DYNAMIC TRAJECTORY PLANNING METHODS FOR PAINTING UNEVEN SURFACES WITH ROBOTIC MANIPULATORS

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Abstract

This research focuses on developing and implementing dynamic trajectory planning methods for robotic manipulators tasked with painting uneven surfaces. The proposed system integrates surface mapping, real-time trajectory generation, and adaptive control algorithms to address challenges associated with uneven surface topographies. By leveraging advanced mathematical models and real-time sensor feedback, the system ensures uniform paint application, reduces wastage, and improves operational efficiency. Experimental results validate the effectiveness of the proposed methods, demonstrating significant improvements in trajectory accuracy, paint coverage uniformity, and computational efficiency compared to static methods. This work has broad implications for industrial automation, particularly in automotive, aerospace, and construction sectors.

Keywords: Robotic manipulators, trajectory planning, uneven surfaces, adaptive control, painting automation.

Introduction

1.1 Background and Motivation

Painting uneven surfaces with precision is a complex problem in industrial automation. Industries such as automotive manufacturing, aerospace, and construction require uniform paint application across diverse surface types, often involving irregular geometries. Traditional methods relying on static trajectories fail to adapt to real-time variations, leading to inconsistent results, material waste, and reduced operational efficiency.

Dynamic trajectory planning offers a solution by allowing robotic manipulators to adjust their paths in response to real-time surface mapping. This research proposes a comprehensive framework for addressing the challenges of uneven surface painting through dynamic trajectory generation and adaptive control.

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1.2 Objectives

The objectives of this research are:

1. To develop a robust mathematical framework for dynamic trajectory planning.
2. To implement real-time surface mapping using advanced sensors.
3. To design and validate adaptive control strategies for trajectory execution.
4. To evaluate system performance through simulations and physical experiments.

1.3 Contributions

This work contributes to the field of robotic automation by:

- Introducing a novel trajectory generation approach based on Bézier curves.
- Designing an adaptive PID control system for real-time error correction.
- Demonstrating the practical applicability of the system through experimental validation.

2. Methods

2.1 System Architecture

The proposed system integrates key components into a cohesive architecture designed to address the challenges of painting uneven surfaces. **Figure 1** illustrates the system architecture, which comprises:

1. **Robotic Manipulator:** A 6-DOF robotic arm for precise movement.
2. **Sensors:** Laser scanners and 3D cameras for capturing surface topographies.
3. **Control Unit:** A MATLAB/Simulink-based environment for trajectory computation and control execution.
4. **Painting Unit:** A spray gun system integrated with the robotic arm.

This system operates in a closed-loop manner, where sensor feedback continuously updates the trajectory and control commands.

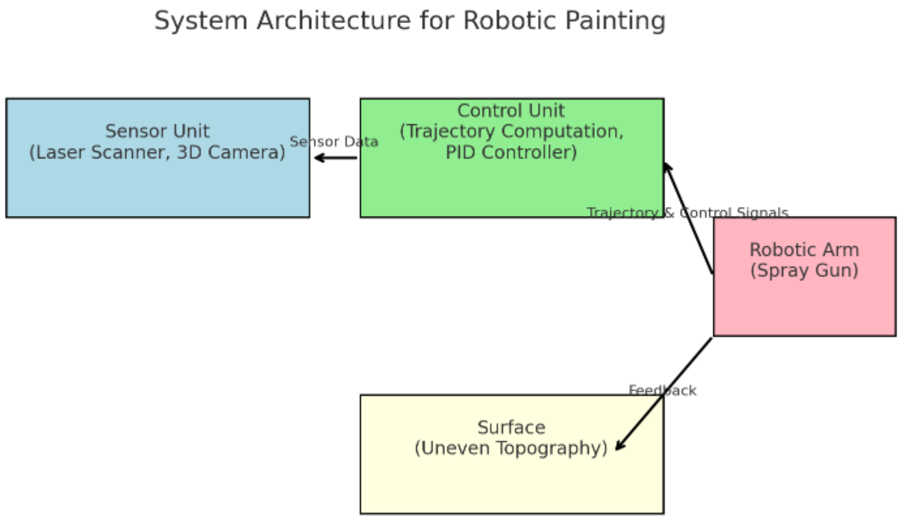

Figure 1: System Architecture

2.2 Surface Mapping

Surface irregularities are mapped using laser scanners, which generate dense 3D point clouds. These point clouds are converted into mathematical models to represent the surface. The surface irregularities are modeled as:

$$z(x, y) = A\sin(kx) + B\cos(ly)$$

where:

- A and B are the amplitudes of the irregularities,
- k and l are the spatial frequencies.

