CAD-based automated robot trajectory planning for spray painting of free-form surfaces

Article *in* Industrial Robot · October 2002

DOI: 10.1108/01439910210440237

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Research article

CAD-based automated robot trajectory planning for spray painting of free-form surfaces

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Keywords

CAD, Robots, Painting

Abstract

Automatic trajectory generation for spray painting is highly desirable for today's automotive manufacturing. Generating paint gun trajectories for free-form surfaces to satisfy paint thickness requirements is still highly challenging due to the complex geometry of free-form surfaces. In this paper, a CAD-guided paint gun trajectory generation system for free-form surfaces has been developed. The system utilizes the CAD information of a free-form surface to be painted and a paint gun model to generate a paint gun trajectory to satisfy the paint thickness requirements. A paint thickness verification method is also provided to verify the generated trajectories. The simulation results have shown that the trajectory generation system achieves satisfactory performance. This trajectory generation system can also be applied to generate trajectories for many other CAD-guided robot trajectory planning applications.

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Industrial Robot: An International Journal
Volume 29 · Number 5 · 2002 · pp. 426–433
© MCB UP Limited · ISSN 0143-991X
DOI 10.1108/01439910210440237

Introduction

Spray painting is an important process in the manufacture of many durable products, such as automobiles, furniture and appliances. The uniformity of paint thickness on a product can strongly influence the quality of the product. Paint gun trajectory planning is critical to achieve the uniformity of paint thickness and has been an active research area for many years. Currently, there are two trajectory generation methods: typical teaching method and automatic trajectory generation method.

Typical teaching method is tedious, time-consuming, and the paint thickness is dependent on the operator's skill. Automated generation of paint gun trajectories can not only be time-efficient and minimize paint waste and process time, but can also achieve optimal paint thickness.

Automated trajectory generation has been widely studied. Suh *et al.* (1991) developed an Automatic Trajectory Planning System (ATPS) for spray painting robots. Their method is based on approximating the original free-form surface as a number of individual small planes. The bicubic B-spline algorithm was applied to generate the geometric model of surfaces. Their simulation showed over- and under-painted areas on a painted surface. Asakawa and Takeuchi (1997) developed a teachingless path generation method using the parametric surface to paint a car bumper. The paint thickness was 13 to 28μm while the average thickness was 17.7μm. In addition, they did not report how to find the spray overlap percentage and the gun velocity. By dividing a compound surface into several patches, Sheng *et al.* (2000) developed an algorithm to cover a compound surface. Although their algorithm can guarantee the coverage of a compound surface, the problem of paint thickness is not addressed. Antonio (1994) developed a framework for optimal trajectory planning to deal with the optimal paint thickness problem. However, the paint gun path and the paint deposition rate must be specified. In practice, it is very difficult to get the paint deposition rate for a free-form surface. Alternatively, some commercial software, such as ROBCAD™/Paint

The authors would like to acknowledge National Science Foundation for its partial support to this work under Grant IIS-9796300, IIS-9796287, EIA-9911077 and DMI 0115355.

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(Tecnomatix, 1999), can generate paint gun trajectories and simulate the painting process. However, the gun paths are obtained in an interactive way between the user and ROBCAD™/Paint, which is inefficient and error-prone.

Achieving uniform paint thickness for free-form surfaces is still a challenging research topic. The complex geometry of free-form surfaces is one of the main reasons. To achieve uniform paint thickness for free-form surfaces, the spatial gun path, gun direction and velocity should be planned based on the local geometry of the free-form surface. In this paper, a new trajectory generation scheme for free-form surfaces is developed such that the paint thickness requirements are satisfied. A car door and hood, which are free-form surfaces, are used to test the scheme. Simulations are performed to verify the generated trajectories. The results of simulations have shown that the trajectory generation system achieves satisfactory performance.

