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MODELING THE SPRAY TRAJECTORY OF A ROBOT MANIPULATOR ON UNEVEN SURFACES BASED ON SURFACE NORMAL VECTORS IN MATLAB

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Abstract

In this paper, the problem of generating a spray trajectory for painting uneven surfaces using a robot manipulator, based on surface normal vectors, is studied in the MATLAB environment. On uneven surfaces, it is not sufficient for the spray gun to simply move at a certain distance above the surface; its orientation must also align with the surface normal. Otherwise, the spray angle increases, the paint footprint elongates, and the coating quality deteriorates. In this paper, a model of an uneven surface is created using a sinusoidal function, the trajectory of the spray gun above the surface is generated, and the normal vectors are computed. Furthermore, the distribution of coating thickness over the 3D surface and the coating quality indicators are evaluated using MATLAB. The results demonstrate that an adaptive trajectory based on surface normal vectors plays a crucial role in improving coating quality.

Keywords: Uneven surface, robot manipulator, surface normal vector, spray trajectory, MATLAB, coating thickness, adaptive painting, 3D model.

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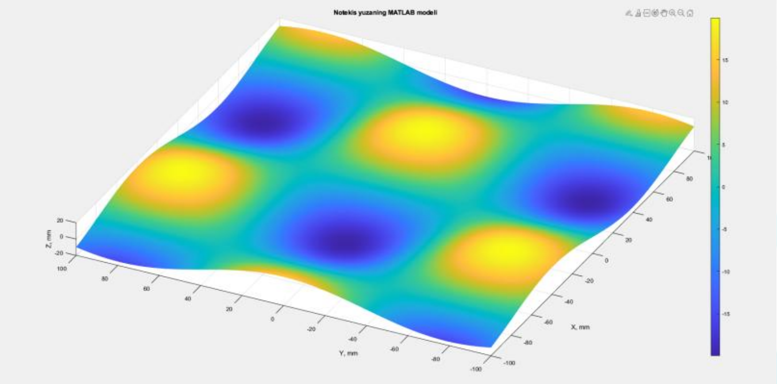
Introduction

Uneven surface model and robot spray trajectory.

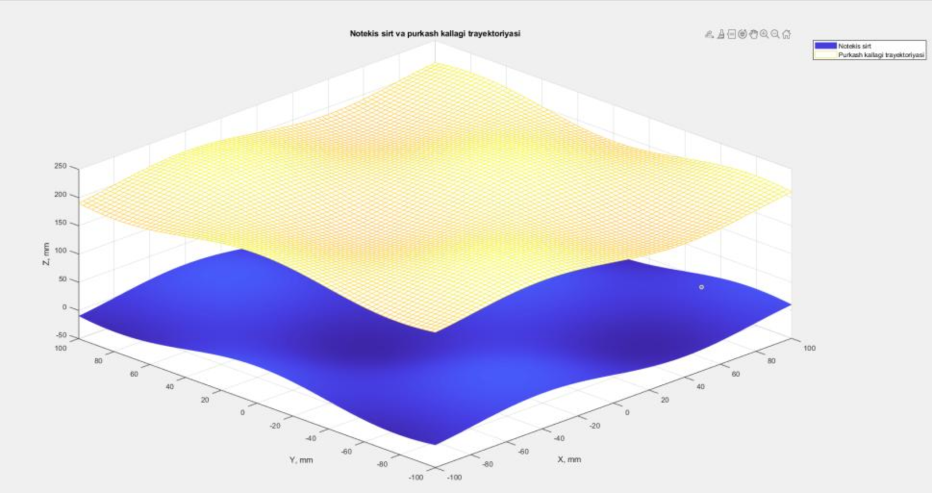
Painting uneven surfaces is one of the most complex tasks for robot manipulators. On flat surfaces, maintaining a constant spray distance and angle is relatively straightforward. However, on curved, wavy, or complex-shaped surfaces, the robot end-effector must adapt to the surface at each point. If the robot does not account for the surface shape, the distance may decrease in some areas and increase in others, leading to uneven coating thickness. Therefore, creating an uneven surface model and generating a spray trajectory over it in MATLAB is considered essential.

A simplified uneven surface can be modeled using a sinusoidal function. Although such a surface does not fully represent the complexity of real industrial parts, it is sufficient for testing trajectory planning algorithms. The advantage of a sinusoidal surface is that its height varies smoothly, allowing the robot end-effector to track the surface profile. A 3D surface is generated in MATLAB using X, Y, and Z coordinates. This surface is taken as the part to be painted. Subsequently, the spray gun is moved over this surface at an optimal distance.

