QUALITY CONTROL PARAMETERS FOR ROBOTIC BRIDGE PAINTING

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ABSTRACT: To protect a steel bridge from corrosion, periodic painting is needed. Bridge painting operations are dangerous and hazardous to human health. A robotic bridge painting system is being developed to replace the human being. One major problem with robotic bridge painting is how to achieve the specified coating quality, which includes two aspects: (1) the coating thickness; and (2) the coating appearance. To ensure quality of the robotic bridge painting, the writers have investigated: (1) the parameters that affect the coating thickness and appearance; (2) the values of the parameters to achieve the required thickness and appearance for the robotic painting; and (3) the thickness distribution functions of the bridge painting under various conditions. The specified painting quality can be achieved by using the results of this study to set up and control the robotic bridge painting system.

INTRODUCTION

There are two reasons for using paint. The first, and oldest reason, is to beautify and enhance the appearance of an object. The second reason is to protect an object from its environment or the wear inflicted through use. The technology involved in the preparation and use of anticorrosive coating systems for bridge structures was born in the middle of the nineteenth century (Hare 1987). The first iron bridge, the Wynch Bridge, was built over the River Tees in England in 1741 and was not painted; it collapsed some 60 years from corroded chains, thereby validating the need for protection (Ferguson 1976). The cast-iron bridge at Coalbrookdale in Shropshire, England was not painted when it was built in 1779; 9 years later it was coated with a bituminous varnish. Since then, it was painted many times and still exists today (Ferguson 1976).

Steel bridge-painting operations are dangerous and hazardous to human health. A typical painting operation involves sandblasting the bridge surface to remove old paint and rust, and then repainting it to protect the surface from the environment. Workers access the area using a scaffold or similar device. Heavy equipment and protective clothing for the workers are required. The protective clothing is very hot, especially in warmer climates. As a result, workers experience rapid fatigue and must break at regular intervals to regain their strength. Workers are exposed not only to the harmful paint components but also to the risk of falling. According to the National Safety Council, 70% of all series injuries to coating workers are caused by falls (Smith 1990). Strenuous working conditions and worker fatigue contribute to an inconsistent quality of the applied paint. Thus, bridge painting is well suited for robotic automation.

The development of a robotic paint system is justified by the potential improvements in safety, quality, and productivity. With a robotic bridge painting system, human operators can be removed from the dangerous work location under the bridge deck of a safe place on top of the deck. There they can operate the robotic system safely. In addition, the painting quality might improve, because the robotic system does not suffer from exhaustion or fatigue. Consistent, high quality painting can be achieved by protecting the worker from hazardous environments, productivity is effected since workers do not need to wear the protective clothing.

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ROBOTIC PAINTING SYSTEMS IN CONSTRUCTION

Development of robotic systems for construction application has advanced dramatically over the past few years (Thompson 1994). Robotic systems were initially developed to reduce labor requirements, shorten construction time, reduce costs, and improve quality. Benefits such as the elimination of dangerous work areas for employees and conformance to standards of the Environment Protection Agency, the Toxic Substance Control Act, and the Occupational Safety and Health Administration have improved the worker's environment and morale (Thompson 1994).

Since the benefits of robotic applications are significant, researchers have conducted studies to determine which construction tasks might be suitable for robotic applications. Most of these studies have concluded that the application of surface coatings is very suitable for robotics (Skibniewski and Hendrickson 1988). Tasks of this type lend themselves to robot application, because they are labor intensive, require relatively little obstacle avoidance, and consist of simple, repetitive motions.

Robotic surface painting research has been carried out by several universities and industries throughout the world. Kumagai Gumi, Ltd. of Tokyo, Japan has developed the ''FR-1'' surface-finishing robot for walls (Tokioka et al. 1989). The FR-1 is an independent motion unit to which various process modules can be attached for blasting, painting, and inspection. The machine adheres to the wall by developing a vacuum under a hood on the motion unit. Motion is controlled by cables passing through pulleys mounted on the roof. The process is continuous, moving vertically on the wall, and requires a crew of three workers for operation. The robot is capable of covering from 45–50 m^2/h.

Researchers at the University of Texas at Austin have successfully developed a prototype automated machine system to blast and paint large diameter steel storage tanks common in the petrochemical industry (Warne 1994). The prototype design, the Automated Surface Finishing System, was completed in 1990. The machine can sandblast and paint a section of a large storage tank at a rate of approximately 278-m^2/h. At this productivity level, the system and its two operators replace two, three-man finished crews.

The researchers at the North Carolina State University developed a Robotic Bridge Paint Removal System in 1993 (Moon and Bernold 1995). The purpose of the system is to provide a safe working environment during bridge paint removal operation. The first prototype was successfully demonstrated in August 1994. The system can be improved and expanded to perform bridge painting operations.

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

A major aspect of robotic bridge painting is how to achieve the specified quality that includes two elements: (1) the coating

J. Constr. Eng. Manage., 2001, 127(2): 142-148

thickness; and (2) the coating appearance. Paint on steel bridge is applied in a series of coats ranging from 1–6 mils; one mil is equal to 0.025 mm (0.001 in.). The coating thickness is an important quality control parameter in steel painting operations (*Participant Manual* 1985). Each project specifies its own level of quality, which is the minimum thickness that must be satisfied. For example, the North Carolina Department of Transportation (NCDOT) requires four layers of coating on the steel bridge surfaces; the minimum thickness of each layer is 1.5 mils.