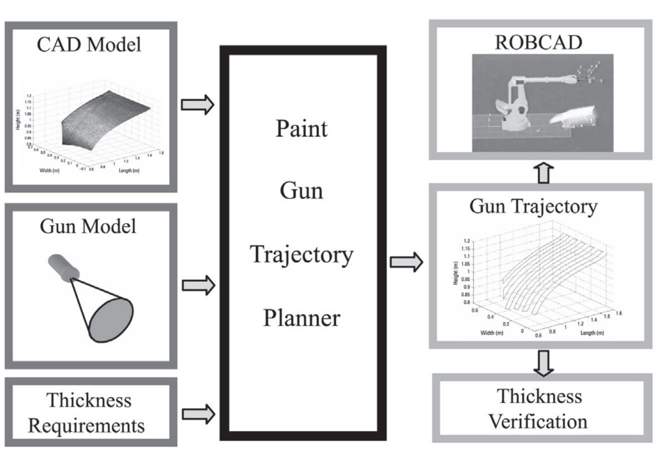
Task conditions and requirements

A general framework for the automated CAD-based paint gun trajectory generation system is shown in Figure 1.

First, a gun trajectory planner develops a paint gun trajectory for a free-form surface on the basis of:

- a CAD model of the free-form surface;
- a gun model;
- thickness requirements; and
- some assumptions (gun standoff, the flow rate of paint, the atomizing pressure and solvent concentration are fixed).

Figure 1 CAD-based paint gun trajectory planning systems



The trajectory is then loaded into *ROBOCAD*™/Paint for simulation and input to a verification module to verify paint thickness for the free-form surface. Finally, the control commands are downloaded into a specific controller to drive painting robots to paint the free-form surface.

Parametric surfaces, such as B-Spline surface, Bezier surface and NURBS surface are popular in CAD modeling. These surfaces generally satisfy certain continuity and smoothness constraint, and most of them have small areas and low curvature. Although parametric representation can accurately model complex surfaces, its local nature results in difficulties for trajectory planning (Lai and Wang, 1994). To obtain time-efficient paint gun trajectories and sufficiently utilize the workspace of the painting robot, it is desirable to plan long-run paint gun trajectories. A triangular approximation of a free-form surface, which is non-parametric, serves this goal. The error introduced in rendering a free-form surface into triangles can be decreased by reducing the size of triangles. Figure 2 shows the triangular approximation of half a car hood used to test the trajectory generation algorithm.

The paint gun is modeled as a spray cone shown in Figure 3. R is the spray radius and ϕ is the fan angle and h is the gun standoff. The position and orientation of the paint gun tip with respect to a fixed Cartesian reference frame can be specified as to the gun tip position and the roll, pitch and yaw angles (Fu and Gonzalez, 1994). The Z axis of the tool frame (gun tip frame) is defined as the gun direction. Once the gun direction is determined, the Z-axis of the tool frame is defined. The X-axis of the tool frame is the gun moving direction.

To generate a paint gun trajectory requires the knowledge of paint deposition rate. The profile of the paint deposition rate can be roughly approximated by parabolic curves (Persoons and Van Brussel, 1993). A typical paint deposition rate profile is shown in Figure 4. The profile is important in determining the overlap percentage of two neighbor paths as well as the gun velocity to achieve uniform paint thickness. The paint deposition rate depends on many parameters, such as the gun standoff, the flow rate of paint, the atomizing pressure and solvent concentration. It is important to keep the gun standoff fixed during the painting process (Suh *et al.*, 1991;

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Figure 2 The triangular approximation of half a car hood

