It's Time for Your Robot

By Scott Adams, The Boeing Company

Adding a painting robot to a production process can bring with it improved quality and productivity. The functionality and cost of robotic paint systems has improved tremendously over the past two decades, and the technology is earning its way into small and medium-size production operations.

Coating systems bring tremendous value in decorative application and functionality to products. At the same time, the industry goes to great lengths to minimize or eliminate human exposure to overspray and solvent vapors.

For repetitive coating processes, a robot can be a great way to minimize human exposure, provide a stable and uniform film across months and years of production, and maximize production throughput. It is not difficult to program a robot to move along a path at a given speed and trigger a paint applicator nor is it difficult for a human to wave their arms and trigger a spray gun. Knowing how to properly configure the applicator, coordinate triggers and motions, and manage process variables is what separates a highly skilled painter from an unskilled sprayer.

There can be a dozen or more interrelated factors at play during a coating application process. What seems simple on the surface has left many capable engineers and chemists wringing their hands in frustration while spraying hundreds or even thousands of test panels to find optimal application settings for their robotic application process.

A trial-and-error setup approach is expensive, time consuming, and frustrating for everyone involved. Fortunately, there is a very successful and time-tested structured methodology employed by many of the coating industry's most capable users, applicator manufacturers, robot manufacturers, and material formulators.

With a data-driven and structured approach, any organization with a robot and a paint applicator can leverage these techniques to greatly reduce the time and effort required to set up a high-quality robotic painting process. There is a wealth of technical literature available on paint atomization, coating formulation, and robotic optimization.

A person new to this rapidly growing field of automated paint application may find themselves overwhelmed with data or may not realize that they are reinventing wheels that were perfected long ago.

This article will walk through the first and often the most complex part of a robotic application setup process, explain practical techniques, define some basic process acceptance criteria, and define typical terminology used by some of the industry's most capable paint application specialists.

APPLICATION PROCESS OVERVIEW

A successful robotic paint application plan is rooted in well-informed choices, trials and tests that revise or confirm those choices, and an approach that successively builds complex processes with confirmed data. It is nearly impossible to "guess and check" robot path and applicator parameters that will result in a stable quality coating without wasting significant time and material.

Another approach often doomed to failure involves creating an "efficient" path for the robot and then attempting, usually for weeks or months, to find applicator parameters

to Paint!

Robot painting the wing of a Boeing 777 in Everett, WA. ©Photographer Credit: Ronald Wu

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that meet the requirements of the robot path. An analogy of trying to install the roof of a house before the foundation is poured comes to mind. A systematic setup process can be performed on relatively inexpensive metal coupons and masking paper that will save a tremendous amount of time, expense, rework, and headaches.

The steps outlined in *Figure 1* illustrate the process. Avoid the urge to skip steps in the interest of time, money, or professional ego. If the assumptions are correct, the test will be quick, easy, and use minimal resources. If the assumption is incorrect and not realized at the proper stage, all the downstream steps will be wasted effort and will need to be repeated. Each of these tasks will be described with the general criteria for acceptance before moving on to the next step.

PROCESS CONSIDERATIONS

When initially designing an automated painting process there are some basic parameters that the system must be designed around. Some of these items are simple and straightforward. Some will be defined by the product that will be coated or the materials that will be used. Some of these values can be estimated with basic spreadsheet calculations. At this stage the numbers need not be firm or exact, but effort spent defining process needs will reduce the number of trials and design iterations that will be needed later.

Fluid-flow rate

What is the rate of the coating material that needs to be atomized? This is typically measured in cc/minute. For a new product, this is something that may need to be estimated. Begin by determining the required film thickness on the work piece. Then decide if the coating be applied in a single coat or if multiple coats are needed.

Calculate this using the percent solids *by volume* of the coating material and the surface area to be coated. The necessary fluid-flow rate from each applicator can be determined through an estimated real-world transfer efficiency (typically 30-45% for high pressure air atomized guns, 65-78% for high volume low pressure (HVLP) guns, and 55-95% for rotary atomizers with electrostatics) (Sadegh Poozesh, 2018), and the expected gun-on time for the robotic process. For paint applicators the fluid flow should usually be somewhere between 100 cc/min and a maximum of about 500cc/min. High flow rate, dual-headed, and airless applicators are less common but also available for special applications

Painting Tip Speeds

For a given paint film thickness, higher fluid flow allows the robot to move faster and complete the application process in less time. Often the goal is to maximize the use of the robot and apply coating as quickly as possible. This is a solid concept up to a point. As the robot tip speed increases beyond about 800mm/sec, the paint spray pattern begins to distort.

The degree of this distortion depends on the application method, the material properties, the fluid-flow rate, the target geometry, and the air flow in the spray booth. Often at approximately 1000mm/sec, the pattern is distorted enough to have a significant impact on the film uniformity, color, and appearance.

A fast-moving robot also decreases transfer efficiency and results in excess overspray buildup on the robot and surrounding surfaces. Typical application speeds are usually between 500mm/sec and 800mm/sec and seldom exceed 1000mm/sec. Film thickness tends to scale linearly with tip speed so for many applications it is wise to target a midpoint to allow some room to adjust film thickness as the process is refined.

Number of Passes

As the process is initially defined it is easy to assume that a continuous film of a particular coating will be applied in a single pass. Can it really be applied in a single coat without sagging? What happens when the application temperature changes slightly from summer to winter? What happens if there is a slight variation in the viscosity or shear rate of a batch of material? Will a single coat deliver the appearance (e.g., orange peel and gloss) and color that the process demands?