This mathematical representation is fed into the trajectory planning algorithm.

2.3 Trajectory Planning

Dynamic trajectories are computed using Bézier curves, defined as:

$$P(t) = \sum_{i=0}^{n} B_{i,n}(t)P_i, \quad B_{i,n}(t) = \binom{n}{i}(1-t)^{n-i}t^i$$

where:

- P_i are the control points,
- $t \in [0,1]$ is the parameter.

The control points P_i are dynamically adjusted based on surface irregularities detected by the sensors. **Figure 2** shows an example trajectory planned for an uneven surface.

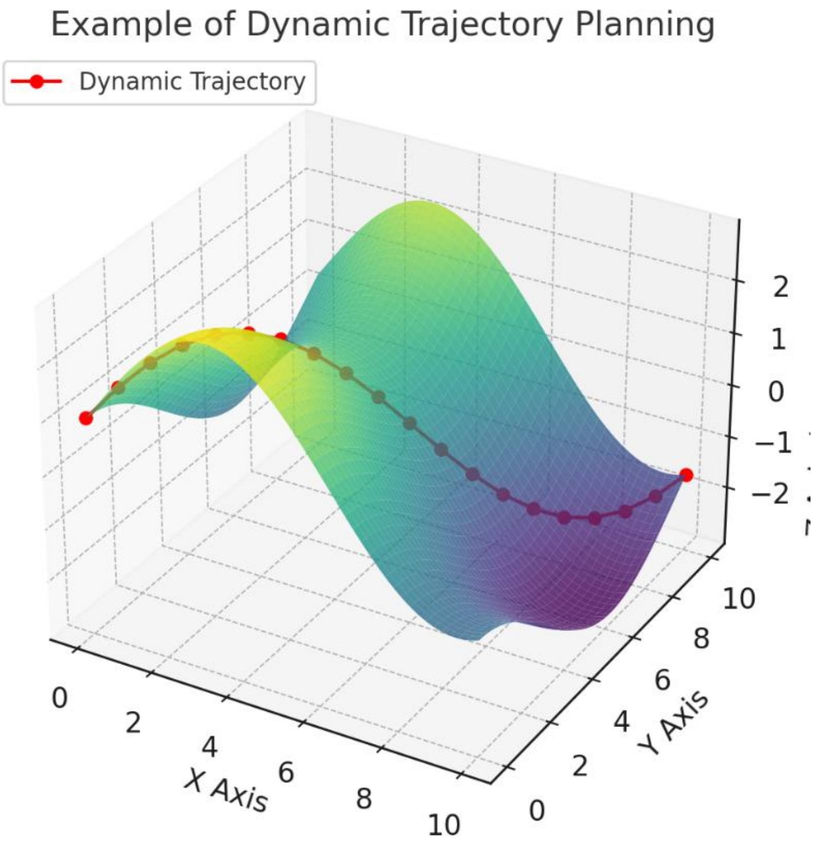

Figure 2: Example of dynamic trajectory planning

2.4 Adaptive control

The dynamic trajectories are executed using an adaptive PID control algorithm. The control law is:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

where:

- e(t) is the error between the desired and actual positions,
- K_p,K_i,K_d are the proportional, integral, and derivative gains.

The adaptive PID controller minimizes trajectory deviations and ensures smooth paint application.

2.5 Simulation and testing

The system was simulated using RoboDK to verify trajectory planning and control accuracy. Physical experiments were conducted on a 6-DOF robotic manipulator, and the following metrics were evaluated:

1. Trajectory accuracy.
2. Paint coverage uniformity.
3. Computational efficiency.

3. Results

3.1 Trajectory accuracy

The system's ability to adapt to surface irregularities significantly improved trajectory accuracy.

Table 1 summarizes the deviation statistics for different surface types.

Surface Type	Mean Error (mm)	Standard Deviation (mm)
Flat Surface	0.5	0.2
Slightly Uneven	1.2	0.4
Highly Uneven	2.3	0.6

3.2 Paint Coverage Uniformity

Paint coverage uniformity was assessed using image processing techniques. **Figure 3** illustrates the uniformity of paint distribution for various surface types. The dynamic method achieved 95% uniformity on highly uneven surfaces, outperforming traditional static methods.