Appearance is another important quality control parameter in the steel bridge painting operation. An appearance check ensures that the surface will not corrode more rapidly than expected. Common appearance failures include: (1) edge failure; (2) dry spray; (3) holidays/pinholes; and (4) runs/sags (*Participant Manual* 1985).

Application methods commonly used for steel bridge painting include: (1) conventional air spray; (2) airless spray; and (3) air-assisted airless spray. Conventional air spray uses compressed air to atomize paint. The tiny atomized paint drops are applied to the surface. For airless spray, the paint is pumped at high pressure through a small orifice, which results in atomization without the use of pressurized air. The air-assisted airless spray uses the normal airless spray equipment with low-pressure air added to help atomization. The finer the atomization, the higher the quality of paint finish will be achieved. Air-assisted airless spray also reduces overspray and paint injection danger, because the fluid pressure is relatively low. For this research, the air-assisted airless spray method was used, because it delivers the best quality of spray paint.

For air-assisted airless spray, the coating thickness distribution is not even along the vertical section of a spray pass. The thickness reaches the highest level at the center of the vertical section and decrease towards up and low edges. A thickness distribution function (a mathematical equation) may be used to describe the thickness distribution along the vertical section for one spray pass.

To use the robotic painting system on a steel bridge surface, there is a need to determine the spray gun moving path that should cover the surface. One possible path is the staircase path (Chang et al. 1991). This requires making parallel passes on the surface of the steel bridge until the entire surface is covered, as shown in Fig. 1. In this research, the staircase path was used, because it is simple and easily performed. Two major issues need to be addressed before implementing the staircase path. One is to determine the spray painting effective width, which is a section of the overall spray painting width on which no single thickness measurement is less than the specified thickness (e.g., 1.5 mils). The second issue is the overlap between the two parallel passes. The overlap should be large enough to achieve the required thickness and appearance between the two parallel passes. The effective width and overlap can be determined if the thickness distribution function is known.

The objectives of the research are to investigate the following aspects of air-assisted airless spray which have not been conducted in the previous research including: (1) the parameters that affect the coating thickness and appearance; (2) the values of these parameters to achieve the required thickness and appearance; and (3) the coating thickness distribution functions under various conditions.

PARAMETERS AFFECTING THE ROBOTIC BRIDGE PAINTING

The process planning parameters of bridge painting operations were studied first to determine whether or not the parameters affect the thickness and appearance. Process planning is the fundamental step needed to sequence a task and to describe how a particular task will be accomplished (Chang et al. 1991). For the robotic bridge painting operations, process planning is the function that establishes what parameters are needed to paint a piece of steel bridge surface and to achieve the specified quality.

After reviewing the literature and interviewing the painting experts, a series of process planning parameters for painting operations were generated. To paint a steel bridge surface, the parameters relating to set up of the spray gun should include: (1) spray gun angle; (2) air pressure; (3) fluid pressure; and (4) distance between the spray gun and the steel surface. The spray gun angle is the angle between the central axis of the spray gun and the surface that needs to be painted. To reach different areas on the steel bridge, the gun should be set up from different angles.

The air and fluid pressures under which the paint is atomized are perhaps the most important painting process control parameters. Any change in these pressures will affect the paint pattern and the degree of atomization. To have the proper atomization and perform the painting operation safely, the air pressure should be 68.9–137.8 kPa (10–20 psi), and the fluid pressure should be 2,067–3,445 kPa (300–500 psi).

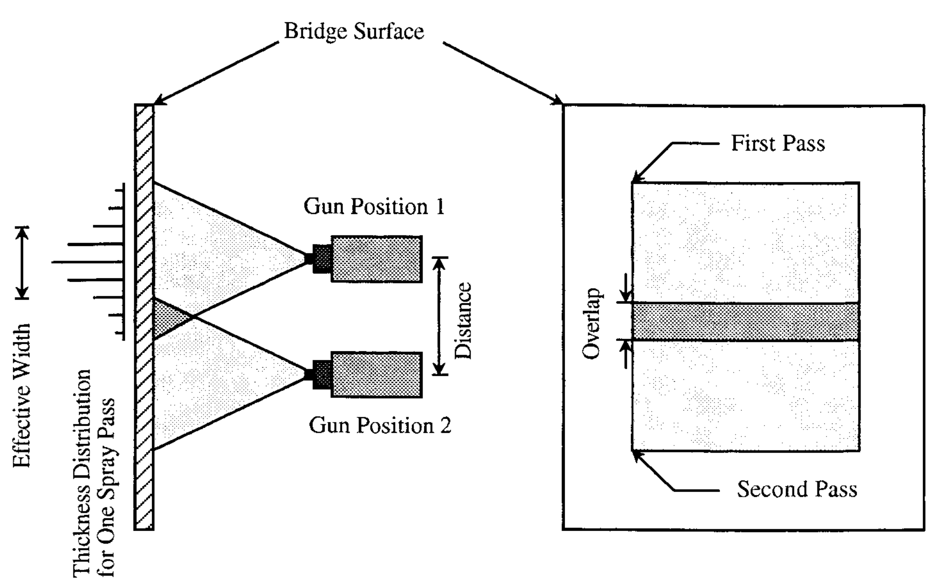

FIG. 1. Staircase Movement Path for Spray Gun

J. Constr. Eng. Manage., 2001, 127(2): 142-148

If the distance is too small, the spray painting may produce an uneven finish. If the distance is too large, the spray droplets may dry before they reach the surface. Experts recommend that the distance should be 20.3–30.5 cm (8–12 in.) between the gun and the steel surface.