Conversely, will multiple passes result in fluid flows below the capability of the automation or result in a rough collection of dry droplets on work piece? These questions are often hard to answer at the beginning of a paint automation project but a little research and testing in a paint application lab can avoid a tremendous amount of rework later in the setup process.

Work Piece Geometry

The geometry of the surface that the coating will be applied to will have a very large impact on the selection of components. On a deeply contoured surface shaped like the inside of a rain gutter, it might be wise to use a high-velocity spray gun with a narrow fan pattern and plan for multiple strokes at different angles to coat the entire surface.

Surfaces that are much larger than the robot may allow for larger low-velocity spray patterns which results in a higher transfer efficiency process. In situations where a high-voltage/high-transfer efficiency applicator is being considered, part geometry will be a primary factor in the uniformity of the applied coating.

In the initial concept stage, it is rare for all assumptions to be perfectly correct, but it starts the process of refining the robot and application equipment. These assumptions allow an engineer to figure out how many robots will be necessary. A rough estimate of fluid flows and tip speeds can help define requirements for the fluid-delivery system.

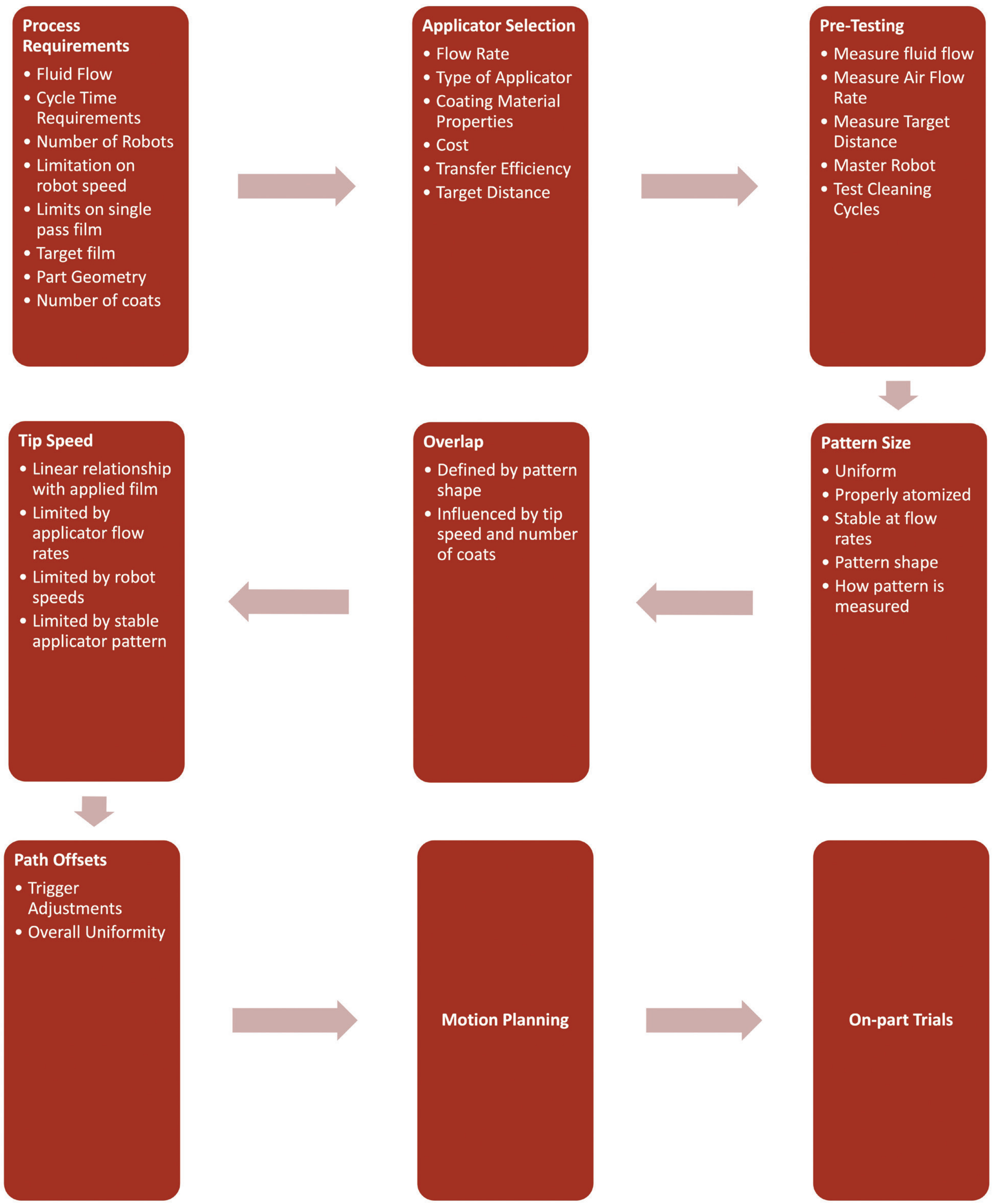
Gaining an understanding of the fluid-delivery system will help refine the robot size and payload capacity, which will help identify suitable commercial automation for a particular process. A requirements-based understanding of the process will pave the way to the selection of an appropriate applicator.

APPLICATOR SELECTION

The paint applicator is the most critical piece of hardware in any paint application process. The applicator performs the critical role of atomizing the liquid material, distributing the atomized droplets within the spray plume, and transporting those droplets to the target surface to create a uniform film.

There are many techniques to atomize coatings. Whether it is a high-volume, low-pressure (HVLP) spray gun, an electrostatic rotary “bell” atomizer,

FIGURE 1—General Robotic Coating Application Setup Process



or a high-pressure airless spray gun, the applicator performs the same role. Within each of these applicator types, there is a wide selection of commercial offerings available for different materials and uses.

