2009-01-3280

Precision Robotic Coating Application and Thickness Control Optimization for F-35 Final Finishes

Neal A. Seegmiller, Jonathan A. Bailiff and Ron K. Franks
Lockheed Martin Aeronautics Company

ABSTRACT

In order to meet the F-35 Joint Strike Fighter's strict radar cross-section and weight requirements, stealth coatings must be applied to extremely precise thickness tolerances. To meet these unprecedented tolerances, Lockheed Martin Aeronautics Company has implemented a unique Robotic Aircraft Finishing System (RAFS). This paper details the capabilities of RAFS hardware for precision coating application as compared to legacy systems. The iterative process of optimizing spray parameters and robot programs for coating thickness control on challenging F-35 geometry is also presented. Finally, results from the first coating of a production aircraft at RAFS are compared with previous hand-spray results. In keeping with Security and International Traffic in Arms Regulations, restricted information on coating materials and tolerances is not presented.

INTRODUCTION

In order to meet the F-35 Joint Strike Fighter's strict radar cross-section and weight requirements, stealth coatings must be applied to extremely tight thickness tolerances, measured in thousandths of an inch. This paper details how these unprecedented tolerances are achieved using the Robotic Aircraft Finishing System (RAFS) at Lockheed Martin's Fort Worth plant. Both careful hardware design and coating process development contribute to precise coating thickness control on the F-35. The majority of design and development work described in this paper has been led by engineers in the Manufacturing Technology group at Lockheed Martin Aeronautics Company. In keeping with Security and International Traffic in Arms Regulations, restricted information on coating materials and tolerances is not presented.

The Ishikawa diagram in Figure 1 lists key factors that affect coating thickness. This paper will first explain how system factors are controlled through hardware design, emphasizing the unique capabilities of RAFS over legacy coating systems. Next the paper will explain how process factors are chosen and optimized during coating process development. A new method of displaying coating thickness results to the Numerical Control (NC) programmer to assist with the modification of robot programs will be highlighted. Finally, results of the first production coating operation at RAFS will be presented and compared with hand coating results.

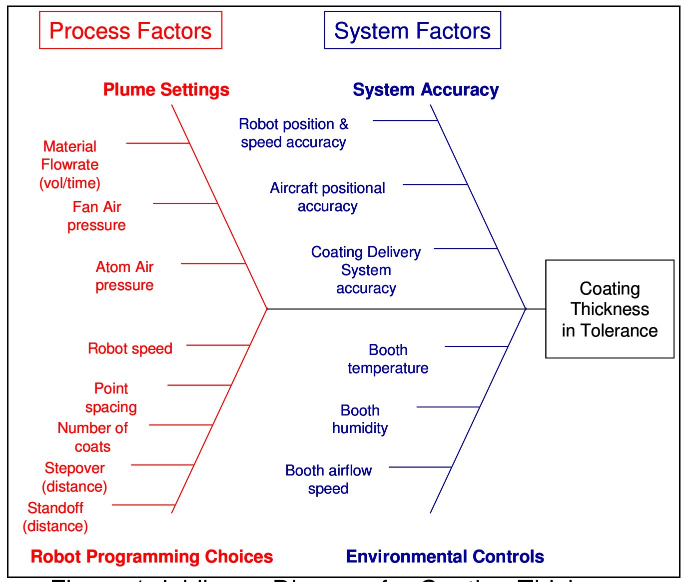

Figure 1. Ishikawa Diagram for Coating Thickness

HARDWARE DESIGN

The Robotic Aircraft Finishing System applies special Radar Absorbing Material (RAM) coatings over the entire surface of the fully assembled F-35, except for the horizontal and vertical tails and various small parts which are coated at a separate Robotic Component Finishing System (RCFS). RAFS comprises three 6-axis robots mounted to auxiliary axis rails (Figure 2). All robots have x and y-axis rails, and the aft robot has an additional z-axis lift to maneuver around the vertical tails on the top surface of the aircraft. Installation of RAFS was completed in June 2008. Coating process development is conducted using the fiberglass Finish Application Mockup (FAM) of the F-35 seen in Figure 2