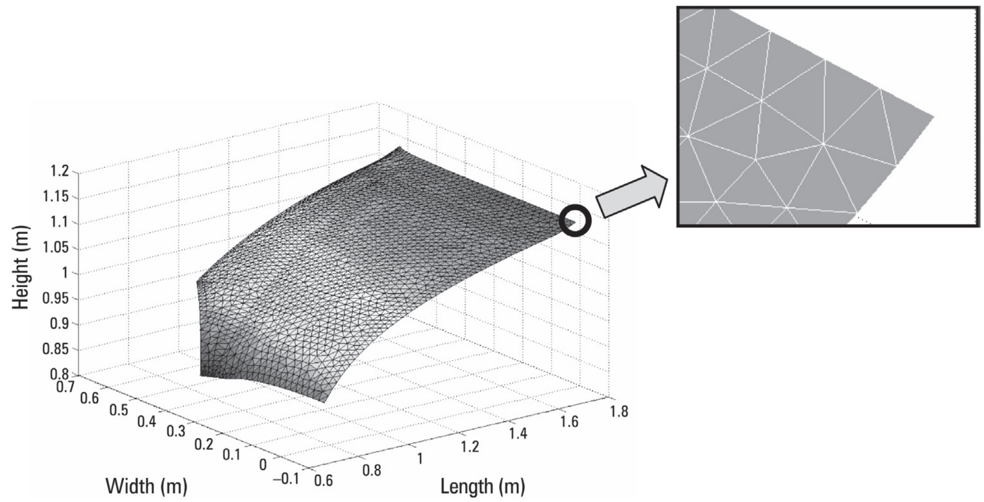
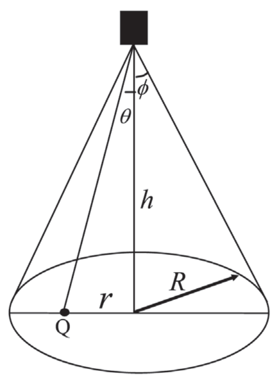


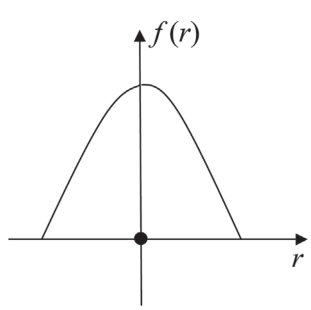
Figure 3 The paint gun model



Asakawa and Takeuchi, 1997). Here the flow rate of paint, the atomizing pressure and solvent concentration are assumed to be fixed (Antonio, 1994) too. Therefore, the paint deposition rate is only related to the distance *r*, namely, the deposition rate can be expressed as a function of *r*,*f(r)*.

After a free-form surface is painted, the average thickness of the surface is required to be q_d and the thickness deviation is less than or equal to the required thickness deviation Δq_d. Assume that a plane is painted and the

Figure 4 The paint deposition rate profile

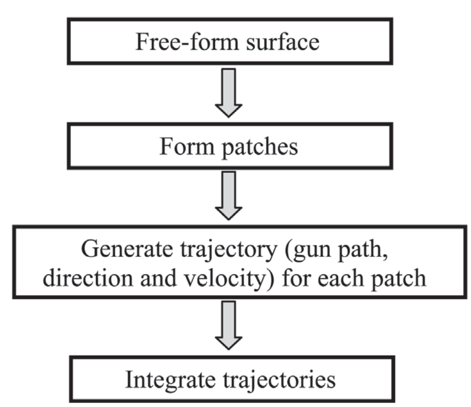


thickness is optimized using a given gun deposition rate, the maximum and minimum paint thickness can be calculated (Chen *et al.*, forthcoming). Then a threshold angle β_{th} can be calculated using the thickness requirements. Therefore, if the maximum deviation angle of a free-form surface is less than the threshold angle β_{th}, the paint thickness of the free-form surface can satisfy the thickness requirements. The maximum deviation angle is the maximum angle between the normal of the free-form surface and the opposite spray gun direction.

CAD-based trajectory generation algorithm

The gun trajectory planner is the core of the gun trajectory generation system for free-form surfaces. Figure 5 shows how the planner works. After reading a CAD model of a free-form surface, the free-form surface is split into

Figure 5 Gun trajectory planner



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patches to deal with the local geometry of the free-form surface. Then the gun trajectory for each patch, including the gun path and direction and velocity, will be generated based on the thickness requirements, the gun model and assumptions. Finally, the generated trajectories are integrated to form an overall trajectory for the free-form surface.

Patch forming algorithm

During spray painting, a free-form surface is covered only by one spray cone at each time instant. The patch forming method is based on minimizing the maximum deviation angle of spray cones. To optimize the paint thickness on a free-form surface, the maximum deviation angle of every spray cone has to be minimized. Assume that there are N triangles which are covered by a spray cone, the spray cone is projected to a plane. The normal of the plane must be a vector which minimizes the maximum deviation angle of the spray cone. A deviation angle is introduced to describe the relationship between the normal of the plane and the normals of the N triangles. A deviation angle is the angle between the normal of a triangle and that of the plane. Here a search method is used to find a normal of the plane (Figure 6).