The physics involved and tradeoffs between application methods are beyond the scope of this article, but it is important to understand the coating material properties, the fluid-flow rate, pattern size, part geometry, required transfer efficiency, and atomization requirements, which all factor into the decision.

The manufacturer of a particular coating is typically a great source of information about successful application techniques. After all, the material formulator likely performed a tremendous amount of testing before bringing the material to market and "tuned" the material properties for a particular application technique. If the coating has been successfully applied using a manual spray gun in a current process, that equipment may serve as a good starting point for a robotic applicator.

In many cases applicator manufacturers offer both manual and automated versions of the same applicator. Fluid tips and air caps may even be interchangeable between manual and automated guns. This might be beneficial from an operator and equipment maintenance standpoint but realize that a paint robot is not a substitute for a human. It cannot "read" the coating as it is being applied as a skilled painter can. It will be much more difficult to adjust tip speed and compensate for coating-shear-rate changes across the pot-life of a multicomponent system.

Likewise, applicator options such as rotary "bells" and dual-headed spray guns are only viable for use with paint robots. If the dizzying array of applicator options leads to confusion, do not hesitate to reach out to applicator manufacturers for advice. With some basic information, a technical representative should be able to help you identify the best choices within a product line. In many cases, the applicator manufacturer may be willing to demonstrate their applicators with your coating.

The cost of the applicator also tends to be a relevant factor in the decision-making process. Features such as high voltage, dual main needles, air turbines, and integrated fluid recovery systems all add functionality, but they also add complexity and cost. For a simple application of a functional coating at a low or medium production rate, this technology may cost more than it will ever save.

At the other end of the spectrum, an automotive original equipment manufacturer with decorative painting processes applying hundreds or even a thousand gallons of paint per robot per day would never consider an applicator without these features. In high-volume production, even a small improvement in transfer efficiency and cleanliness pays off quickly.

Determining which applicator features are important requires an accurate assessment of a how a particular paint robot will be used. Using the simplest and lowest-cost paint applicator to apply an expensive paint with important color and appearance requirements may turn out to be a very expensive decision once the material waste and part rework is considered.

Settling on a very feature-rich and expensive applicator when the functionality is not required can be equally expensive and frustrating. Would you ever consider buying a Formula 1 race car and training a pit crew to maintain it just to drive to the grocery store? Choose the applicator wisely and prepare to validate that choice in the next step of the process.

APPLICATOR TESTING

Naturally, every application engineer wants to proceed directly to spraying paint and begin to define spray parameters as quickly as possible. The robot programmer(s) are going to need the index, tip speed, tool center point, and associated application details defined before they can start any offline programming, but those details are meaningless unless the system is stable, and the values can be trusted.

This is a painful lesson too often realized later in the process. Whether the testing is occurring on a surrogate lab system or on the actual production robot, begin by verifying assumptions and checking the calibration of the robot, fluid-delivery system, and the selected applicator.

If the system has been properly configured, the calibration checks should only take a short time to verify. Remember, mistakes at this stage can compound over weeks and months and risk a tremendous amount of rework. Those charged with setting up the coating process are cautioned not to make any assumptions about the equipment and to personally verify the robot mastering, the fluid-system calibration, the process-air calibration, and the fluid-system purge cycles.

The robot mastering process conveys to the robot controller the physical position of each link and axis of the robot. Robot motion is planned and executed by a kinematic engine in the robot's controller to ensure that the tool center point (TCP) of the applicator moves past the part to be painted in a particular orientation and speed.

If the joints of the robot are not where this kinematic engine believes they are, the applicator orientation relative to the part may be incorrect, the target distance across the part may not be correct, and the velocity of the applicator may not be stable. In a worst-case scenario, the robot or applicator could collide with the part or a solid object within the spray booth.

During their lives, all robots will need to be remastered when a part is replaced or power to an encoder is lost. It is practically impossible to correct an application program that has been optimized on an incorrectly mastered robot. A process that may have been finely tuned and running perfectly for years can be lost due to brief power flicker, a dead "D-cell" backup battery, and the need to remaster the robot.

The mastering process varies by robot manufacturer, but typically involves moving the robot into a mastering fixture or aligning precision machined marks on each axis. It is important to follow the robot manufacturer's written mastering procedure and be as precise as possible for repeatable results.

Paint fluid calibration is the next critical step. The exact procedure will vary based on the mechanics of the fluid-delivery system but typically consists of commanding a fluid-flow rate, dispensing for 30 seconds or 1 minute, and measuring that volume of material with a graduated cylinder or by calculating the dispensed volume based on the mass and known material density. This is repeated at the lowest expected paint flow, a midpoint, and the maximum fluid-flow rate. A calibration factor may need to be adjusted.

The acceptable precision will depend on the fluid system components, but positive displacement pumps are often capable of better than +/-5% by volume. Be aware that the shear rate of the coating can impact the precision. It is therefore important to use production intent coating for this step in the process. Do not calibrate with a thin solvent and expect the dispense rate to be correct for a thicker paint material.

Compressed air is used to shape spray patterns and atomize paint, and, in some applicators, it is used to drive a turbine for atomization or to generate a high-voltage charge. It is important that the volume and pressure of this air is precisely controlled.

For traditional high-air-pressure atomizers and HVLP guns, it is possible to measure the air pressure at the applicator's air cap with a common air-cap-pressure tool. If the air cap is perfectly clean this is a very meaningful number. The pressure correlates to the velocity of the air used to break up fluid ligaments into droplets and form the spray pattern.