Figure 2. Robotic Aircraft Finishing System Photograph

ROBOT POSITIONAL ACCURACY - High positional accuracy is required to coat within exact part boundaries and to maintain the correct standoff distance, both essential for precise thickness control. RAFS is designed for a tool center point (TCP) positional accuracy of 0.08 inches and a repeatability of 0.06 inches at full payload. The system repeatability was verified in an independent metrology study using a Krypton Infrared Camera which tracked the motion and speed of LEDs mounted at the TCP. This positional accuracy is most impressive for a system with auxiliary rails spanning the length of the F-35 and 76 inch long end-of-arm-tooling.

This high positional accuracy is achieved by using mature Commercial Off-the-Shelf (COTS) technology wherever possible. Fanuc R2000iA 125L material handling robots are used instead of common “paint sprayer” robots because of their higher precision and payload capability (needed to support the long end effectors). The material handling robots were converted for use in a Class I Division 1 environment as defined by the National Electric Code (NEC). To further reduce deflection and vibration at the TCP the current end effectors are constructed from lightweight, rigid composite tubing (Figure 3).

In addition, each 6-axis robot and its 2-3 auxiliary rails are controlled by a single off-the-shelf Fanuc R-J3iB controller. This allows seamless coordination of rail and robot motion when coating large surfaces. One of the primary challenges of the CASPER system used to apply F-22 coatings until 2003 was coordinating the motion of a 6-axis robot and the scara arm to which it was mounted with independent custom controllers [1].

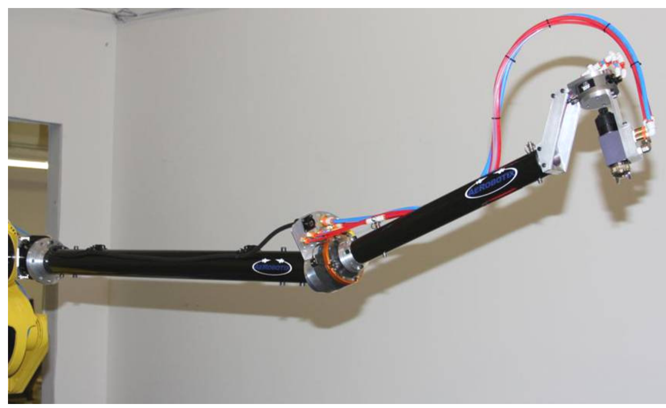

Figure 3. Long End Effector Constructed from Composite Tubing by Aerobotix, Inc.

AIRCRAFT POSITIONAL ACCURACY - Repeatable positioning of the aircraft in the booth is equally as important as the positional accuracy of the robots. For this reason the aircraft’s custom Paint Cell Dolly (PCD) is designed for a floor location (x, y direction) accuracy of 0.125 inch. Using three servo motor driven jacks, the PCD can position the aircraft vertically (z direction) to a repeatability of 0.010 inch. The PCD also uses an in-floor track and guiding pins to help novice tug drivers position the aircraft correctly. By comparison, positioning the B-2 in its coating system is far more difficult [2].

Because of the high positional accuracy of both the robots and the PCD, it is anticipated that there will be no need for complex User-frame adjustments for each individual aircraft as is required for the F-117A, F-22, and other coating systems [1, 3].

COATING DELIVERY SYSTEM - The Coating Delivery System (CDS) controls all aspects of metered paint delivery to the High-Volume Low-Pressure (HVLP) Kremlin gun mounted at the end effector. Several advances in the RAFS CDS enhance coating thickness control.

First, the RAFS CDS uses a reciprocating positive displacement pump (or Linear Displacement Pump) made by Fluidic Systems to deliver the polyurethane-based paint at an exact volume rate, regardless of density or viscosity. Most legacy systems, including Lockheed Martin's F-22 and F-16 systems, instead use a fluid regulator device which relies on pot pressure to drive paint through the lines. As the paint catalyzes and its viscosity increases over time, the material flowrate through the fluid regulator can deviate from the setpoint.