The spray gun path planning that describes how to move the gun must be decided during the process planning. Two parameters—the moving speed and the moving path—describe the movement of the gun. If the gun moves too quickly, the paint reaching the steel surface may not be thick enough. If the gun moves too slowly, running will occur. Experts suggest that the speed should be 25.4–35.6 cm/s (10–14 in./s). The moving path is the staircase path, which was discussed earlier. If the area of steel surface, the spray painting effective width, and required overlap are known, then the number of spray passes to cover the steel surface area can be determined.

FEATURE NOMENCLATURE FOR STEEL BRIDGES

The concept of ''feature'' is used in many fields. However, a unified definition of feature does not exist (Fu et al. 1993). There are form features (also called shape features or geometric features), design features, and manufacturing features. The definition of a feature is application-dependent. In this research, features are defined as meaningful representation of geometry that can be used to reason about the spray painting process. This means that a set of process planning parameters on a given bridge feature are needed to set up and move the spray gun. Each feature corresponds to a set of parameters that include: (1) the spray gun angle; (2) the air pressure; (3) the fluid pressure; (4) the distance; and (5) the moving speed.

To create a ''catalogue'' of features, bridge design drawings provided by the NCDOT Bridge Maintenance Department were studied. The highway steel bridge structure was organized into four basic components: (1) beam (or girder); (2) bracing; (3) bearing; and (4) connections. In cooperation with the engineers at NCDOT Bridge Maintenance Department, basic features for each of the four components were developed. Examples of the I-beam features are shown in Fig. 2. Different features have different parameter values, which can be investigated through lab experiments.

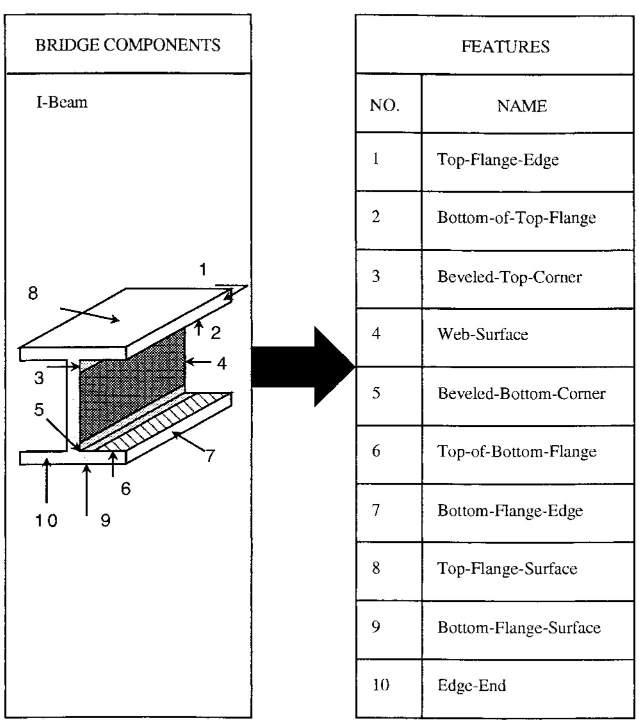

FIG. 2. Feature Characterization for Bridge I-Beam

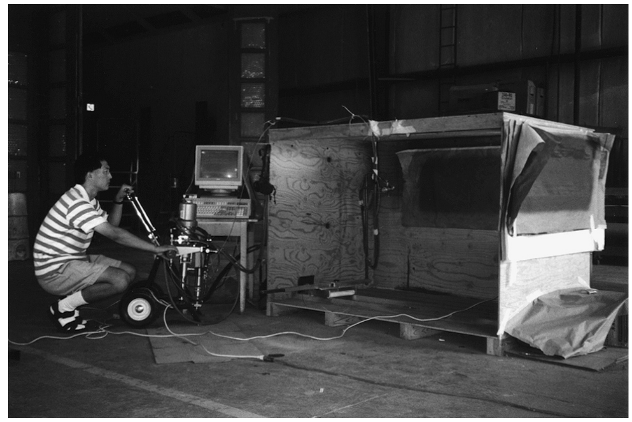

FIG. 3. Experimental Facilities Layout

LAB EXPERIMENTS ON WEB-SURFACE FEATURE

Factorial experiments were conducted to investigate: (1) the values of the process planning parameters for the bridge features; and (2) the thickness distribution functions. A factorial experiment is one in which responses are observed for every combination of factor levels (Freund et al. 1993). In this research, the responses were the coating thickness and appearance. The factors were the spray gun angle, the air pressure, the fluid pressure, the distance, and the moving speed. The various settings of these factors in the experiments are called levels. The experimental apparatus includes: (1) a Graco AA3000 automatic air-assisted airless spray gun; (2) a Graco pump; (3) a stepper motor; (4) a Centroid motion controller; and (5) a personal computer. Fig. 3 shows the experimental facilities layout.