Unfortunately, if the holes in the air cap or shaping air ring become obstructed, an inline air pressure transducer may continue to hold the same pressure but at a greatly reduced flow rate. The spray pattern may deviate significantly with little or no indication to the robot operator. When this happens the coating quality and uniformity can be impacted.

For this reason, much of the robotic paint industry has transitioned to measuring and controlling the volumetric airflow rates. It is important to calibrate integrated robot flow-rate transducers with the use of a calibrated inline airflow meter as the robot is being configured. An incorrect calibration can cause major problems when components are replaced in the future.

Loading paint material and cleaning that material from the fluid-delivery system is the final step in the pre-testing process. Paint residue left inside the paint lines, valves, and fittings can induce all sorts of unexpected behavior. Sticking valves may not open or close as intended and could cause material from one system to flow into another. Residue may restrict fluid flow in the system or cause a high-voltage pinhole to form in Teflon paint lines. Pumps and mixing elements may not pump correctly or mix material as intended. Flakes or globules of coating can break free from the lines during application and either plug the applicator or produce defects on the coated part.

These problems can quickly result in an unstable process. The programmed cleaning process must be checked and adjusted. A sound cleaning strategy avoids pushing waste material through the paint applicator, uses fractional second pulses of compressed air and solvent to clean the lines in controlled sections, and prevents buildup in the fluid-delivery system.

Once the system visually looks clean, it is recommended that fittings be removed and inspected, pumps opened and inspected, and the system inspected again after several weeks or a month of operation. The "best" cleaning cycle will be different for every machine configuration, for each paint material, and for each purge solvent.

Once the basic calibrations for the robot, fluid-delivery system, applicator, and cleaning process have been verified, there is confidence that the robot is performing as it is being commanded. The next step is to begin defining the application window.

SPRAY PATTERN DEVELOPMENT

The goal of defining a spray pattern is to find the proper values of paint applicator parameters to produce a uniformly atomized and distributed pattern of droplets for a particular application. In most cases the individual applicator settings consisting of fluid flow, atomizing air, and fan air for a spray gun, or fluid flow, turbine speed, and shaping air settings for a rotary atomizer, all interact with each other. Changing just one of these values results in a change to the spray pattern.

To further complicate matters, the interactions are seldom simple nor do they have a linear relationship with the resulting spray pattern. For a robotic application process, it is critical to maintain a consistent spray pattern size. The first step is to identify a spray pattern size that is achievable across the range of desired fluid-flow rates.

There are excellent resources available from both paint applicator manufacturers and coating suppliers that help guide a user in understanding how to visually set up an applicator spray pattern. These resources illustrate many different spray conditions and often provide guidance on which settings to change to visually improve the pattern.

For the sake of simplicity, the examples described here will focus on a large pattern HVLP spray-gun applicator. The examples are not intended to be a comprehensive overview of every atomization condition, but rather to introduce the concept of objective measurement of spray patterns. Guidance will be different for air atomized guns, airless guns, and rotary atomizers, but the pattern development methods and techniques described below will apply to all.

STATIC SPRAY PATTERN

One can simply jog the robot with the applicator to a vertical surface covered with paper, set the desired target distance from the board, and position the applicator so that the pattern is oriented horizontally (for a spray gun). Triggering the applicator for 3-8 seconds can often evaluate the drip pattern and find a starting point.

This is exactly the same procedure used to set up a spray gun for a manual paint process. Once a uniform drip pattern is achieved for a given fluid flow, the robot operator records the settings and moves on to the next fluid flow until they have worked their way across desired range. At this stage the evaluation is crude and measurements imprecise, but it is quick and highly effective. If the pattern does not visually look uniform and well atomized at this stage, there is no need to proceed forward with the next step of dynamically checking the spray pattern.

Be aware that multiple solutions for stable spray patterns at a given fluid-flow rate are often possible. These solutions may produce a similar pattern size but the particle size distribution of the droplets could be different. For functional coatings multiple solutions may all be usable, but for some coatings there might be trade-offs between orange-peel, color position, and the amount of volatile solvents remaining in the coating after application (Ellwood, 2014). In the most demanding applications, highly structured designs of experiments and sophisticated spray analysis equipment are used to find optimal settings.

TESTING THE DYNAMIC APPLICATOR PATTERN

The purpose of this check is to determine whether the paint applicator is producing a well-atomized and stable pattern and be able to objectively determine the size and profile of the film being applied. It consists of a long strip of metal, typically either aluminum or steel at least three times the expected pattern width. The strip is often cleaned to remove oils and contaminants, abraded or chemically deoxidized to remove any surface oxides, wiped with isopropyl alcohol, and finally wiped with a tack cloth just before testing.

The path of the robotic applicator should be programmed so that the target distance from the applicator to the panel will be the same target distance that is planned for production. For most paint applicators this range is typically between 8 and 10 inches. This can be quickly and easily verified with the use of two cable ties taped to the applicator such that the tip is 8 to 10 inches from the applicator and forms a "V."

This verification is best conducted on a vertical test board with the bottom at least 3-4 feet from the paint booth floor. It is recommended that the test board be placed at a location within the booth with airflow representative of the part to be painted. The robot path should be set up normal to the panel plane, in the center of the panel, and programmed so that it triggers on and off no fewer than 24 inches away from each side of the panel.

While triggered on, the applicator should apply a film layer to the center of the panel. Depending on the material, the fluid-flow rate and the sag resistance of the paint material, making two passes over the exact same line on the panel to establish the pattern shape may reduce measurement noise.

The coating should be dried or cured in accordance with the applicable coating specification for that coating system. Once the panel is fully cured, film measurements are taken in the center down the length of the panel using a Fisher Isoscope, Fisher Dualscope, Elcometer or similar eddy current film measurement device.