First, two triangles, A and B, whose normals have the maximum angle, are found. The average of the two normals is used as an initial normal of the plane. The deviation angle between the normal of A (or B) and the initial normal of the plane is computed as an initial maximum deviation angle. Then the deviation angles are found for other triangles. If there are some deviation angles greater than the initial maximum deviation angle, the normal of the plane is re-calculated using the normals of A, B and a new triangle, C, whose deviation angle is the maximum. The initial maximum deviation angle is updated. The process continues until the deviation angles are less than the initial maximum deviation angle. Then the normal of the plane is obtained and the maximum deviation angle for the spray cone is minimized.

To satisfy the paint thickness requirements, the maximum deviation angle of a generated patch should be less than the threshold angle. Neighbor relationship of triangles is applied here to form patches (Figure 7).

A seed triangle is arbitrarily chosen as the first triangle of a patch. Before adding a new neighbor triangle, a maximum deviation angle in a spray cone, centered at the center of the seed, is calculated. If the maximum deviation angle is less than the threshold angle, the triangle is added into the patch. Otherwise, it is discarded. After all triangles are found, they are taken as seeds and new triangles are added into the patch. The process is repeated until no more neighbor triangles can be added into the patch. Then the first patch is found. If there are remaining triangles, a seed is chosen from the remaining triangles and the patch forming method is applied again to form a new patch. The process for patch forming continues until no triangles are left. Then the free-form surface is divided into a patch or several patches.

Trajectory generation algorithm

A gun trajectory includes a gun path, direction and velocity. A bounding box method (Sheng *et al.*, 2000) is adopted here to generate the gun path. For a given patch, a bounding box of the patch is a box which contains the whole patch exactly. Figure 8 shows a patch and its bounding box.

The front direction of the bounding box is the opposite direction of the area-weighted average normal direction of the patch (Sheng *et al.*, 2000). A plane, which is perpendicular to the right and goes through the center of the bounding box, cuts the patch. An intersection line is created. By dividing the intersection

Figure 6 The algorithm to generate the normal of a plane

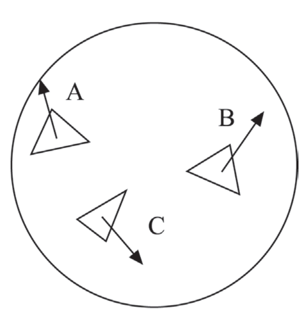

Figure 7 The patch forming algorithm: a neighbor triangle A is added to a patch

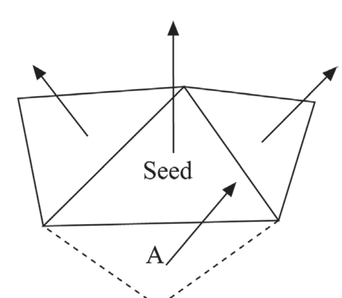

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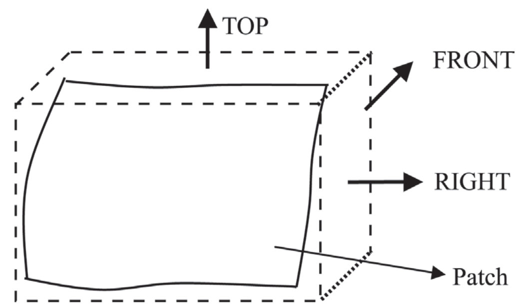
Figure 8 A patch and its bounding box



line using an overlap distance calculated from the overlap percentage, a series of points are generated. A series of cutting planes, which pass through the points and are perpendicular to the normals of the triangles which the points belong to, cut the patch. The generated intersection lines form a gun path. Therefore, the trajectory generation problem becomes how to find an overlap percentage and gun velocity since the gun orientation can be determined using the gun direction generation method.

The gun velocity and the overlap percentage are determined by optimizing the painting process of a plane. Figure 9 shows paint accumulation of a point w on a plane while a paint gun moves.