Data Collection

The Steel Structures Painting Manual, Volume 2, specifies the procedure for measuring the coating thickness (*Painting Manual* 1994). First, five separate spots spaced evenly over each 9.3 m^2 (100 ft^2) of area were randomly selected. The diameter of the spot was approximately 2.54 cm (1 in.). Three readings were made on each spot. The average of the three readings was the spot measurement reading. Second, the average of five spot measurements for each 9.3 m^2 area should not be less than the specified thickness. Third, no single spot measurement in any 9.3 m^2 areas should be less than 80% of the specified thickness.

In the lab experiments, steel strips 7.6 cm $\times$ 50.8 cm (3 in. $\times$ 20 in.) were used as substitutes for the bridge features. The area of a strip was much less than 9.3 m^2. Also, to develop the thickness distribution functions, the data was collected in a way that was easy for data analysis. As a result, the measurement procedure was modified as follows: (1) select one vertical section around the middle of steel strip surface (considered sufficient because the spray gun manufacturer guarantees that coating thickness is consistent at a given horizontal level); (2) choose measurement points that are spaced evenly over the vertical section, so the distance between the points is 2.54 cm (1 in.); (3) take three measurements around each point, the average of which is the point measurement; and (4) make sure no single spot measurement is less than 80% of the specified thickness. The MIKROTEST coating thickness gauge, made by Elektro-Physik, Inc., was used to measure the thickness.

If there were no appearance failures, such as edge fail, dry spray, and run, the appearance was accepted, and value 1 was assigned to appearance. Otherwise, the appearance was rejected and value 0 was assigned to appearance.

J. Constr. Eng. Manage., 2001, 127(2): 142-148

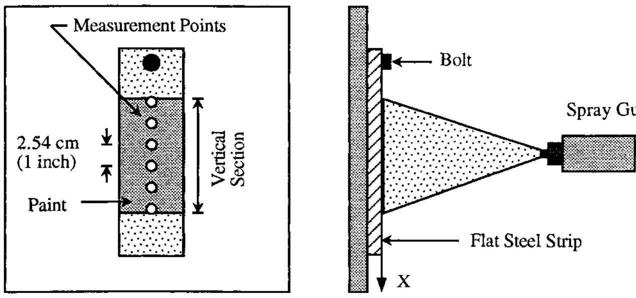

FIG. 4. Experiment Setting for "Web-Surface" Feature

Experiment Phase One

In Phase One, the spray gun was set perpendicular to the steel strip surface. The factors were the air pressure, the fluid pressure, the distance, and the speed. The air pressure, the distance, and the speed had two factor levels, which were 68.9 and 137.8 kPa (10 and 20 psi), 20.3 and 30.5 cm (8 and 12 in.), and 25.4 and 35.6 cm/s (10 and 14 in./s), respectively. The fluid pressure had three levels, which were 2,067, 2,756, and 3,445 kPa (300, 400, and 500 psi). The numbers of levels are determined based on the fact that significant observations can be made at each factor level. The set of factor levels consisted of all combinations of these levels, which were 24 ($2 \times 2 \times 2 \times 3$). Fig. 4 shows the experiment setting for phase one.

Data Analyses for Phase One

Data analysis was conducted using the multiple linear regression method (the least-squares approach). Results of the data analysis indicated that the regression model for the thickness is

$$Y_t = 2.46 + 0.0002X_1 - 0.0013X_2 - 0.022X_3 - 0.027X_4 \quad (1)$$

where Y_t = coating thickness; X_1 = fluid pressure; X_2 = air pressure; X_3 = distance; and X_4 = moving speed. Since the coating appearance was acceptable for all the experiments, there was no need to perform the analysis on the appearance (same case for the rest of the experiments described in this paper). There are eight combinations (out of 24 tested) that achieve the minimum thickness of 1.5 mils (measured thickness). Using (1), the predicted thickness with 95% level of confidence for each of the eight combinations was also calculated. The results—measured thickness and predicted thickness—are shown in Table 1. There was a consensus that a probability of 95% gave a good indication of the overall effectiveness of an operation in the construction industry (Oglesby et al. 1989).

The multiple coefficient of determination R^2 was 0.89 for the thickness model; $R^2 = 0$ implied a complete lack of fit of the model to the data; and $R^2 = 1$ meant a perfect fit, with the model passing through every data point. In general, the larger the value of R^2, the better the model fit the data.

Although there were eight (out of 24) combinations that could be selected to meet the 1.5 mils thickness requirement, the writers recommended that the number three setting in which the air pressure, the fluid pressure, the distance, and the moving speed were set at 137.8 kPa (20 psi), 3,445 kPa (500 psi), 30.5 cm (12 in.), and 25.4 cm/s (10 in./s), respectively, should be used. For this setting, the lower bound (lower 95% in Table 1) of the thickness was 1.5 mils, which was the target number for this research.

