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Simulation of Multiple Nozzle Surface Finishing Operations

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ABSTRACT

This paper describes a graphical computer simulation program which was developed to study the behavior of interacting nozzles performing a surface finishing operation. The software simulates spraying operations with complex nozzle motions in order to determine the extent and uniformity of coverage on the finished surface. The software has been applied to the study of an automated paint spraying system which is to be used to finish large petroleum storage tanks. The goal of the study was to investigate various nozzle configuration, travel motions, and painting parameters and to determine which variables lead to the widest and most uniform surface coverage. Graphical and numerical results of this study are presented and recommendations for optimal painting performance are made.

INTRODUCTION

Graphical computer simulations are often used to visualize processes and to optimize parameters involved in system design. It can be beneficial from both a time and financial standpoint to simulate an unknown process and obtain an understanding of the process variables before prototypes are built. This paper discusses the use of graphical computer simulation for determining some of the operating parameters for a surface finishing system using multiple nozzles with overlapping spray fans.

The Construction Industry Institute (CII) has sponsored a project at The University of Texas at Austin to automate the surface preparation and coating of large petroleum storage tanks. The intent of the project is to build a machine that can replace the crews which have traditionally prepared and painted these tanks. The requirements imposed on the project by the sponsor are that the machine be self guided, requires one crew for operation, and should be capable of operating at rates equivalent to the productivity of two traditional crews. Several attempts have been made to develop similar automated painting equipment, but they have all had performance limitations [Takeno and Matsumura, 1988; Tokioka, 1989; Takeno and Matsumura, 1989; Shimizu, 1989].

In an attempt to better understand the coating process, simulation software was developed to allow visualization and to aid in the determination of optimal parameters. The software provides both numerical and graphical results depicting a simulated surface coverage pattern. Fixed parameters which were set by the operating rate requirements included the number of nozzles (2) and the travel rate (up to 20 cm/sec). The remaining variables to be optimized are the distance between the nozzles and the working surface, and the degrees of freedom of the nozzles. The goal is to determine the variables which produce the largest and most uniform surface coverage while remaining within the desired surface thickness specifications. Although the results in this paper pertain to a particular type of painting nozzle, the software was written in a very general format and nozzle parameters can be varied to simulate other processes such as sand blasting, insulation spraying, and shotcreting [Skibniewski, 1988].

DEFINITION OF THE SIMULATION METHOD

The first step in simulating the spraying operation was to develop a model of the nozzle spray fan shape. For the painting nozzles used in this project, the nozzle fan was approximated to have a polygonal cross-section and a typical projected fan pattern as shown in Figure 1. The fan geometry (the cross-section polygon shape) was determined experimentally based on a test pattern projected onto a flat surface a known fixed distance from the nozzle. Knowing the fan geometry, the nozzle pattern can be projected onto a surface at any distance and at any orientation to determine the resulting coverage. The flow rate out of the nozzle was assumed to be constant and spherically uniform resulting in a constant intensity of paint within the fan at a given radius. This assumption did not allow for the feathering of paint near the edges of the pattern which is common in some nozzles. Finally, overspray and paint drift were neglected since they are difficult to model accurately, and also because these effects can be minimized through careful spraying system design. Experimental coverage thickness results were later compared to the simulation results to verify that these assumptions were reasonable and acceptable.

The computer software developed is a discrete time simulation of the nozzle spraying process (written in C using GL2 graphics calls on an Silicon Graphics Personal Iris Workstation). In each time step of the simulation, the software calculates the position and orientation of each nozzle and projects the nozzle fan patterns onto the surface being sprayed (refer to Figure 1). The intensity of the paint is then calculated and added to each surface element (dA) which falls within the projected pattern . This procedure is repeated for each time step until a representative distance of travel and coverage has been calculated.