Also on RAFS, an Endress+Hauser Coriolis flowmeter is used to measure the density and flowrate of the material, providing feedback to the pump's closed-loop proportional-integral-derivative (PID) controller. The state of the art flowmeter helps to maintain a flowrate accuracy of ± 3 percent by volume and is not sensitive to vibration, allowing it to be mounted with the other CDS components on a cart which moves with the robot along an auxiliary rail.

During a coating operation, the gun first triggers on at an off-part location and does not move on part until a "fluid stable" condition is reached, as determined by the flowmeter. The flowrate, fluid density, fan air pressure, and atomizing air pressure are constantly monitored; if any parameter deviates from its operator-defined allowable range the robot will pause at an off-part location. The operator may resume from the same off-part location once the problem is resolved.

BOOTH ENVIRONMENTAL CONTROLS - Booth temperature and humidity are controlled independently to optimize the coating cure rate, which can affect coating thickness. Large supply and exhaust fans above the booth ceiling drive airflow at a constant 100 feet per minute; faster airspeeds could distort the plume shape and reduce transfer efficiency. As a result of Computational Fluid Dynamics (CFD) analysis performed by Dürr Industries, Inc. a filter bank was installed at the front of the booth to create more diffused, laminar airflow.

COATING PROCESS DEVELOPMENT

In addition to the careful design of RAFS hardware, extensive coating process development is required to achieve precise thickness control. This section explains the iterative method of optimizing CDS parameters and robot programs.

PLUME AND PANEL STUDIES - Plume and Panel Studies must be conducted in order to set the CDS parameters (flowrate, fan air pressure, atomizing air pressure) and to validate robot programming choices (standoff distance, stepover distance, robot speed). First, the shape of the plume is characterized in both the major and minor axis directions by repeatedly spraying a single stroke on a test panel, then measuring the thickness profile of the spray with a micrometer. Major and minor axis thickness profiles for a sample plume are shown in Figure 4; note that the plumes are approximately symmetrical about both axes.

By summing major axis plume thickness profiles spaced at the chosen stepover distance, one can predict the evenness and approximate thickness of each coat of paint (Figure 5). A poor plume and stepover combination may cause "tiger-striping," with visible high and low thickness regions.

All plume study predictions are validated by spraying multiple coats on test panels. The test panel coating thickness is measured in a grid pattern to check evenness and to calculate the thickness deposited per coat (or "build-per-pass"). The build-per-pass can increase slightly with the number of coats, as transfer efficiency increases on wet surfaces.