Number three setting was repeated twice to determine the thickness distribution function. The method was suggested by the painting experts and used through all experiments. The main reason for repetitions were to estimate the variance. Data analysis showed the three data sets fit a logistic density function, which was

$$Y = A_0 + A_1 * e^{-\lambda X}/(1 + e^{-\lambda X})^2 \quad (2)$$

where X = distance coordinate on the vertical section of the steel strip ($X = 0$ at the center of the spray pass); and Y = thickness for each X. Using the non-linear regression procedure in SAS software package, λ, A_0, and A_1 are calculated and equal to 0.37, -1.10, and 14.35, respectively. Thus, (2) can be written as follows:

$$Y = -1.10 + 14.35 * e^{(-0.37X)}/(1 + e^{(-0.37X)})^2 \quad (3)$$

Fig. 5 shows the measurement points and the curve of (3). Based on this function, the effective width for the single spray pass was 15.7 cm (6.2 in.), and the distance between the spray gun positions for the two parallel passes was 23.4 cm (9.2 in.) to achieve the required overlap. For N parallel passes (N = 1, 2, 3, . . .), the effective width of the area that the spray gun covers was $15.7 + 23.4*(N - 1)$ cm.

For robotic bridge painting operations, physical impediments may exist so that the spray gun may not be set at a 30.5 cm (12 in.) distance. If this occurs, the spray gun has to be set from different distances. From the spray painting operation standpoint, it would be convenient to keep the fluid and air pressures consistent, which means the air pressure and the fluid pressure are set at 137.8 kPa (20 psi) and 3,445 kPa (500 psi), respectively, throughout the entire operations. The speeds for different distances can be calculated using (1). Employing the same method, the thickness distribution functions of different distances were developed. Table 2 shows the settings for distance at 20.3 cm (8 in.), 25.4 cm (10 in.), and 30.5 cm (12 in.), and the values of the parameters λ, A_0, and A_1 for (2).

Experiment Phase Two

Obstacles may exist that prohibit the operator from setting the spray gun perpendicular to the steel surface. If this occurs, the spray gun has to be set up from different angles for the feature of "Web-Surface." The second phase of the experi-

TABLE 1. Predicted Thickness with 95% Level of Confidence

Experiment number (1)	Fluid pressure (kPa) (2)	Air pressure (kPa) (3)	Distance (cm) (4)	Speed (cm/s) (5)	Measured thickness (mil) (6)	Predicted thickness (mil) (7)	Lower 95% (mil) (8)	Upper 95% (mil) (9)
3	3,445	137.8	30.5	25.4	1.6	1.6	1.5	1.7
6	3,445	137.8	20.3	25.4	1.7	1.8	1.7	1.9
7	3,445	68.9	20.3	25.4	2.1	1.9	1.8	2.0
10	2,756	68.9	20.3	25.4	1.8	1.8	1.7	1.8
12	2,067	68.9	20.3	25.4	1.6	1.6	1.6	1.7
15	3,445	68.9	30.5	25.4	1.6	1.7	1.6	1.8
19	3,445	68.9	20.3	35.6	1.6	1.6	1.6	1.7
22	2,756	137.8	20.3	25.4	1.8	1.7	1.6	1.8

J. Constr. Eng. Manage., 2001, 127(2): 142-148

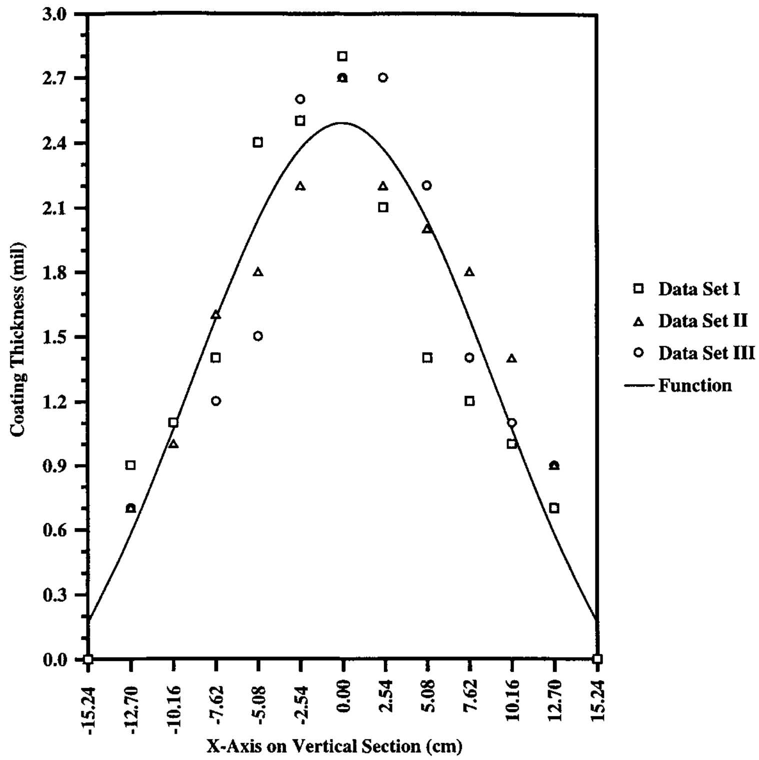

FIG. 5. Thickness Distribution on Vertical Section of "Web-Surface" Feature

TABLE 2. Spray Gun Settings and Parameters for Logistic Density Functions

Distance (cm) (1)	Speed (cm/s) (2)	Fluid pressure (kPa) (3)	Air pressure (kPa) (4)	A_0 (5)	A_1 (6)	λ (7)
20.3	35.6	3,445	137.8	−3.51	21.98	0.34
25.4	30.5	3,445	137.8	−1.32	11.96	0.32
30.5	25.4	3,445	137.8	−1.10	14.35	0.37