The following MATLAB code creates an uneven surface model, where the Z coordinate is computed using sine and cosine functions, resulting in a curved and wavy surface. The high and low regions of the surface are represented in the graph using colors. This model is convenient for testing the robot manipulator trajectory. The next code generates the spray gun trajectory over the surface.



When generating the spray gun trajectory, a second surface is created at a specified distance above the original surface. If the spray distance is taken as 200 mm, the spray gun moves 200 mm above the surface while replicating its profile. In this simplified model, the robot end-effector is considered to be displaced only along the Z-axis. In a real robotic system, the end-effector should move along the surface normal vector. Nevertheless, this model is useful for illustrating the concept of maintaining a constant spray distance. The following code displays both the surface and the spray trajectory together.

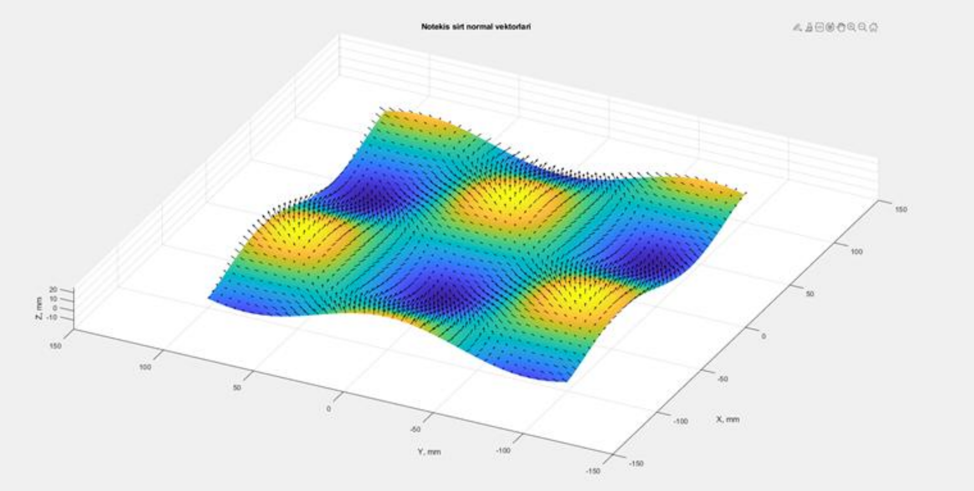


Determination of spray angle based on surface normal vectors.

To achieve high-quality painting of uneven surfaces, the robot manipulator must orient the spray gun to align with the surface normal at each point. The surface normal vector, which is perpendicular to the surface, plays a key role in determining the spray direction. When the spray gun aligns with the normal vector, the spray angle is minimized, ensuring uniform paint deposition. If the gun deviates from the normal, coating quality deteriorates. Therefore, computing surface normal vectors is a crucial step in robotic painting algorithms.

In MATLAB, the surface normal vectors are computed by determining the gradients of the surface in the X and Y directions. The gradients indicate how the surface changes. If the surface is flat, the gradient is small, and the normal vector is nearly vertical. If the surface has a sharp curvature, the normal vector tilts accordingly. The normal vector components are taken as $-Z_x - Z_y$, and 1, and are then normalized to obtain unit vectors.

The following MATLAB code computes and visualizes the normal vectors for an uneven surface. The gradient function is used to determine the partial derivatives of the surface, and the quiver3 function is used to draw vectors in 3D space. The result shows how the robot spray gun should be oriented at each point. This code is important for orientation-based trajectory planning, especially on complex surfaces, as this approach improves coating quality.



Control based on normal vectors ensures surface adaptability in robotic painting. In such an approach, the robot manipulator moves not only according to specified coordinates but also taking into account the surface orientation at each point. This reduces the spray angle and increases coating uniformity. In real systems, surface normal vectors can be obtained from CAD models or 3D scanning data. The MATLAB model, in turn, allows this process to be examined under laboratory or scientific analysis conditions. As a result, a mathematical foundation is established for generating adaptive trajectories for robot manipulators.