For each point on the plane, there are at most two neighbor paths which contribute to the paint thickness of the point. To find an optimal velocity and an overlap percentage, the mean square error of the thickness deviation from the required thickness must be minimized (Chen *et al.,* forthcoming). After calculation, the velocity can be expressed as a function of the overlap distance for a given average thickness. Therefore, only an overlap distance is to be optimized. A golden section method (Rao, 1983) is adopted here to optimize the overlap distance and gun velocity by iteration.

Figure 10 shows part of a gun path, sample points and a spray cone. The distance

Figure 9 Paint accumulation of a point *w* on a plane while a paint gun moves

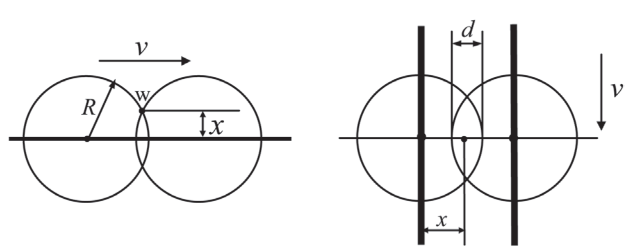
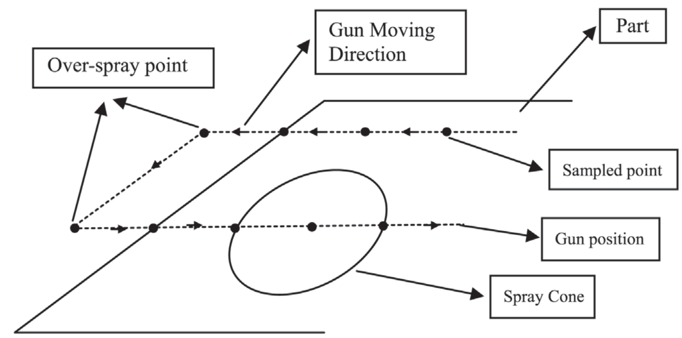


Figure 10 The gun positiion, sample points and a spray cone



between two sample points along the gun path can be chosen according to the computing time and paint thickness variation requirements (here it is the radius of a spray cone). The over-spray points are used to deal with the insufficient thickness problem occurring at the edges of a part.

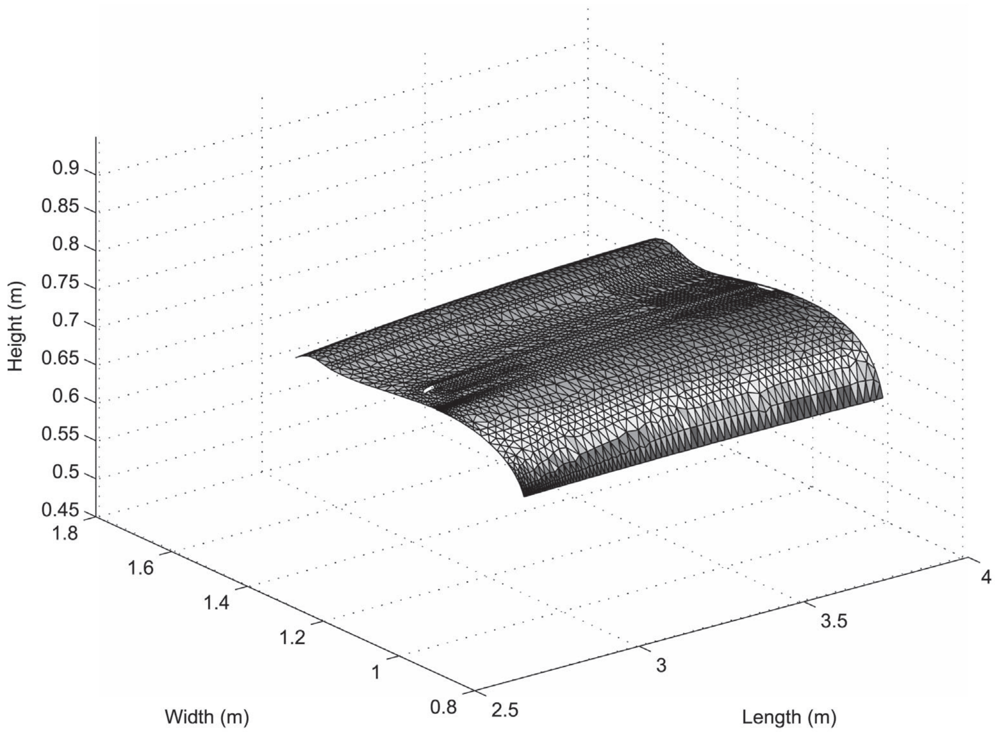
To achieve uniform paint thickness, the gun direction has to be determined based on the local geometry of a free-form surface. The gun direction generation method is similar to the generation of the normal of a plane in Patch Forming Algorithm, except that the gun direction is the opposite direction of the normal of the plane. For each gun center with the determined gun direction, a local maximum deviation angle is found. For a gun path composed by a series of gun center points, a global maximum deviation angle is defined. The global maximum deviation angle is the maximum value of all maximum deviation angles. According to the patch forming method, the global maximum deviation angle must be less than the threshold angle β_{th}. Therefore, the paint thickness of the free-form surface can satisfy the thickness requirements without considering the gun standoff variation.