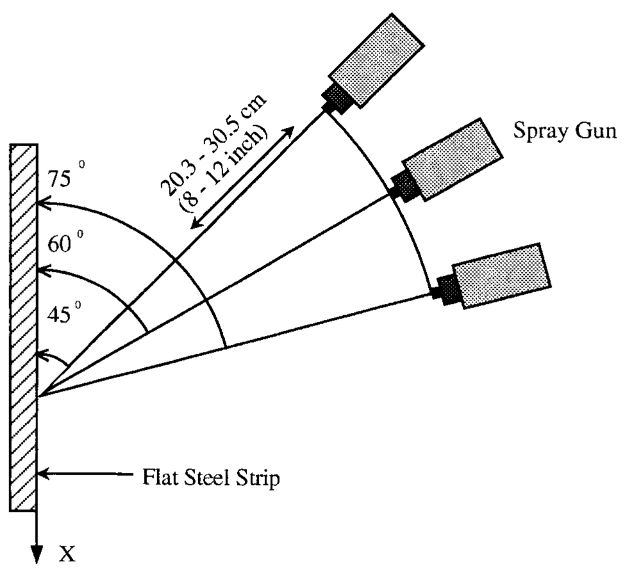

FIG. 6. Experiment Setting for "Web-Surface" Feature with Different Angles

ments was designed to investigate how the thickness distribution functions change for the different spray angles at various distances. The air pressure and the fluid pressure were set at 137.8 kPa (20 psi) and 3,445 kPa (500 psi), respectively. The distance had three factor levels, which were 20.3 cm (8 in.), 25.4 cm (10 in.), and 30.5 cm (12 in.). The spray gun angle had three factor levels, which were 45°, 60°, and 75° (Fig. 6). The spray gun can either face up or down. Experiment results showed there was no significant difference between facing up and down. The speed was 35.6 cm/s (14 in./s) for distance at 20.3 cm (8 in.), 30.5 cm/s (12 in./s) for distance at 25.4 cm (10 in.), and 25.4 cm/s (10 in./s) for distance at 30.5 cm (12 in.).

The results of the data analysis indicated the data fit the gamma density function, which is written as

$$Y = B * X^{\alpha} * e^{(-\beta X)} \tag{4}$$

where X = distance coordinate on the vertical section of the steel strip (X = 0 at the up edge of the spray pass); and Y = thickness for each X. Table 3 lists the values of the parameters B, α, and β for different gamma density functions. Fig. 7 shows the curves of the functions for different angles at distance 30.5 cm (12 in.). The figure shows that when the angle gets smaller, the effective width also gets smaller. Therefore, the productivity of the spray painting operation decreases along with decreasing the spray gun angle.

VALIDATION OF THE LAB EXPERIMENTS

Field experiments were conducted using the prototype robotic bridge painting system at the NCDOT to validate the lab experiment results. Major test apparatuses included: (1) a mod-

TABLE 3. Values of the Parameters for Gamma Density Functions

Distance (cm) (1)	Speed (cm/s) (2)	SPRAY GUN ANGLE 45° B (3)	45° α (4)	45° β (5)	60° B (6)	60° α (7)	60° β (8)	75° B (9)	75° α (10)	75° β (11)
20.3	35.6	0.40	2.19	0.50	0.43	3.16	0.79	0.50	3.20	0.80
25.4	30.5	0.10	3.35	0.60	0.30	2.77	0.60	0.20	3.40	0.70
30.5	25.4	0.11	3.07	0.50	0.10	3.60	0.60	0.08	4.54	0.80