The position and orientation of each nozzle for a given time step is determined from kinematics equations describing the nozzles' motions. Because a general purpose program was desired, each nozzle was allowed five degrees of freedom: x- and y-axis translation (in a plane parallel to the surface) and x-, y- , and z-axis rotation (to allow total control over nozzle orientation) (refer to Figure 1). The position of a nozzle is given by

$$\begin{aligned} N_x &= vt + R\cos(\omega t) \\ N_y &= N_{yo} + R\sin(\omega t) \\ N_z &= h \end{aligned}$$

where $\mathbf{N} = (N_X, N_Y, N_Z)$ are the coordinates of the nozzle center, v is the translational travel speed of the nozzle along the travel (x) axis, t is the time from the start of the simulation, R is an offset radius that the nozzle rotates about (parallel to the x-y plane) providing a circular motion, ω is the circular rotation frequency, N_{yo} is the initial y-coordinate of the nozzle, and h is the height above the surface being sprayed. The orientation of the nozzle is given by vector **n**,which points in the direction of the nozzle's centerline, given by

$$\mathbf{n} = [R_x]_\theta [R_y]_\phi \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$

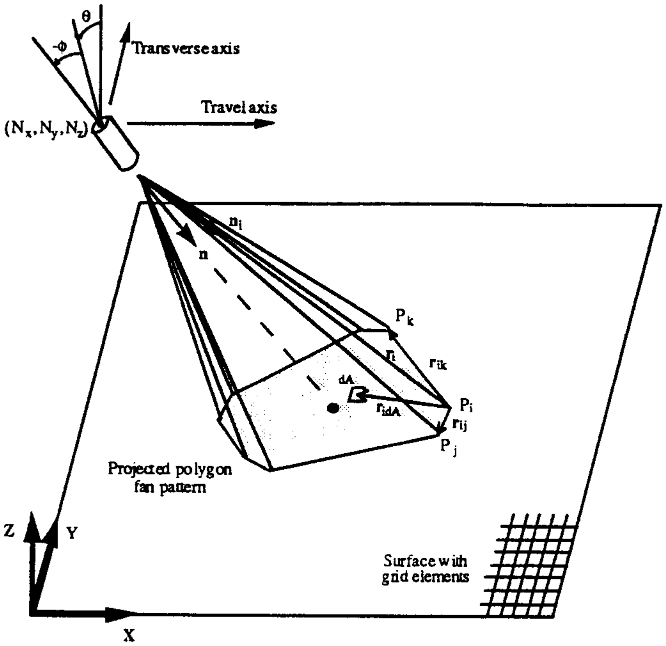


Figure 1

Nozzle Kinematics and Projected Fan Pattern

where the rotation matrices are given by [Paul, 1981]

$$[R_x]_\theta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \qquad [R_y]_\phi = \begin{bmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{bmatrix}$$

where θ is the angle of the nozzle about the axis of travel and φ is the angle of the nozzle about the transverse axis (which is perpendicular to the travel axis). θ and φ are given by

$$\theta = \theta_{amp}\sin(\omega_\theta t) \quad \text{and} \quad \phi = \phi_{amp}\sin(\omega_\phi t)$$

where θ_{amp} and ϕ_{amp} are the respective amplitudes and ω_θ and ω_ϕ are the respective frequencies of the nozzle oscillations about the travel and transverse axes. If θ and φ are both zero, the nozzle is oriented along the negative z-axis perpendicular to the surface being coated.

The nozzle position N and orientation **n** are used to define the position and orientation of the nozzle fan and the resulting projected fan pattern. By projecting each fan edge vector $\mathbf{n}_i$ onto the surface, the projected fan pattern vertices ($\mathbf{P}_i$) can be determined. The location of each vertex is given by the vector equation

$$\mathbf{P}_i = \mathbf{N} + r_i \mathbf{n}_i$$

where r_i is the distance from the nozzle (N) to the projected vertex ($\mathbf{P}_i$) along the edge $\mathbf{n}_i$. The x- and y-coordinates for each projected fan polygon vertex can then be expressed as