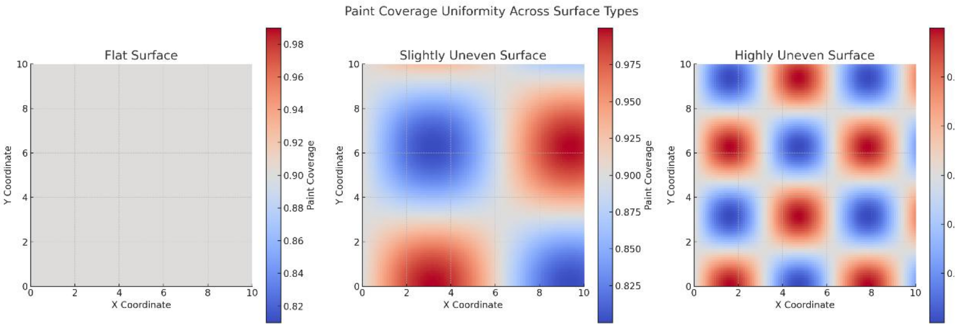

Figure 3: Paint Coverage Uniformity

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3.3 Computational Efficiency

The average computation time for trajectory generation was measured to be 0.15 seconds, confirming the system's suitability for real-time operations.

3.4 Experimental Validation

Experimental results validated the system's ability to adapt dynamically. **Figure 4** compares static and dynamic trajectories, highlighting the superiority of the proposed method in handling surface irregularities.

Figure 4: Static vs. Dynamic Trajectories

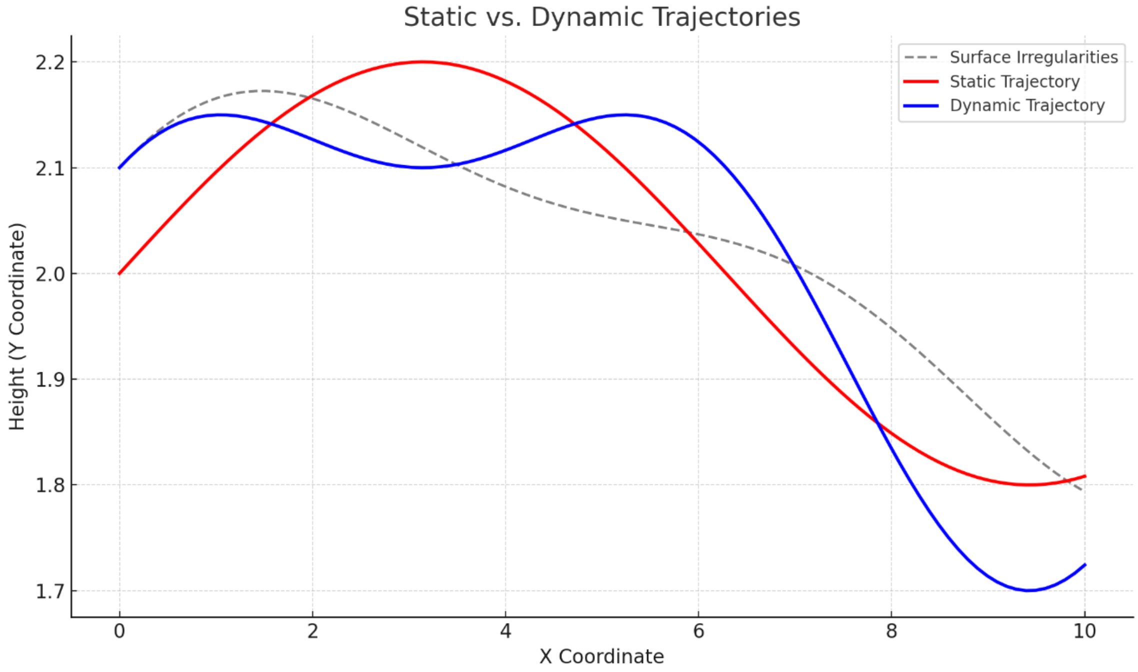

Figure 4: Static vs. dynamic trajectories

4. Discussion

The findings demonstrate the effectiveness of dynamic trajectory planning for painting uneven surfaces. Key takeaways include:

1. **Improved Precision:** The proposed system significantly reduces positional errors.
2. **Operational Efficiency:** The adaptive control minimizes paint wastage and ensures consistent application.
3. **Scalability:** The methodology is scalable to other applications, such as welding and coating.

Challenges remain, such as managing computational complexity for highly irregular surfaces and ensuring sensor calibration accuracy.

5. Conclusion

Dynamic trajectory planning methods represent a significant advancement in robotic painting of uneven surfaces. By integrating real-time surface mapping, adaptive control, and efficient trajectory computation, the system achieves superior performance in terms of precision and efficiency. Future work will explore machine learning integration for predictive adjustments and optimization for large-scale industrial applications.

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