When using these instruments, it is extremely important to inspect the table or surface that the panels will be measured on to ensure there are no metal supports or fasteners that will be under the panel. Any metal other than the panel being measured will interfere with the accuracy of the instrument and film measurements will not be repeatable. It is also important to recalibrate the instrument using the calibration films nearest to the expected measurement range before each batch of measurements. This may require multiple calibrations per measurement session depending on the elapsed time and the coating thickness.

INTERPRETING DYNAMIC PATTERN DATA

Establishing a stable dynamic pattern is the fundamental building block that the rest of the paint process is based upon. The applicator's primary job is to break up the paint material into a uniform distribution of particles. The more capable the applicator is for a given material, the narrower that droplet size distribution is.

This is important to ensure that the film "knits" together on the surface of the part without dripping, sagging, or mottling. To explain what the dynamic pattern of a normal spray pattern should look like, it is necessary to explain a few common application problems and show what is not normal.

Under-atomizing the paint will result in large droplets that contain larger amounts

FIGURE 2—Easy Stand-off Distance Check Method

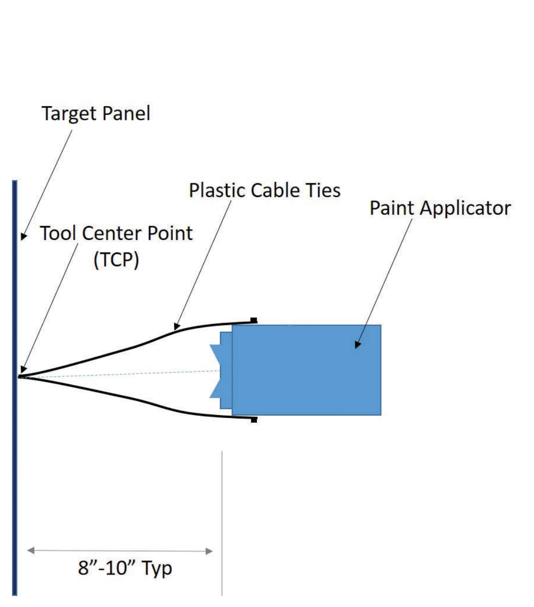
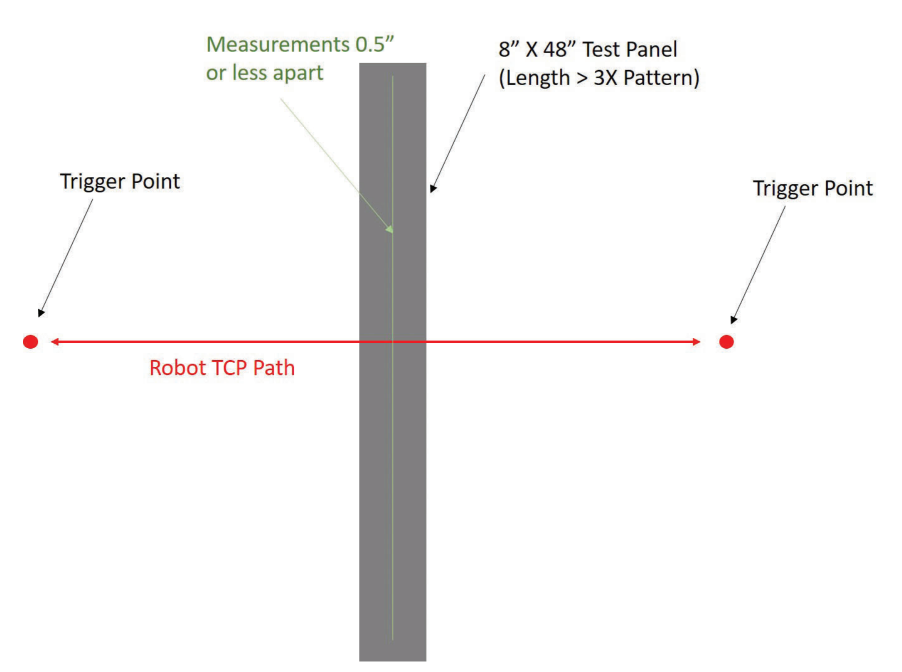


FIGURE 3—Dynamic Spray Pattern Test Configuration



of solvent, because not as much paint evaporates during the transport phase. Under-atomization typically results in films that are very prone to sagging, running, or experiencing solvent-pop issues.

Over-atomizing the material results in small droplets that do not have sufficient solvents remaining once they reach the part to "knit" together (droplets reflow) on the part surface to create a continuous film. Over-atomized paint, often referred to as dry spray, tends to visually look as though it has a dull or rough appearance. Under a microscope it has the appearance of individual droplets stuck together with gaps between the drops.

This film may not have the strength of a continuous film from an adhesion standpoint. Over-atomized droplets are much smaller and tend to have less momentum to make it to the part during the transport phase. Downdraft air currents tend to have a greater impact on these small particles within the booth, resulting in poor transfer efficiency.

A poor applicator setup can also result in both under-atomized and over-atomized droplets being produced at the same time. This occurs due to the variation in drag forces the droplets encounter as a function of position from the applicator. Fortunately, these conditions can typically be recognized by the shape of the spray pattern.

The applicator is also designed to distribute the atomized paint particles as uniformly as possible and to create a pattern. Improper adjustments can result in sharp peaks and valleys within the pattern. It can also result in larger and wetter droplets being deposited in one area with more finely atomized particles being deposited in another area.

There are many more potential causes of a distorted spray pattern than can be explored here, but the same applicator guides used for static testing will also assist with the analysis of the dynamic pattern. Recognizing the basic profiles of under-atomization and over-atomization while considering the overall pattern shape will provide insight when adjusting spray parameters.