$$P_{ix} = N_x - \frac{n_{ix}}{n_{iz}} N_z$$

$$P_{iy} = N_y - \frac{n_{iy}}{n_{iz}} N_z$$

The next step is to add paint to any surface grid element which lies within the projected fan pattern. The method used to determine if a grid element dA falls within the projected fan polygon involves testing the location of dA with respect to each polygon vertex . If the cross product z-component conditions

$$\left(\mathbf{r}_{ik} \times \mathbf{r}_{idA}\right)_z > 0 \qquad \text{and} \qquad \left(\mathbf{r}_{idA} \times \mathbf{r}_{ij}\right)_z > 0$$

are met for each vertex i of the projected polygon, then the element dA is within the polygon and is thus receiving paint for the current time step. The thickness of paint added to each dA element receiving paint for the current time step is calculated from the intensity of the paint at the dA location. The intensity of paint, and therefore the thickness of paint added, is calculated as a function of the distance and orientation between the nozzle and the element using solid angle geometry [Janna, 1986].

TEST CASES AND RESULTS

Several test cases with various nozzle configurations and motions were selected and each case was evaluated with the simulation software. To evaluate and compare the performances of each case, the following parameters were assumed constant: paint flow rate (3.1 cm^3/sec per nozzle), travel speed (17.8 cm/sec), and the number of nozzles (2). The parameters which were varied to obtain optimal (widest and most uniform) coverage results for each case were: vertical distance between the nozzle and surface, and nozzle degree of freedom amplitudes and frequencies of oscillation.

The criteria used to select variables and evaluate the results were both quantitative and qualitative in nature. First, the nozzle height was determined by the requirement that the coating thickness be between 0.076 and 0.127 mm for each pass over the surface. This is a typical range given by paint manufacturers and often used by companies when specifying tolerances for painting contracts. Next, the effective pattern width of the tandem nozzles was determined from the requirement that overlapping passes on the surface meet the 0.076 to 0.127 mm thickness requirement. This requires a minimum thickness of 0.038 mm and a maximum thickness of 0.0635 mm at the edges of the pattern. The uniformity of the coating across the effective width was qualitatively evaluated. It is desired to have as uniform a coat as possible with a limited number of peaks and valleys throughout the coverage width. Finally, the relative complexity of physically implementing a desired mechanical oscillation system was judged. Reliability of the oscillatory system was considered critical and some proposed test cases were immediately discounted due to this criterion.