Implementation and simulation

Implementation and trajectory verification

The algorithm was implemented in C++ on a PC with Pentium III 860MHZ processor. Two parts, a car hood and door, shown in Figures 2 and 11 respectively, were used to test the algorithm. The triangular approximation was exported from GID (http://gid.cimne.upc.es/) with an error tolerance of 2mm. The car hood and door have 3,320 and 4,853 triangles respectively.

Figure 11 The triangular approximation of a car door



Assume that the required average thickness is $q_d = 50\mu$m and the thickness deviation percentage is 35 percent. The spray radius R = 50mm. The paint deposition rate is $f(r) = (R^2 - r^2)/10\mu$m/s. After optimization, the gun velocity and the overlap distance were calculated as: ν =323.3mm/s and d = 39.2mm. The threshold is 45.6°. Using the patch forming method, the car hood and door form only one patch respectively.

Once the overlap distance is determined, the gun paths were generated using the bounding box method. The generated gun paths are shown in Figures 12 and 13 for the car hood and door respectively.

Figure 12 The generated path for a car hood

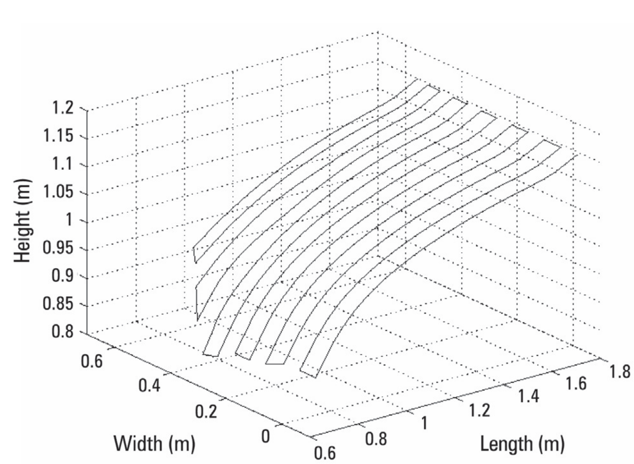
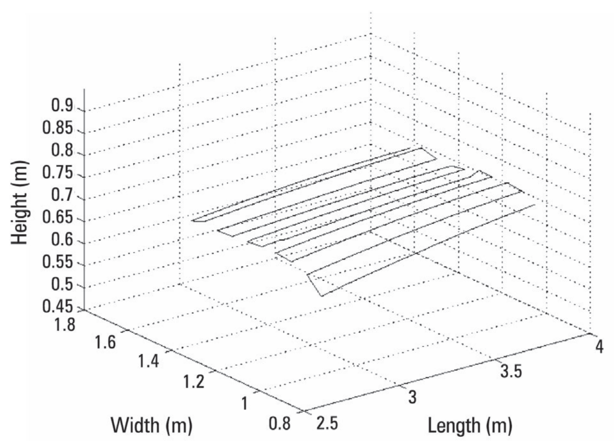


Figure 13 The generated path for a car door



The gun direction was found for each sample point and the global maximum deviation angles were calculated for each part respectively. The number of triangles, global maximum deviation angle and painting time for each part are shown in Table I.