J. Constr. Eng. Manage., 2001, 127(2): 142-148

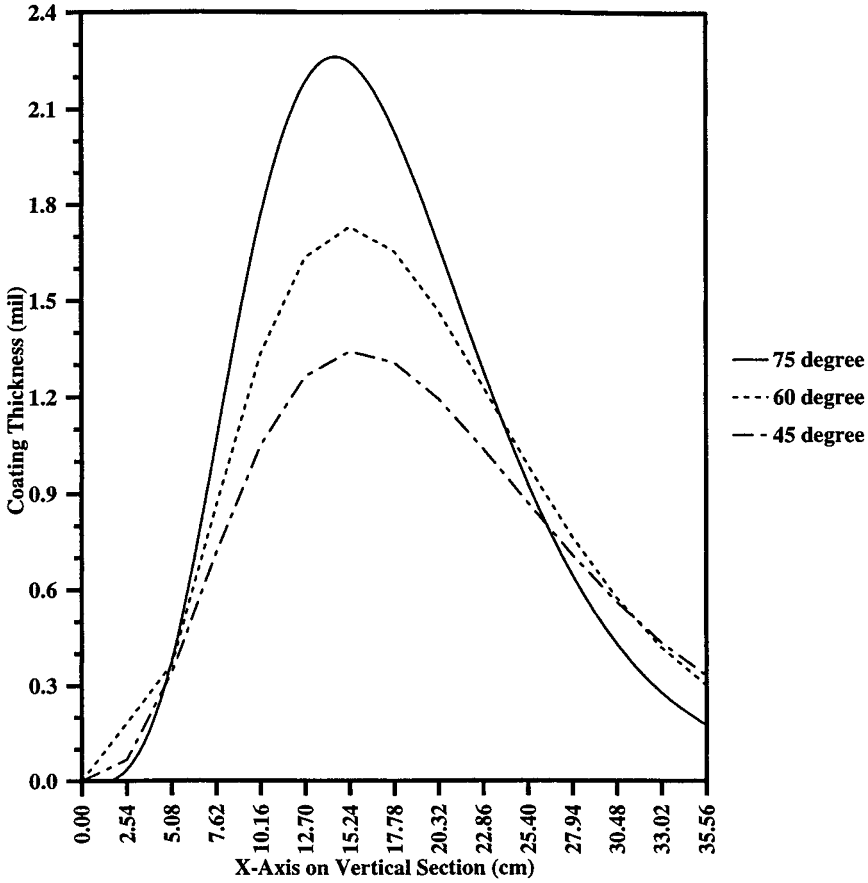

FIG. 7. Thickness Distribution Curves for Different Angles at Distance 30.5 cm

FIG. 8. Overview of Field Test Facilities

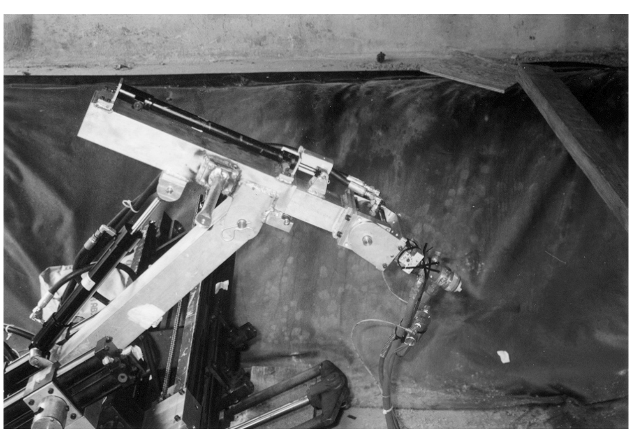

FIG. 9. Field Test Facilities—Robot Ram and Spray Gun

ified Peeper crane truck with three crane boom sections; (2) a robot arm; (3) an air-assisted airless spray gun; (4) a spray pump; and (5) an air compressor. Fig. 8 shows the overview of the testing site, and Fig. 9 presents the robot arm with the spray gun. The coating thickness was measured according to the same procedure as in the lab experiments.

The dimension of bridge painting area was 60.96 cm length by 38.10 cm width (24 $\times$ 15 in.) without physical obstacle. To cover the width of 38.10 cm (15 in.), two spray passes were needed. Based on the results from lab experiments, the robotic painting system was set up as follows: (1) the spray gun was perpendicular to the surface; (2) the air pressure was 137.8 kPa (20 psi); (3) the fluid pressure was 3,445 kPa (500 psi); (4) the distance was 30.5 cm (12 in.); (5) the moving speed was 25.4 cm/s (10 in./s); and (6) the reposition distance of the spray gun between two spray passes was 23.40 cm (9.2 in.). The reposition distance was calculated using (2) with the condition that the overlap between the two spray passes must be greater or equal to the specified thickness (1.5 mils).

Two test runs were conducted in the field. Results of the tests indicated that both the coating thickness and appearance satisfied the quality requirements within the specified bridge painting area. Also, comparisons were made between the thickness measurement data and the predicted area from the developed thickness distribution function, as shown in Table 4. The maximum difference between the measurement value and predicted value was 0.2 mils (measurement value − predicted value = 0.2 mils). For some measurement points, the values were smaller than the predicted values. However, the percentage of difference was not greater than 20%, which is the limit set by the Steel Structures Painting Manual (*Painting Manual* 1994). Thus, it was concluded that using the predicted value generated from the thickness distribution function (2) can achieve the specified quality requirements.

J. Constr. Eng. Manage., 2001, 127(2): 142-148

TABLE 4. Data Analysis for Field Experiments

Measurement number (1)	Precited value (mil) (2)	First run data (mil) (3)	(3)–(2) (mil) (4)	(4)/(2) (%) (5)	Second run data (mil) (6)	(6)–(2) (mil) (7)	(7)/(2) (%) (8)
1	0.0	0.0	0.0	—	0.0	0.0	—
2	0.5	0.6	0.1	20	0.5	0.0	0
3	1.0	0.9	−0.1	−10	1.1	0.1	10
4	1.4	1.4	0.0	0	1.3	0.1	7
5	1.7	1.6	−0.1	−6	1.8	0.1	6
6	2.0	2.0	0.0	0	2.1	0.1	5
7	2.1	2.3	0.2	10	2.2	0.1	5
8	2.0	2.1	0.1	5	2.0	0.0	0
9	1.7	1.8	0.1	6	1.7	0.0	0
10	1.6	1.7	0.1	6	1.6	0.0	0
11	1.5	1.5	0.0	0	1.6	0.1	7
12	1.6	1.6	0.0	0	1.6	0.0	0
13	1.7	1.8	0.1	6	1.7	0.0	0
14	2.0	2.0	0.0	0	2.1	0.1	5
15	2.1	2.2	0.1	5	2.3	0.2	10
16	2.0	2.1	0.1	5	2.2	0.2	10
17	1.7	1.7	0.0	0	1.8	0.1	6
18	1.4	1.5	0.1	7	1.5	0.1	7
19	1.0	1.0	0.0	0	1.2	0.2	20
20	0.5	0.6	0.1	20	0.5	0.0	0
21	0.0	0.0	0.0	—	0.0	0.0	—