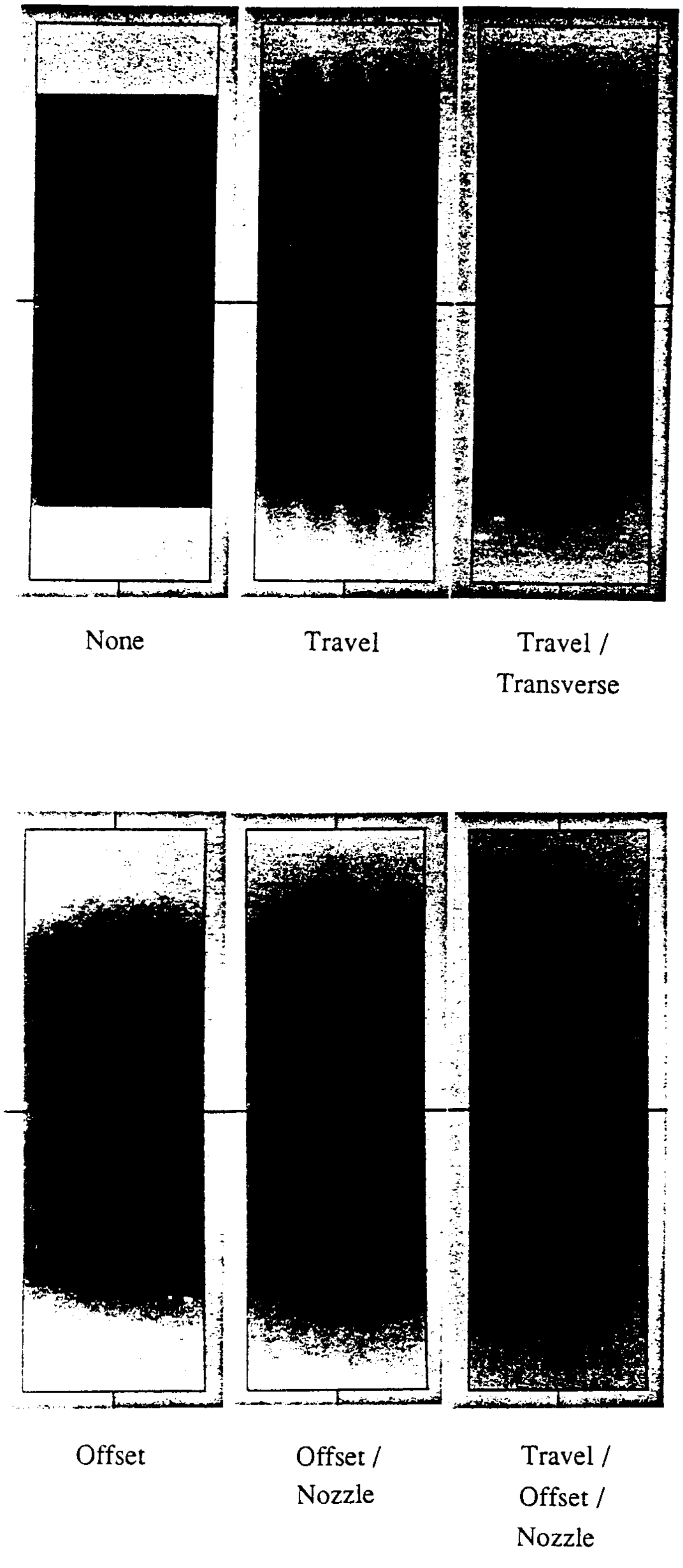
Prior to the presentation of the test cases and their results, a brief description of terminology is required. Test cases were named according to the axes the nozzles were allowed to rotate and/or oscillate about. These axes are the Travel axis, the Transverse axis, the Nozzle axis, and an Offset axis. The Travel axis degree of freedom (DOF) represents nozzle oscillation perpendicular to the direction of travel; the Transverse axis DOF represents nozzle oscillation parallel to the direction of travel; the Nozzle axis DOF represents spinning of the nozzle about its own axis; and the Offset axis DOF represents circular motion (offset a given radius) of the nozzle about a vertical axis in a horizontal plane. Hence, for the test case named Travel, the nozzles were allowed to oscillate about the travel axis only. Likewise, the test case referred to as Offset / Nozzle allowed the nozzle to simultaneously perform circular motion (with a radius of 6.35 cm) and spin about its axis to maintain a constant projected fan pattern orientation. The test case referred to as None allowed only pure translation along the axis of travel.

Six test cases and their results are summarized in Table 1 and photographs of the simulated coverage patterns (graphical output from the software) are shown in Figure 2. Cross-sectional paint thickness profiles for each test case are shown in Figures 3 and 4. Note that three profiles are given for the coverage along the travel axis which correspond to locations along the transverse direction from the center of the coverage width (indicated by Y in Figures 3 and 4). All of the transverse profiles coincide with a location at the center of the simulated travel distance.