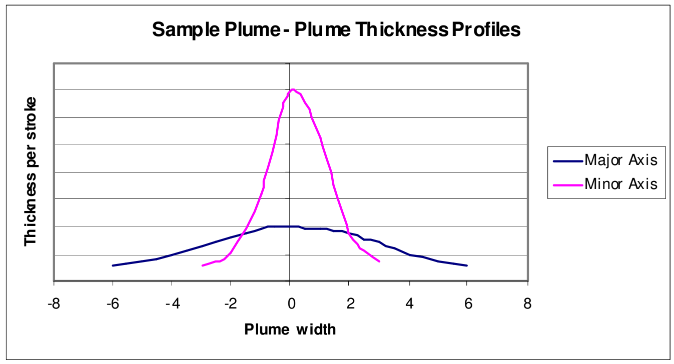

Figure 4. Plume Thickness Profiles – Major and Minor Axes

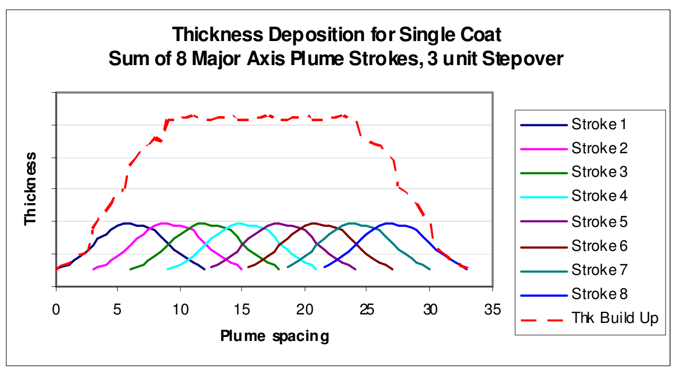

Figure 5. Coat Thickness and Evenness Prediction

OFFLINE ROBOT PROGRAMMING - The robots are programmed offline using DELMIA V5 and FASTSURF software, licensed by Dassault Systemes and CENIT respectively. This simulation software proved invaluable in the design of the booth [4]. Currently, the software enables NC programmers to quickly generate robot path points by referencing a 3D CAD model of F-35 geometry. Ideally, at each path point the plume is positioned normal to the aircraft surface and at the chosen standoff distance; however, in confined areas such as the inlet ducts this is not always possible.

The robot executes linear moves between points with continuous termination type in order to maintain robot speed and standoff distance while spraying on part. Typically, when an aircraft surface is coated for the first time the speed between all path points is set to a single, baseline value.

The spacing between points on adjacent strokes is decided by the stepover distance for the chosen plume; however, the spacing between points along a stroke may be tailored for individual surfaces. The independent metrology study at RAFS confirmed that spacing points too close together along a stroke can slow down the robot, as the robot may round corners between points at less than the programmed speed. On the other hand, spacing points too far apart may cause the plume to deviate from the nominal standoff distance on high-curvature surfaces.

The FASTSURF software also contains deposition modeling functionality which predicts coating thickness based on plume shape, robot path, and surface geometry; however, predictions are not sufficiently accurate to meet required tolerances, particularly when aircraft geometry requires the plume to be off-normal from the surface. Future improvements in deposition modeling could help to reduce the number of development sprays required.

COATING THICKNESS MEASUREMENT - In order to efficiently utilize coating thickness results to optimize the coating process, measurements are taken at a subset of the robot program path points. These points are both repeatable and easily identifiable to the NC programmer.

Prior to measurement, the inspection points must be visibly marked on the coating surface. Two methods of marking robot program path points are currently in use for development sprays. The newest method developed by Manufacturing Technology is an air-actuated point marking device which mounts conveniently to the fan cap threads of the Kremlin gun and connects to an existing airline (Figure 6). To use this device, the CDS is disabled and the robot motion program is executed from a teach pendant. When a measurement point is reached the air cylinder gently extends an ink marker into contact with the coating surface. The marking device can be operated automatically by inserting macro commands in the robot program which actuate the device at specified points. Alternatively, a laser pointer can be mounted to the Kremlin gun and points can be marked manually while stepping through the program.

For the collection of coating thickness data in production, an intelligent laser projection system is under installation in the booth adjacent to RAFS. The system will align to the aircraft using indoor GPS, then sequentially project measurement points to within ±0.060 inch. The system is expected to be fully operational by 2010.

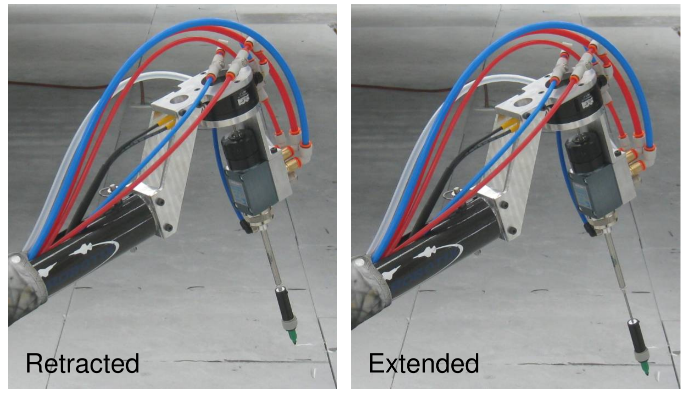

Figure 6. Air-Actuated Point Marking Device

After marking, coating thicknesses are measured using custom probes developed by Fischer Technology, Inc. The probes utilize non-destructive eddy current and magnetic induction test methods to sense the coating thickness. For accuracy, the probes are recalibrated for each new batch of coating material. Measurements are stored in a handheld data logging unit, then exported to Microsoft Excel for analysis.

