

ADAPTIVE TRAJECTORY PLANNING AND TECHNOLOGICAL OPTIMIZATION FOR PAINTING UNEVEN SURFACES USING A ROBOT MANIPULATOR

Sh. S. Djuraev

D. X. Tuxtasinov

A. A. Askarov

Namangan State Technical University,
160103, Namangan, Uzbekistan

Abstract

This paper analyzes adaptive trajectory planning, coating quality assessment, and technological optimization for painting uneven surfaces using a robot manipulator. Based on MATLAB modeling results, the relationships among spray distance, spray angle, coating thickness, and surface normal vectors are summarized. It is substantiated that for high-quality painting on uneven surfaces, both the position and orientation of the robot manipulator must be controlled together. The paper presents an adaptive trajectory planning algorithm, scientific novelties, and practical significance. The results show that the MATLAB model is an effective tool for designing, testing, optimizing, and eventually implementing robotic painting processes in real robot systems.

Keywords: Adaptive trajectory, robot manipulator, uneven surface, coating quality, MATLAB, optimization, surface normal vector, painting technology.

Introduction

Analysis of Experimental and Simulation Results.

The MATLAB modeling results show that spray distance strongly affects coating thickness. When the distance decreases, paint particles accumulate in a small area and form a thick layer. While this may be beneficial for certain parts, it often leads to increased paint consumption and reduced surface quality. When the distance increases, the spray area expands and the coating becomes thinner. If the distance is too large, some paint particles may not reach the surface. Therefore, selecting

an optimal distance and maintaining it consistently along the trajectory is very important.

The results obtained for spray angle also provide important conclusions. The quality indicator is high when spraying close to the surface normal. When the angle is up to 15–20°, the decrease in quality may be relatively small. However, at angles greater than 30°, coating quality decreases significantly. In this case, the paint footprint becomes elongated and the coating is non-uniform. Thus, the robot manipulator must orient the spray gun to align with the surface normal.

The combined analysis of distance and angle further clearly demonstrates the complexity of the robotic painting process. Maintaining only an optimal distance is insufficient, because quality also decreases when the angle increases. Similarly, even if the angle is correct, if the distance deviates from the optimal value, the coating thickness will not meet the requirements. Therefore, the position and orientation of the robot manipulator must be controlled together. The 3D quality map and contour graphs generated in MATLAB help identify the optimal parameter zone. These results provide useful recommendations for practical robotic painting systems.

When coating thickness was modeled on an uneven surface, the non-uniform distribution of thickness along the surface was clearly observed. Coating thickness decreased in areas where distance and angle errors were present. A trajectory based on normal vectors, however, allows the spray gun to adapt to the surface. This approach reduces the spray angle and improves coating quality. Using statistical calculations, the mean thickness, minimum and maximum values, and uniformity coefficient can be determined. Thus, it is confirmed that the MATLAB model is an effective tool not only for graphical visualization but also for numerical analysis.

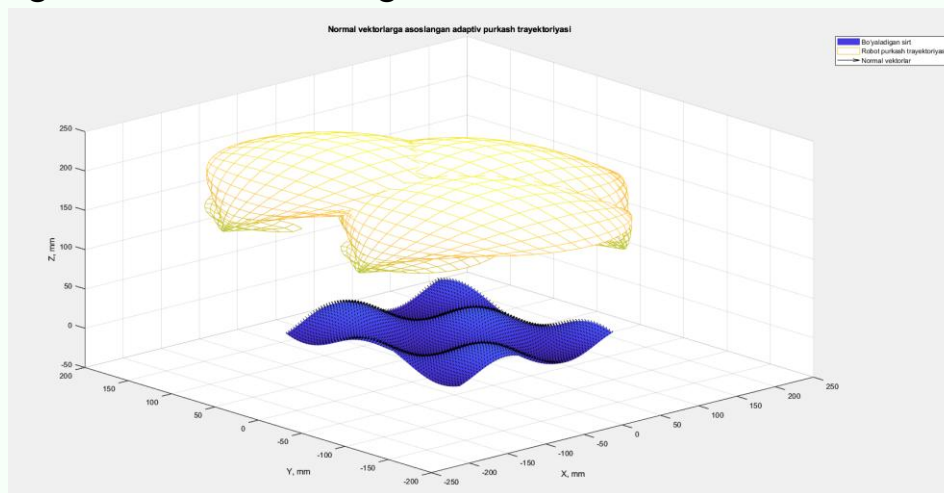
Algorithm for Robot Manipulator Trajectory Planning

To achieve high-quality painting of uneven surfaces using a robot manipulator, an adaptive trajectory planning algorithm must be developed. Such an algorithm must account for surface geometry, spray distance, spray angle, and robot motion constraints. First, a 3D model of the part to be painted is obtained, or a point cloud is generated via scanning. Then, normal vectors are calculated using these surface points. At each point, the spray gun is oriented to align with the surface normal.

Subsequently, the coordinates of the spray gun are determined at the optimal distance.

Trajectory planning is not limited to point calculation. The robot motion must be smooth, continuous, and conform to dynamic constraints. If the trajectory contains sharp turns, vibrations, speed variations, or reduced accuracy may occur in the robot manipulator's motion. Therefore, the calculated points are smoothed using spline or interpolation methods. Additionally, constraints such as joint angles, speed, and the robot's workspace must be checked. An optimal trajectory not only improves painting quality but also ensures safe and stable operation of the robot.

The following MATLAB code shows a simplified model of an adaptive spray trajectory based on surface normal vectors. In this code, an uneven surface is first created, and then the normal vectors are calculated. Subsequently, the spray gun is shifted from each surface point along the normal direction by the optimal distance. The result is a spatial trajectory where the robot end-effector adapts to the surface. The graph shows the surface to be painted, the robot spray trajectory, and the normal vectors. This model serves as a preliminary foundation for developing a real robot control algorithm.