Table 1 Test Results

DOF's	Nozzle Height	Pattern Width	Uniformity	Complexity
None	30.5 cm	59.4 cm	Poor	Low
T	30.5 cm	58.9 cm	Poor	Medium
T/V	34.3 cm	60.1 cm	Good	High
O	33.0 cm	54.4 cm	Good	High
O/N	33.0 cm	63.5 cm	Good	Medium
T/O/N	33.0 cm	68.6 cm	Fair	High

DOFs: T: Travel; V: Transverse; O: Offset; N: Nozzle



None

Travel

Travel / Transverse

Offset

Offset / Nozzle

Travel / Offset / Nozzle

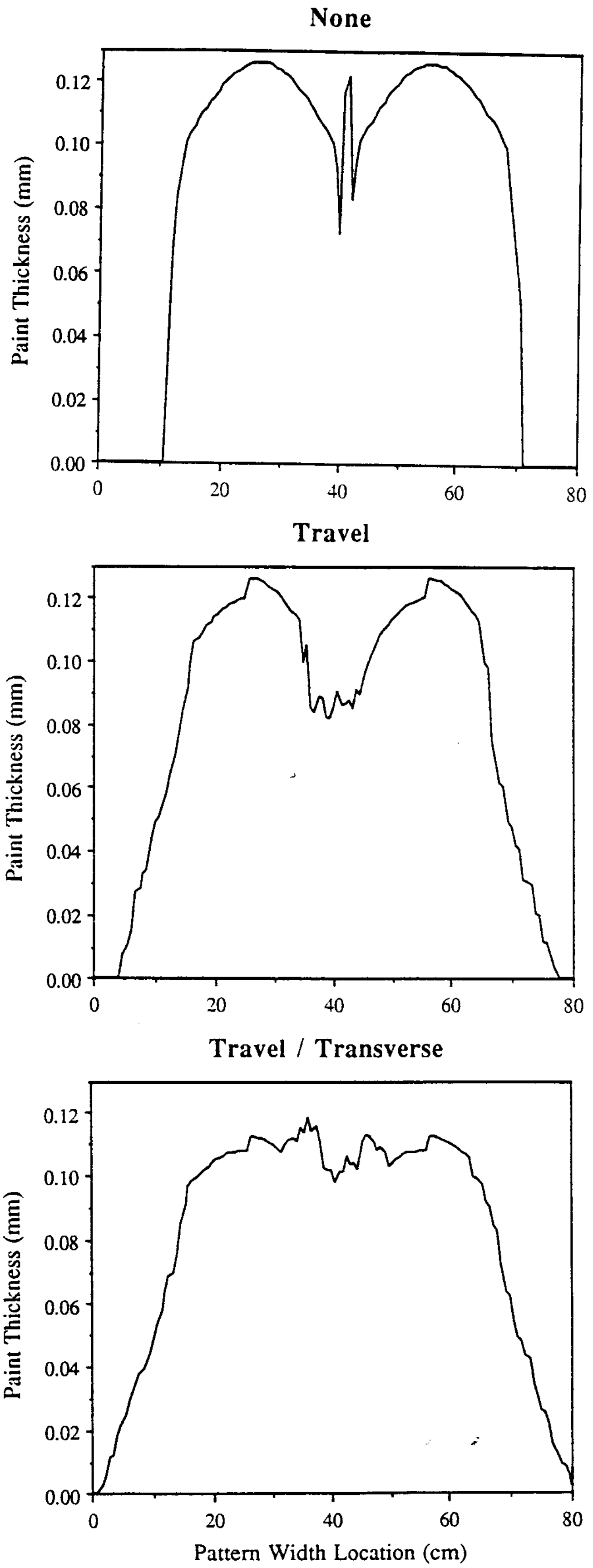


Figure 2 Graphical Depiction of Coverage Patterns

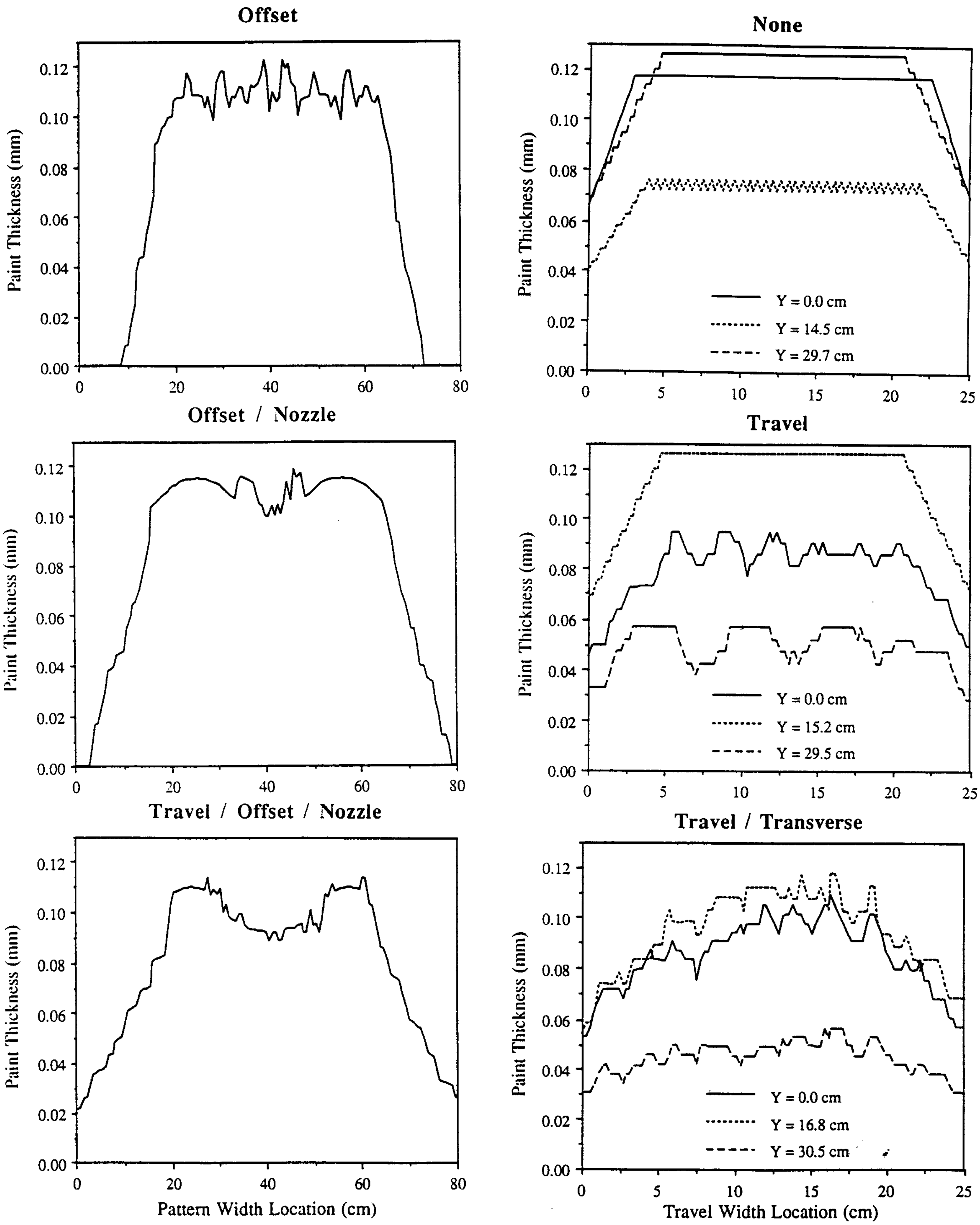


Figure 3

Paint Thickness Profiles (Transverse Width Section)