RESULTS DISPLAY AND ANALYSIS - In order to more effectively visualize coating thickness results, Manufacturing Technology developed a novel method of displaying thickness data. Visual Basic software was created to extract the measurement point coordinates from the robot program (i.e. .ls or .tp file) and display the thickness measurements at these coordinates in the same 3D CAD model used for offline programming (Figure 7).

In addition, the annotations can be color coded to indicate whether a measurement is within, above, or below tolerance. This allows the NC programmer to quickly identify out of tolerance regions with physical aircraft geometry. To further assist the NC programmer, each annotation is named with the same number as its corresponding point in the robot program. Annotations are displayed “parallel to screen,” allowing the results to be viewed from any angle. The same software can be used to effectively visualize the programmed robot speeds at their locations in the robot path (Figure 8).

Using this novel display method, several key trends in coating thickness were identified:

- Coating thickness is decreased on areas of convexity, and increased on areas of concavity.
- Thickness deviation is directly proportional to the degree of curvature.
- Thickness is decreased when spraying on an inverted surface (understood to be the effect of gravity)
- Thickness deviation is high and unpredictable where aircraft geometry forces the plume to become off-normal or deviate from the nominal standoff distance.

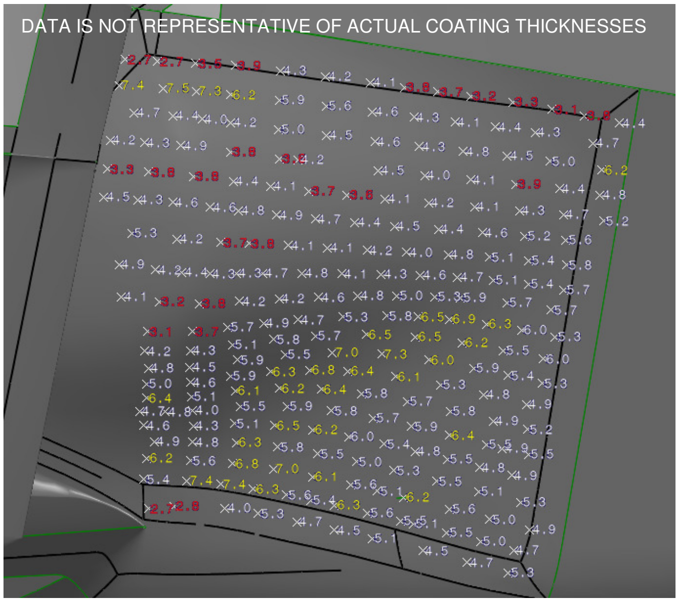

Figure 7. Display of Coating Thickness Data in CAD Model. **DATA IS NOT REPRESENTATIVE OF ACTUAL F-35 COATING THICKNESSES**. Data has been arbitrarily scaled to a mean of 5 units, standard deviation of 1 unit, and tolerance range of 4-6 units.