The global maximum deviation angles β in Table I are less than the threshold angle β_{th} for the two parts. This means the generated gun trajectories satisfy the thickness requirements.

Verifications were performed to verify the paint thickness for the generated trajectories. After simulation, the paint thickness of randomly chosen points on the car hood and

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Table I The calculated parameters

Part	Triangles	β	Painting time
Hood	3,320	13.1°	43.0s
Door	4,853	44.6°	34.4s

door were computed and shown in Figures 14 and 15 respectively. The average, maximum, and minimum paint thickness were calculated (Table II). The simulation results show that the average, maximum and minimum thickness for the car hood and door satisfy the thickness requirements. The trajectories generated using the new algorithm can achieve required paint thickness.

ROBCAD simulation

The generated spray gun trajectories were also exported to ROBCAD™/Paint to simulate the painting process. The robot model used is an ABB irb6K30-75. The work-cell setup is shown in Figure 16(a) and part of gun path in Figure 16(b). The car hood and door after painting are shown in Figure 17. The color shows the paint thickness. The simulation results showed that the generated trajectories can be applied to paint free-form surfaces to achieve the given thickness requirements.

Figure 14 The simulation result of paint thickness for a car hood

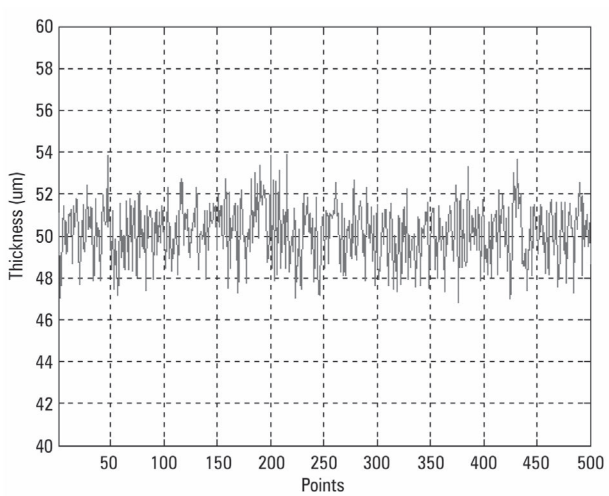


Figure 15 The simulation result of paint thickness for a car door

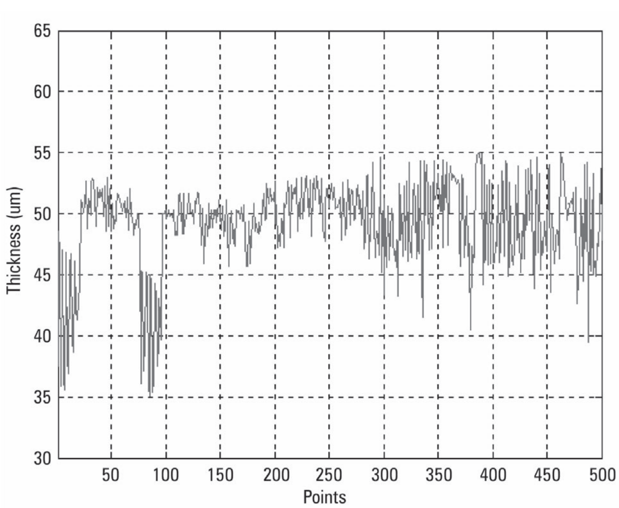


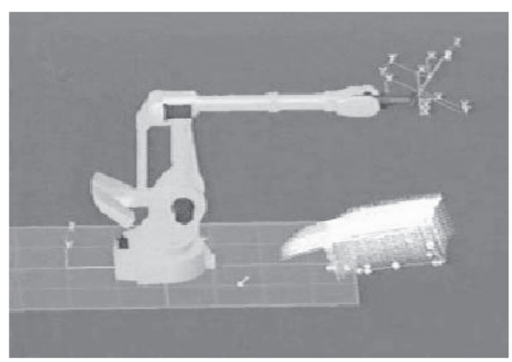
Table II The simulation results

Part	Average thickness $\bar{q}(\mu m)$	Maximum thickness $q_{\max}(\mu m)$	Minimum thickness $q_{\min}(\mu m)$
Hood	50.0	53.9	46.0
Door	49.1	55.0	35.1