The proposed algorithm consists of several sequential steps. The first step is to obtain the surface geometry and convert it into a mathematical model. The second step is to calculate the surface normal vector for each point. The third step is to position the spray gun at the optimal distance along the normal direction. The fourth step is to compute the quality indicator for spray angle and distance. The fifth step is to identify non-optimal regions and adjust the trajectory accordingly.

In this way, the robot manipulator adapts to the uneven surface and performs high-quality painting.

Scientific Novelty

The scientific novelty of this paper is defined by the comprehensive analysis in MATLAB of the combined effect of spray distance and spray angle on coating quality during robotic manipulator painting. Many simple models consider only the effect of distance or only the effect of angle separately. In this work, both parameters are evaluated through a single quality indicator. This approach allows a more realistic representation of the robotic painting process. As a result, an optimal zone map for coating quality was generated. This map can serve as a practical criterion for planning robot manipulator trajectories.

As a second scientific novelty, a simplified yet practically convenient model for coating quality is proposed:

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

This model jointly accounts for the deviation of spray distance from the optimal value and the deviation of the angle from the surface normal. The coefficients k_1 and n in the model can be adjusted based on experimental results. Therefore, it can be adapted to different paint types, different spray guns, and different surface materials. The model is computationally fast in MATLAB and convenient for graphical analysis. This makes it suitable for use in scientific papers, laboratory work, and engineering projects.

The third scientific novelty is the development of an adaptive spray trajectory model based on surface normal vectors for uneven surfaces. This model is founded on the concept of orienting the robot spray gun to adapt to the surface at each point. As a result, the spray angle is reduced and coating thickness becomes more uniform. The main steps of the adaptive painting algorithm were demonstrated in MATLAB by calculating normal vectors and generating the spray gun trajectory. This approach is compatible with working from CAD models or 3D scanning data in real robotic systems. Therefore, the results of this paper have both theoretical and practical significance.

The fourth scientific novelty consists of evaluating coating thickness as a 3D distribution over the surface and calculating numerical quality indicators. The paper introduces criteria such as mean thickness, minimum thickness, maximum

thickness, standard deviation, and uniformity coefficient. These indicators enable the robotic painting process to be assessed numerically rather than only visually. In particular, the uniformity coefficient provides a summary measure of the quality of the robot trajectory. If this approach is combined with optimization algorithms, paint consumption can be reduced and coating quality improved. Thus, this paper contributes to the scientific modeling of robotic painting processes.

Practical Significance

The results of this study have practical significance for designing and tuning robotic manipulator painting systems. Using the model developed in MATLAB, the influence of spray distance and angle on coating quality can be predicted without conducting real experiments. This reduces time, paint material, and production costs. The model allows rapid testing of various parameters and identification of optimal values. Such simulation is especially useful for preliminary engineering calculations when creating a new robotic painting line. Therefore, the approach presented in the paper can be applied in manufacturing enterprises.

From a practical perspective, this model can be beneficial in industries such as automotive manufacturing, mechanical engineering, metal structure production, painting of household appliance bodies, and coating of complex-shaped parts. In these fields, coating quality determines the appearance and corrosion resistance of the product. If the paint layer is too thin, the product may deteriorate quickly or rust. If the coating is too thick, paint consumption increases and surface quality worsens. Therefore, ensuring optimal thickness improves production efficiency. In a robotic painting system, this task is accomplished by correctly selecting the trajectory and spray parameters.

The research results can also be used in education. In courses such as robotics, automation, mechatronics, and MATLAB modeling, a laboratory or practical session can be organized based on this paper. Students can observe through code the relationships among spray distance, angle, coating thickness, and quality indicator. This allows theoretical concepts to be reinforced with practical graphs. Furthermore, different experiments can be conducted by modifying the code. In this respect, the paper has both scientific and educational-methodological significance.

In the future, this MATLAB model can be integrated with a real robot manipulator, distance sensors, cameras, or 3D scanner data. For example, the surface shape could be scanned in advance, and normal vectors and trajectories calculated in MATLAB. This trajectory would then be transmitted to the robot control system. In real time, a distance sensor could check the proximity of the spray gun to the surface and correct the trajectory if necessary. Such a system would serve to create an adaptive robotic painting technology. As a result, production quality, efficiency, and automation level would increase.

Conclusion

This paper has summarized adaptive trajectory planning, coating quality assessment, and technological optimization for painting uneven surfaces using a robot manipulator. MATLAB modeling results showed that spray distance, spray angle, and surface normal vectors directly affect the quality of robotic painting. It was substantiated that on uneven surfaces, the robot manipulator must not only move along the surface but also orient the spray gun to align with the surface normal at each point. The adaptive trajectory algorithm should consist of steps including obtaining surface geometry, calculating normal vectors, maintaining optimal distance, and correcting low-quality zones. This approach allows improving coating quality, reducing paint consumption, and stabilizing robot motion.

The scientific novelty of the study is defined by evaluating the combined effect of spray distance and angle through a single quality indicator, generating an adaptive spray trajectory based on normal vectors for uneven surfaces, and performing numerical analysis of coating thickness over a 3D surface. From a practical standpoint, this model can be used for designing robotic painting systems, selecting technological parameters, and organizing laboratory exercises. In the future, it would be appropriate to extend the model with real robot manipulator kinematics, sensor feedback, a physical model of paint particles, and optimization algorithms. This would create the capability for even more intelligent, adaptive, and efficient control of the robotic painting process.

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