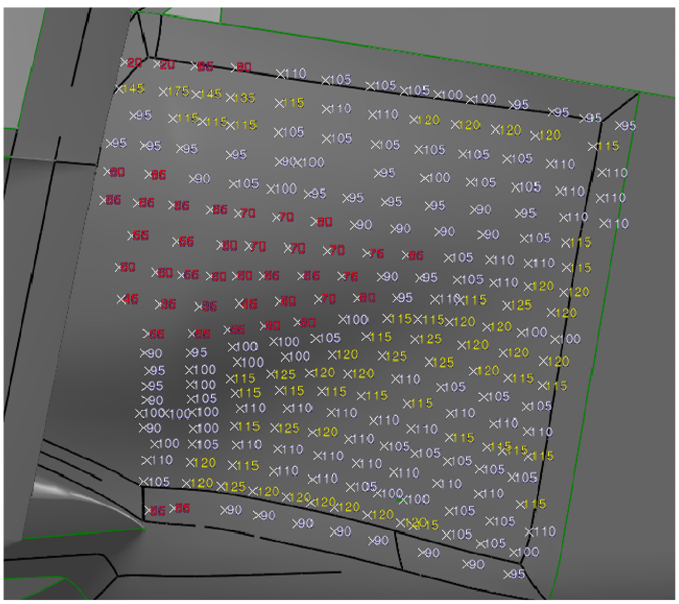

Figure 8. Display of Robot Speed Data in CAD Model. Robot speed data has been arbitrarily scaled to a baseline speed of 100 units

IMPROVEMENT IMPLEMENTATION - After extensive plume and panel studies, first attempts at coating an aircraft surface are typically close to nominal thickness; however, minor adjustments are always required to bring coatings entirely within the stringent F-35 tolerances.

If the range and standard deviation of the thickness measurements are sufficiently tight to fit within the tolerance range but the average is offset from nominal, adjusting material flowrate is the simplest fix. For example, flowrate adjustments are used to compensate for a uniform change in transfer efficiency when spraying on a large, inverted surface. For small adjustments, the change in average or global coating thickness can be approximated as linearly proportional to the flowrate change (see Equation 1). Note that large flowrate adjustments may affect the plume shape, requiring additional plume studies to correct the fan and atomizing air pressures.

$$\overline{T}_f = \left(\frac{F_f}{F_i}\right)\cdot \overline{T}_i \qquad \text{Eq. 1}$$

$\overline{T}_f$: *Final Avg Thickness*, $\overline{T}_i$: *Initial Avg Thickness*

F_f : *Final Flowrate*, F_i : *Initial Flowrate*

If the average of the thickness measurements is close to nominal but isolated areas fall outside of the tolerance range, then adjusting robot speed is the best approach. The change in coating thickness is inversely proportional to the change in speed. Equation 2 is an approximation of the relationship for speed adjustments on a single stroke.

$$T_f = p\cdot\left(\frac{V_i}{V_f}\right)\cdot T_i \qquad \text{Eq. 2}$$

T_f : *Final Thickness*, T_i : *Initial Thickness*

V_f : *Final Robot Speed on Stroke*, V_i : *Initial Robot Speed*

p : *Percentage of Thickness Build Deposited by Stroke*

Note that only a portion of the thickness build at any particular measurement point is deposited by the primary stroke passing immediately over that point. For the plume in Figure 5, approximately 40% of the thickness build is deposited by the primary stroke while the remaining 60% is deposited by adjacent strokes. For this reason speed adjustments on strokes adjacent to the target measurement point may be necessary.

In Figure 8, one can see the NC programmer increases speeds on areas of concavity to decrease thickness, and decreases speeds on areas of convexity to increase thickness. The thickness deviations in Figure 7 could not have been fixed by a global flowrate adjustment because the coating contained regions both above and below the tolerance range.

A more drastic rework of a robot program may require changing point location or spacing along each stroke, or even changing the stroke orientation. In some applications, the robot motion may be smoother if the stroke direction is rotated 90 degrees or made parallel to a chine, radius, or other aircraft geometry.

PRODUCTION OUTCOME

After several months of iterative coating process development at RAFS, the first production coating operation was performed in December 2008. In three days, coatings were applied to all areas forward of the inlet ducts on BF:002, a Short Takeoff Vertical Landing (STOVL) variant of the F-35. The RAFS coating thickness results can be directly compared to BF:001

results, an earlier STOVL variant F-35 which was coated by hand before RAFS became operational.