FIGURE 4—Under-Atomized Dynamic Pattern

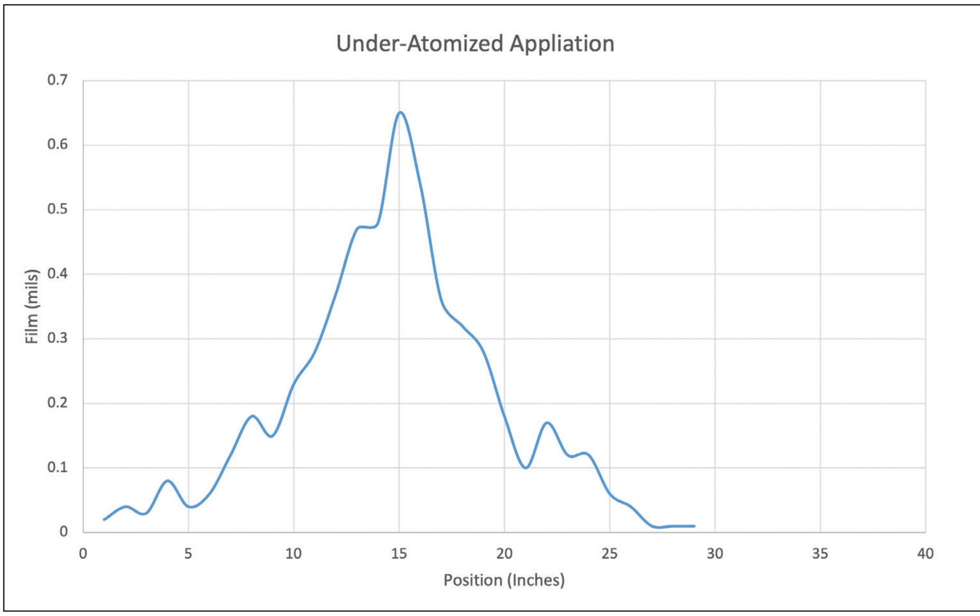
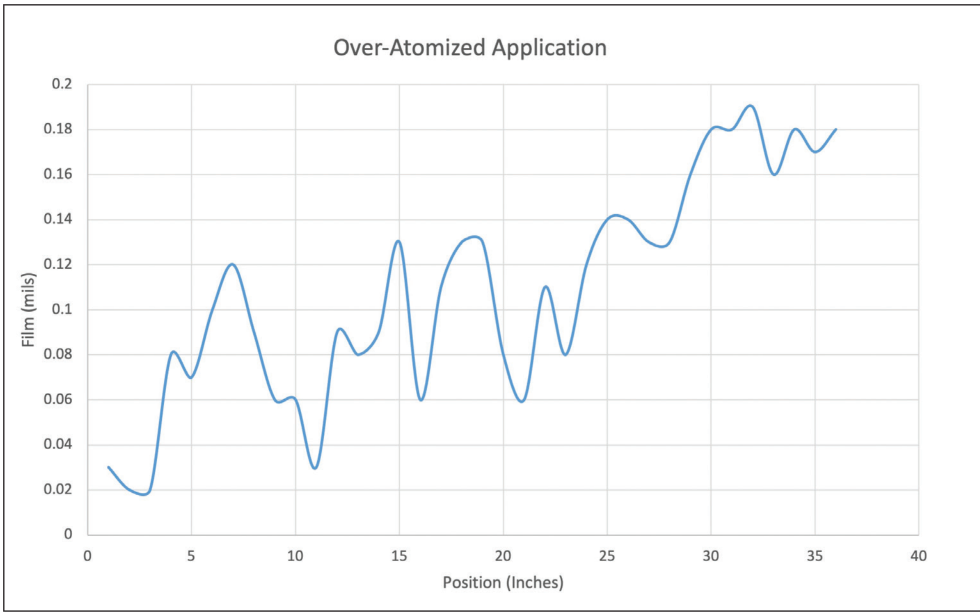


FIGURE 5—Over-Atomized Dynamic Pattern



UNDER-ATOMIZED PATTERN

An under-atomized spray pattern with a spray gun often has a sharp peak in the center as shown in *Figure 4*. On the target surface, individually discernable droplets will be visible at the pattern edges. This pattern has a very narrow pattern size. Because the droplets are relatively large when they reach the target surface, the film has a relatively high concentration of volatiles, which causes the coating to sag or run at film thicknesses where this is typically not a problem. In less extreme cases, increased long wavelength orange peel or "micro-sag" can be seen along the length of the applicator travel.

OVER-ATOMIZED PATTERN

A spray pattern (if it can be called a pattern in this condition) that is over-atomized coats the target as an unstructured cloud of droplets as shown in *Figure 5*. There is little or no clearly defined pattern curve, but the film measurement shows a random thin film across the panel. In this example the film thickness increases at the bottom of the panel. This is likely influenced by the downdraft within the booth. An over-atomized or "dry sprayed" pattern