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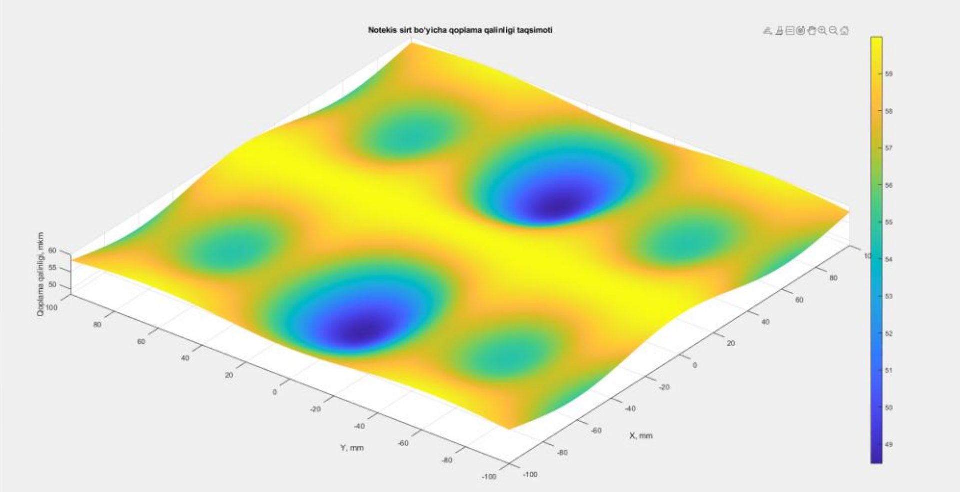
Modeling the 3D distribution of coating thickness on an uneven surface in MATLAB.

In robotic painting, the coating thickness should be uniform across all points of the surface. In practice, however, thickness varies due to factors such as spray distance, angle, robot speed, and surface curvature. Some areas may receive a thick coating, while others receive a thin one. This adversely affects the appearance and protective properties of the product. Therefore, modeling the coating thickness distribution over a 3D surface in advance is very important. MATLAB allows this process to be analyzed both graphically and numerically.

In this section, the coating thickness was calculated based on a quality indicator. First, an optimal spray distance is defined, and then a distance error is artificially introduced over the surface. An angular error is also represented using a sinusoidal model. These errors illustrate, in a simplified manner, the deviations encountered on real uneven surfaces. Then, a quality indicator dependent on distance and angle is computed. Finally, the optimal coating thickness is multiplied by this quality indicator.

The following MATLAB code generates the coating thickness distribution over the uneven surface. In the graph, the X and Y coordinates represent surface points, and H denotes the coating thickness. Colors highlight the thickly and thinly coated areas. This result helps identify deficiencies in the robot manipulator trajectory. If the coating thickness is highly uneven, the spray distance or angle may need to be re-optimized. This model can also be used to estimate paint consumption.



Results show that the coating thickness is not uniform across the surface. In optimal regions, the coating thickness is close to h_0, which in the model is approximately 60 µm. In areas where distance and angle errors increase, the coating thickness decreases. If the distance or angular error is magnified in the model, the coating becomes even more uneven. This indicates the necessity of sensor-based monitoring and adaptive correction in real robotic painting processes. Therefore, the MATLAB model is an effective tool for predicting coating quality.

Calculation of coating quality indicators.

It is not sufficient to evaluate coating quality solely through graphical means; numerical indicators must also be analyzed. One of the most important indicators in painting processes is the average coating thickness. Additionally, the minimum and maximum thickness values indicate the boundaries of the coating. The standard deviation represents the spread of thickness over the surface. A small standard deviation indicates uniform coating, while a large standard deviation indicates poor coating quality.

The coating uniformity coefficient is a convenient metric for summarizing quality. In this paper, the uniformity coefficient was calculated using the following formula:

$$U = \left(1 - \frac{\sigma_H}{H_{mean}}\right) \cdot 100\%$$

where U is the coating uniformity, σ_H is the standard deviation of coating thickness, and H_{mean} is the mean coating thickness. If the standard deviation is very small compared to the mean, U is high. If the thickness is widely spread, U decreases.

The following MATLAB code calculates the key numerical indicators of coating quality. The code first creates a 3D surface and coating thickness model. Statistical values are then obtained using the mean, min, max, and std functions. The results are displayed on the screen using the fprintf operator. These indicators can be analyzed in table or text form in the results section of the paper. They are particularly useful for comparing conditions before and after optimization.

