range of 180–220 mm and an angle in the range of 0–20° can be considered favorable for high quality. However, these values should be refined experimentally under real industrial conditions. The quality map generated in MATLAB proved to be a useful tool for evaluating and optimizing the robot manipulator trajectory. Therefore, the proposed model is effective for the preliminary analysis of robotic painting processes.

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