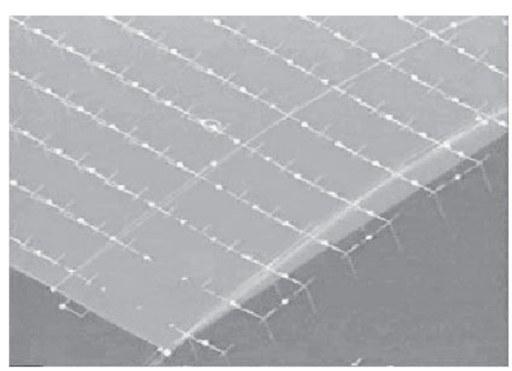
Comparison with other methods

Simulations with fixed gun direction (Case 2) were also performed to show the advantages of the gun direction generation method proposed in this paper (Case 1). The fixed gun direction was determined on the basis of the gun direction search method for the whole car hood. So was the fixed gun direction of the car door. The results are shown in Table III.

Figure 16 (a) The ROBCAD simulation system; (b) Part of gun path



(a)



(b)

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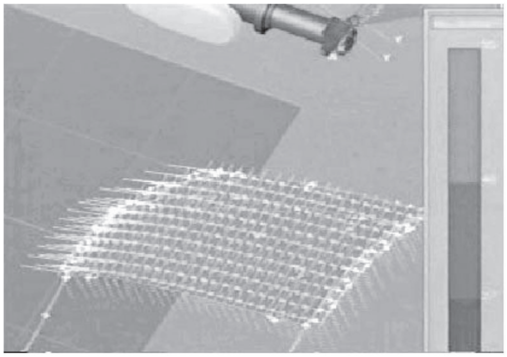
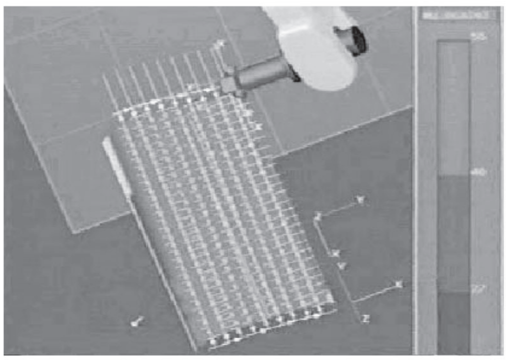
Figure 17 (a) Painted car hood; (b) Painted car door



(a)



(b)

The global maximum deviation angle for each part in Case 1 is much smaller than that in Case 2. The deviations of the average thickness to the required thickness are 0μm and 0.9μm for the car hood and door respectively for Case 1. However they are 1.1μm and 2.4μm for Case 2. The minimum thickness is 46μm and 35.1μm for the car hood and door respectively for Case 1, 40.3μm and 24.3μm respectively for Case 2. The results show that the gun directions generated on the basis of the local geometry of free-form surfaces achieved better paint thickness.

The thickness deviation percentage presented by Asakawa and Takeuchi (1997) is more than 58 percent. For our results, the thickness deviation percentage is less than 35 percent. For the car hood, a much better result (8 percent) is achieved. Although the results presented by Suh *et al.* (1991) are 20 percent, the over- and under-painted areas were not included. Also the paint distribution rate is a constant instead of a parabolic curve.

Table III The simulation results for fixed gun directions

Part	Average thickness $\bar{q}'(\mu m)$	Maximum thickness $q'_{\max}(\mu m)$	Minimum thickness $q'_{\min}(\mu m)$	β'
Hood	48.9	54.3	40.3	32.8°
Door	47.6	54.6	24.3	64.2°

Conclusion

A new CAD-based paint gun trajectory generation system for free-form surfaces has been developed. Simulation results showed that the paint thickness requirements are satisfied. Therefore, this method can be used as an off-line trajectory generation system for free-form surfaces for spray painting robots. Also this trajectory generation method can be applied to many other CAD-guided robot trajectory planning applications, such as spray coating and spray forming. Our future work will focus on the trajectory integration.

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