FIGURE 6—Dog Bone Dynamic Pattern

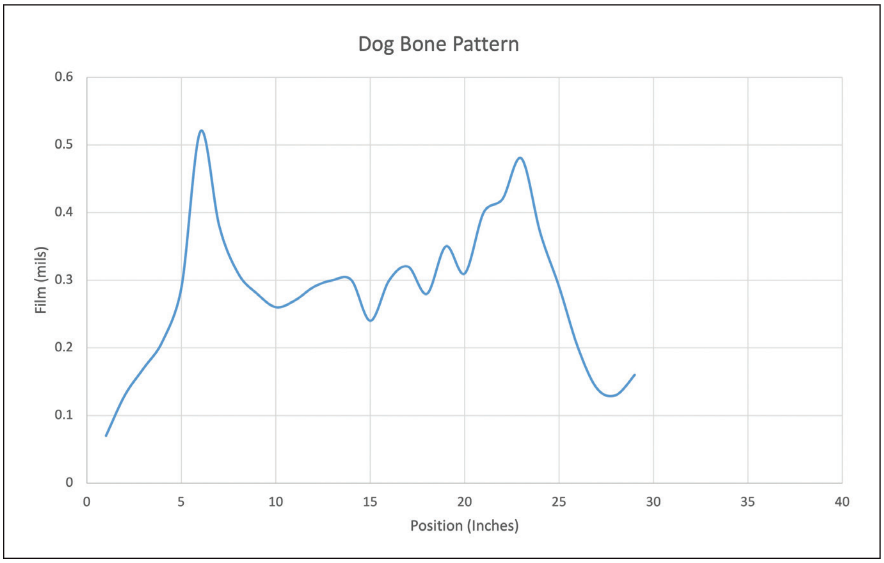


FIGURE 7—Normal Dynamic Pattern

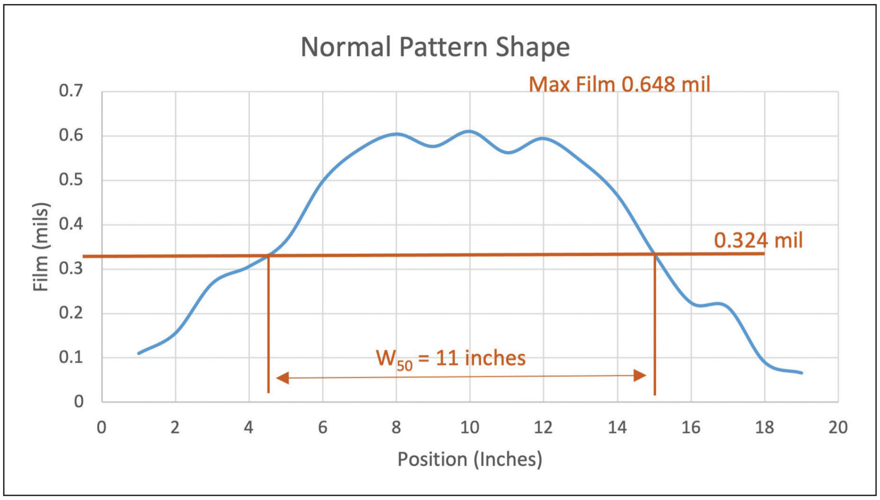
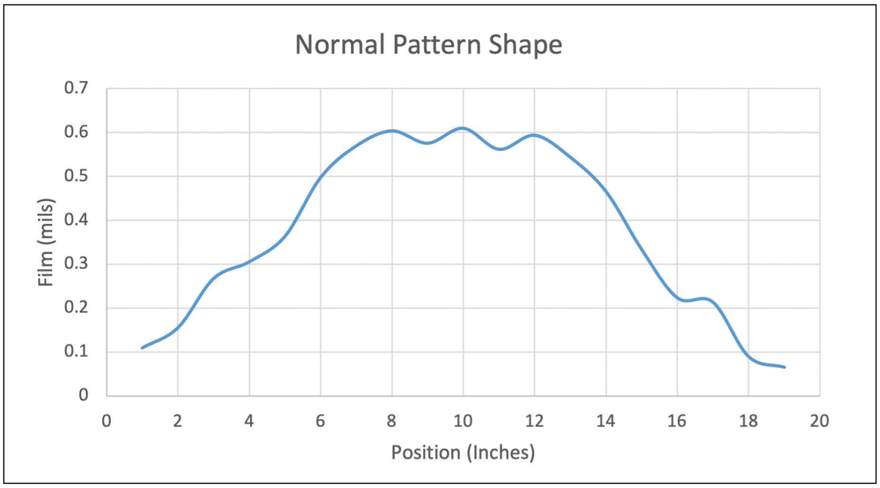


FIGURE 8—Determining Pattern Width



could also return a large W_{50} value, yet a paint engineer would easily recognize this as a cloud of overspray deposited on the test panel and not useful for a production process.

PATTERN SHAPE

The shape of the spray pattern provides a good clue as to what is taking place. The pattern in *Figure 6*, for example, is referred to as a "dog bone" by painters because if it is sprayed statically it consists of a round circle on one side connected with a thin band of paint to another round circle on the other side. This pattern is also likely to produce two different droplet size distributions, under-atomized and over-atomized at the same time. With the dynamic film profile data and a little thought, it is possible to identify problems and make fine adjustments to the spray pattern that will not be obvious with a static pattern or with a simple visual evaluation.

NORMAL PATTERN

A normal applicator spray pattern resembles the shape of a statistically normal curve and has a normal droplet size distribution within the spray plume as shown in *Figure 7*. It is also the most useful dynamic pattern for robotic paint applicators; "normal" in every sense of the word.

This pattern has a symmetric profile from the left side to the right side. The film slopes on the side of the pattern are close to being linear and the top of the pattern is a "plateau" with a stable film. The longer the pattern plateau is and the shallower the pattern edge slope is, the easier it will be to overlap and paint large areas uniformly.

In manufacturing situations where the positional accuracy of the applicator relative to the part may vary slightly from one piece to another, shallow pattern profile edges can provide an increased level of process stability and be a desirable attribute. For small parts, in applications where minimal overspray is important, or where part positional accuracy is not a concern, a pattern with a steeper profile may be desired. For most types of paint applicators, achieving a stable pattern with a normal profile at the desired fluid-flow rate(s) is the goal.