- Mean coating thickness: 56.98 µm
- Minimum coating thickness: 48.47 µm
- Maximum coating thickness: 60.00 µm
- Standard deviation: 2.43 µm
- Coating uniformity: 95.74%

Through these calculations, the quality level of the robotic painting process is precisely evaluated. If the mean thickness is close to the required value but the standard deviation is large, it is concluded that the coating is non-uniform. If the minimum thickness is too low, some areas may be insufficiently painted. If the maximum thickness is too high, excess paint may have been used or there may be a risk of run-off. A high uniformity coefficient indicates that the robot trajectory and spray parameters are properly selected. Thus, such statistical analysis is an important step in optimizing robotic painting processes.

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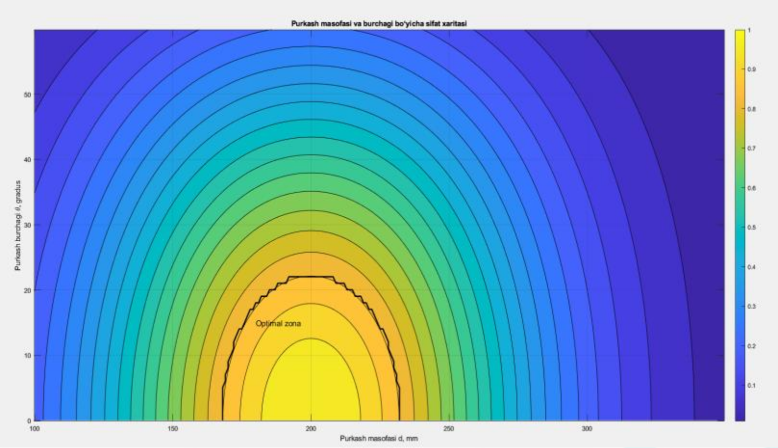
Determination of the optimal zone for distance and angle

One of the important issues in robotic painting processes is determining the optimal range of technological parameters. The spray distance and angle can be acceptable not only at a single value but also within a certain range. For example, although a spray distance of 200 mm may be considered ideal, the range of 180–220 mm may also yield satisfactory results in practice. Similarly, while a spray angle of 0° is optimal, deviations of up to 15–20° are often acceptable. Therefore, constructing an optimal zone map is useful for robot manipulator control. Such a map shows within which parameter ranges high quality is maintained.

To determine the optimal zone, the quality indicator is compared with a threshold value. In this paper, a condition of $S \geq 0.85 S_{max}$ was taken as the criterion for high quality. If a given combination of distance and angle satisfies this condition, it is included in the optimal zone. Otherwise, it is considered an unsatisfactory or cautious zone. Such an approach can enable real-time parameter monitoring by the robot manipulator. For example, if sensors detect that the distance or angle is leaving the optimal zone, the control system corrects the trajectory.

The following MATLAB code generates a quality map over spray distance and angle. The contourf function is used to display quality values as colored contours. A black line indicates the boundary of the high-quality zone. This graph can be presented in the paper as an "optimal zone map." Using the graph, the recommended distance and angle ranges for the robot manipulator are determined. This approach is very convenient for selecting technological settings.



According to the model results, quality is high when the spray distance is close to the optimal value and the angle is small. If the distance is in the range of 170–230 mm and the angle is between 0–25°, coating quality can be relatively stable. However, this range depends on the chosen model parameters and should be refined based on experimental results. The optimal zone map can serve as a criterion for the adaptive control algorithm of the robot manipulator. If the robot end-effector moves out of the optimal zone, the system should adjust the position or orientation of the spray gun. In this way, coating quality is maintained consistently.

Conclusion

In this paper, the surface model, spray gun trajectory, surface normal vectors, and coating thickness distribution for painting uneven surfaces using a robot manipulator were modeled in the MATLAB environment. It was shown that for uneven surfaces, a simple flat trajectory is insufficient; the robot end-effector must adapt to the surface shape at each point. A sinusoidal surface model was created in MATLAB, and the spray gun trajectory over it was generated. The concept of optimally orienting the robot end-effector relative to the surface was substantiated using normal vectors. The 3D distribution of coating thickness showed a decrease in quality in regions where distance and angular errors are present.

According to the research results, an adaptive trajectory based on surface normal vectors allows reducing the spray angle and improving coating uniformity. Coating quality was numerically evaluated using mean thickness, minimum and maximum values, standard deviation, and uniformity coefficient. The high coating uniformity in the model results indicates that the robot trajectory and spray parameters were properly selected. The optimal zone map serves as a convenient criterion for robot manipulator control. In future work, integrating this approach with real 3D scanning data and robot manipulator kinematics will expand the possibilities for creating adaptive robotic painting systems.

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