Table 1 summarizes the coating thickness results on BF:002 and BF:001 for four spray operations which vary by material type, location, target thickness, and tolerance range. The data shows that RAFS produced superior coatings with far less thickness variation than hand-sprayed coatings. Manufacturing Technology and NC programming are continuing process development work to improve coating results while the F-35 program is still in the System Development and Demonstration (SDD) phase.

Table 1. Comparison of Robotic and Hand Spray Coating Thickness Results

	Hand Spray (BF:001)	**Robotic Spray (BF:002)**
Spray 1		
% of Inspection Points In Tolerance	9%	75% *
% Decrease of Robotic Spray Thickness Range (Max-Min) over Hand Spray	90% decrease	
Spray 2		
% of Inspection Points In Tolerance	0%	100%
% Decrease of Robotic Spray Thickness Range (Max-Min) over Hand Spray	75% decrease	
Spray 3		
% of Inspection Points In Tolerance	3%	85%
% Decrease of Robotic Spray Thickness Range (Max-Min) over Hand Spray	89% decrease	
Spray 4		
% of Inspection Points In Tolerance	42%	95%
% Decrease of Robotic Spray Thickness Range (Max-Min) over Hand Spray	70% decrease	

* Note: Remaining 25% of inspection points within 3% of tolerance

CONCLUSION

This paper documents how aircraft coatings can be robotically applied to extremely tight tolerances through careful hardware design and coating process development.

The F-35 Robotic Aircraft Finishing System is designed for precise coating thickness control. Several key capabilities of the system have been highlighted, including the use of COTS technology and a novel Paint Cell Dolly for high positional accuracy, as well as positive displacement pumps for precise paint delivery.

Careful coating process development is required to utilize RAFS hardware to its full potential. Plume and panel studies are conducted to set CDS parameters, and offline programming software is used to efficiently create robot motion programs. The techniques for optimizing robot programs have been presented, including a new method of visualizing coating thickness results in a 3D CAD model of the aircraft.

The RAFS hardware capabilities and process development methods were validated by the first successful coating of a production F-35 aircraft at RAFS in December 2008. Coating thickness control on the robotically coated BF:002 unit was far superior to hand-coating results on BF:001.

ACKNOWLEDGMENTS

In addition to Manufacturing Technology, other groups at Lockheed Martin contributed to the design and development work described in this paper. Specifically, Final Finishes Manufacturing Engineering led the specification of the Paint Cell Dolly, and NC Programming created and modified robot programs for all coating operations. The installation of the Robotic Aircraft Finishing System was contracted to Pratt & Whitney Automation, Inc. and the fabrication of the Paint Cell Dolly was contracted to Innoventor, Inc.

REFERENCES

1. Drotning, W., "Robotic Aircraft Maintenance Activities", Intelligent Systems and Robotics Center, Sandia National Laboratories, Joint Technology Exchange Group, 2001. Available online: http://www.jdmag.wpafb.af.mil/robotic%20aircraft.pdf
2. O'Keefe, M., "Robotic Coatings Automation", Technology Review Journal, Northrop Grumman, 2004. Available online: http://www.is.northropgrumman.com/about/ngtr_journal/assets/TRJ-2004/SS/04ss_OKeefe.pdf
3. Warwick, G. et al., "The F-22 Story, Painting by Numbers", A Flight International Supplement, 1997, p. 27
4. Thornton, J., "Simulations Speed & Smooth Automated Coatings on F-35 Aircraft", Robotics World, January 2006

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CDS: Coating Delivery System. Controls and monitors the delivery of fluid paint to the gun at the end effector

Major Axis (Plume): The width of the plume in the long direction. The major axis of the plume is oriented perpendicular to the direction of robot motion (or the direction of the stroke)

Minor Axis (Plume): The width of the plume in the short direction.

Stepover Distance: The distance between adjacent strokes.

Standoff Distance: The distance from the Tool Center Point of the end effector to the coated surface