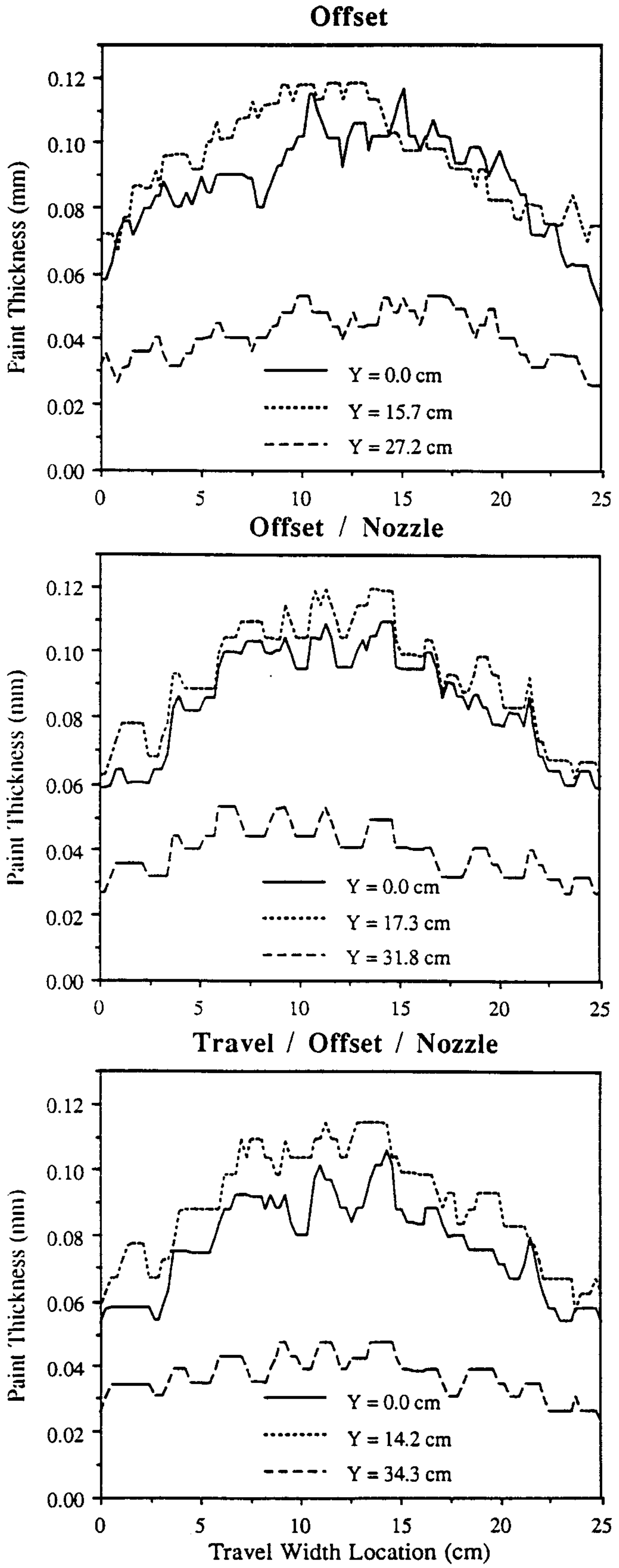


Figure 4

Paint Thickness Profiles (Travel Width Section)

CONCLUSIONS AND RECOMMENDATIONS

This paper presented the development of a general purpose computer simulation program which can be used to evaluate coverage patterns resulting from multiple nozzle spraying operations. The primary goal of the software was to test several different nozzle configurations and motions to choose parameters to be implemented in an automated paint spraying system being developed for the Construction Industry Institute.

Of the six test nozzle motion and parameter cases presented in this paper, only three of the cases produced coatings whose uniformity was considered good (i. e., the profiles were free of excessive peaks and valleys). The pattern widths of these cases (with two nozzles) varied over a 17% range from 54.4 to 63.5 cm. Two of these cases were considered to be too complex to implement due to the mechanical components required to actuate the degrees of freedom. Therefore the case which is deemed best is Offset / Nozzle which moves the nozzles with circular motion while spinning them to maintain constant pattern orientation. This case provided the widest and most uniform surface coverage without excessive mechanical complexity – a simple geared planetary drive or parallel linkage can be used to create the desired motion.

The simulation software was invaluable for visualizing and evaluating various nozzle configurations and painting parameters before building the first painting machine prototype. This provided confidence that a "good" (close to optimal) selection of nozzle characteristics has been chosen and that the prototype will meet the required coating specifications.

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