CONCLUSIONS

One major aspect of robotic bridge painting is how to achieve the specified quality requirements, which are the coating thickness and appearance. The study found that the bridge painting process, planning parameters were: (1) the spray gun angle; (2) the air pressure; (3) the fluid pressure; (4) the distance between the spray gun and bridge surface; and (5) the spray gun moving speed, which had a strong influence on the coating thickness and the appearance. To investigate the values of these parameters, which would achieve the required thickness and appearance, bridge features were developed to represent a steel bridge. Each feature corresponded to a set of process planning parameters, which were used to set up and control the movement of the spray gun. Factorial experiments were conducted to determine the values of the parameters and thickness distribution functions for the ''Web-Surface'' feature.

Based on lab experiments, the multiple linear regression model (between the coating thickness and the process planning parameters), and the thickness distribution functions had been established for the ''Web-Surface'' feature. The thickness distribution function was a logistic density function if the spray gun was set perpendicular to the bridge surface, and a gamma function if the gun was set at other angles (e.g., 60°). Since the coating appearance was acceptable for all the experiments, there was no need to perform the analysis on the appearance.

Field tests had been conducted at the NCDOT to validate the lab experiment results. The outcome of the field experiments indicated that the specified quality was achieved using the parameter values provided by lab experiments. As a result, the robotic bridge painting becomes reality.

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APPENDIX I. REFERENCES

Chang, T. C., Wysk, R. A., and Wang, H. P. (1991). *Computer-aided manufacturing*, Prentice-Hall, Englewood Cliffs, N.J.

Ferguson, P. J. (1976). ''Painting metal bridges—Historical and current trends.'' *J. Oil and Color Chemists' Assn.*, 59(7), 253, Middlesex, U.K.

Freund, R. J., and Wilson, W. J. (1993). *Statistical methods*, Academic, San Diego.

Fu, Z., De Pennington, and Saia, A. (1993). ''A graph grammar approach to feature representation and transformation.'' *Int. J. Comp. Integrated Manufacturing*, London, 6(1,2), 137–151.

Hare, C. H. (1987). ''Protective coatings for bridge steel.'' *Synthesis of Hwy. Pract. 136*, Transportation Research Board, National Research Council, Washington, D.C.

Moon, S., and Bernold, L. E. (1995). ''Robotic bridge paint removal field testing and evaluation of promising technologies.'' *Special Rep.*, Civ. Engrg. Dept., North Carolina State Univ., Raleigh, N.C.

Oglesby, H. C., Parker, W. H., and Howell, A. G. (1989). *Productivity improvement in construction*, McGraw-Hill, New York.

Painting Manual. (1994). *Paint application specifications: Commentary on paint application, systems and specifications*, Steel Structures Painting Council, Pittsburgh, Vol. 2, 405–408.

Participant Manual. (1985). *Painting inspection training course*, S. G. Pinney & Assoc., Inc., Port St. Locie, Fla.

Skibniewski, M., and Hendrickson, C. (1988). ''Analysis of robotic surface finishing work on construction site.'' *J. Constr. Engrg. and Mgmt.*, ASCE, 114(1), 53–68.

Smith, L. M. (1990). ''Identifying and controlling job hazards during climbing and high work.'' *J. Protective Coatings and Linings*, 7(10), 25–26.

Thompson, T. W. (1994). ''An assessment of automated surface finishing technologies.'' MS thesis, Civ. Engrg. Dept., Univ. of Texas at Austin, Tex.

Tokioka, S., Ishigami, S., Sekiguchi, R., Wada, M., Inagaki, H., and Sakai, S. (1989). ''Robotized painting by the wall surface-finish robot (FR-1).'' *Proc., 6th Int. Symp. on Robotics in Constr. in San Francisco*, Construction Industry Institute, Austin, Tex., 531–538.

Warne, K. M. (1994). ''Investigation of process control variables for an automated painting machine.'' MS thesis, Civ. Engrg. Dept., Univ. of Texas at Austin, Tex.

APPENDIX II. NOTATION

The following symbols are used in this paper:

A_0 = parameter of logistic density function;
A_1 = parameter of the logistic density function;
B = parameter of gamma density function;
X = vertical distance along one spray gun pass;
X_1 = fluid pressure of spray gun;
X_2 = air pressure of spray gun;
X_3 = distance between spray gun and steel surface;
X_4 = spray gun moving speed;
Y = thickness along vertical section for one spray gun pass;
Y_t = coating thickness;
α = parameter of gamma density function;
β = parameter of gamma density function; and;
λ = parameter of logistic density function.

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