FIGURE 9—Width of a "Dog Bone" Spray Pattern

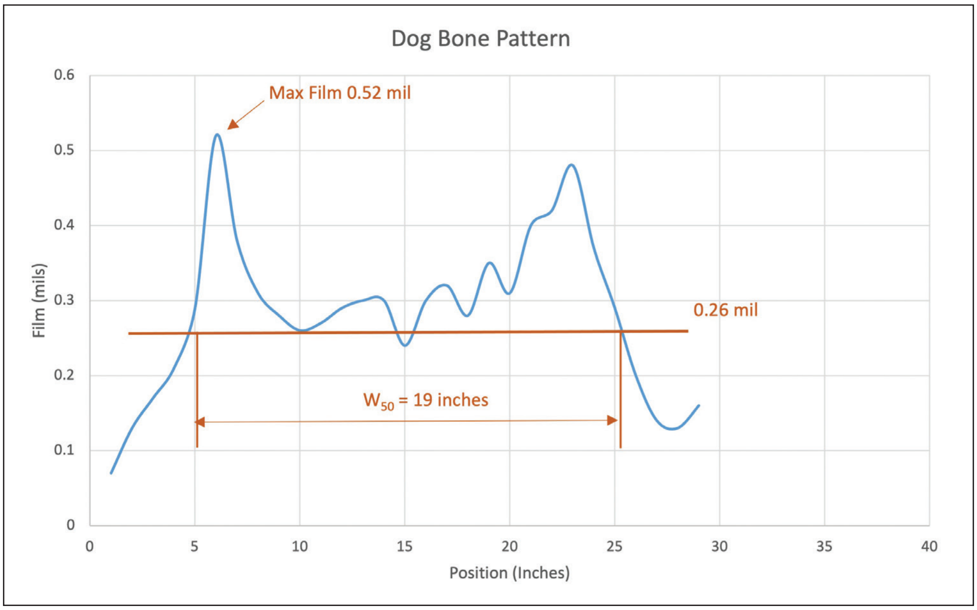
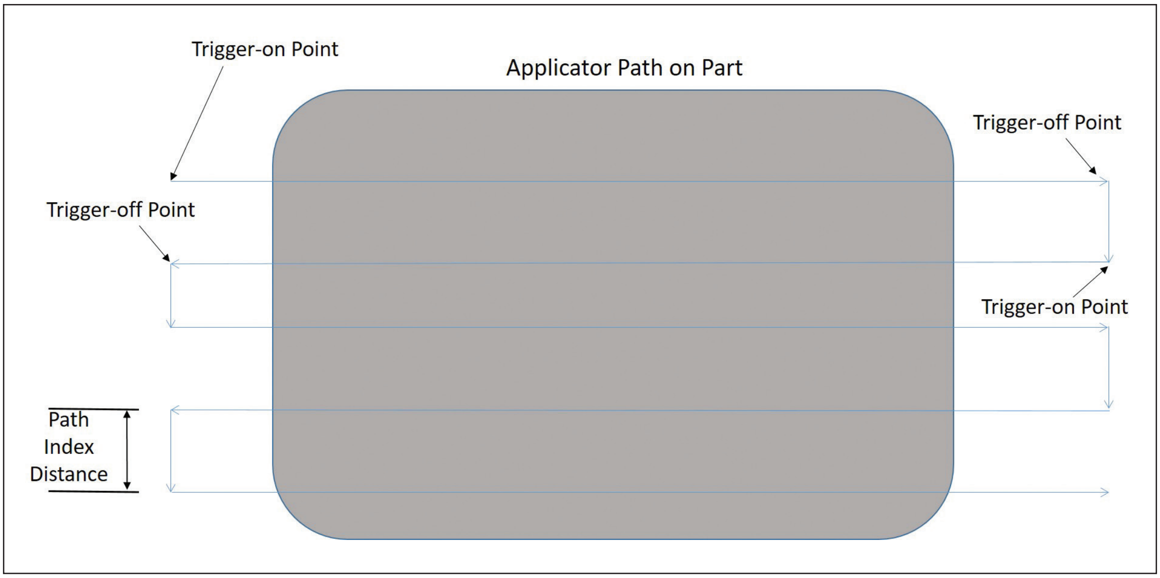


FIGURE 10—Robotic Path Index



Determining the Pattern Width

Determining the paint pattern size is an important factor in establishing the proper robot path offset to create a uniform film on the part as shown in *Figure 8*. Attempting to visually determine the pattern width is highly subjective and can be affected by the lighting where it is being evaluated, how "wet" or "dry" the application was, how much flash time has elapsed since being applied, the hiding capability of the paint, and the human making the determination.

To eliminate those noise factors, the technical paint community has established a standardized method to empirically determine the pattern size. This method is referred to as the W_{50} pattern (Braslaw, 1998).

The first step in determining the W_{50} is to find the maximum film thickness on the panel. The maximum film is then divided in half. The width of the pattern with values that are above 50% of the maximum film is then measured.

While this method is quite useful for determining the approximate pattern width, it is does not provide any information about the quality of the pattern. For example, the "dog bone" pattern from *Figure 6* would return a large pattern size even though several points in the middle of the pattern are below the threshold as shown in *Figure 9*.

Index, Overlaps, and Offsets

Spray-pattern profiles typically resemble a curve with tails of thinning film rather than a flat uniform profile with well-defined edges. To obtain a uniform paint film on a flat part, one must determine the optimal distance between the centerline of each applicator stroke. This distance, illustrated in *Figure 10*, is

FIGURE 11—Idealized Dynamic Spray Pattern

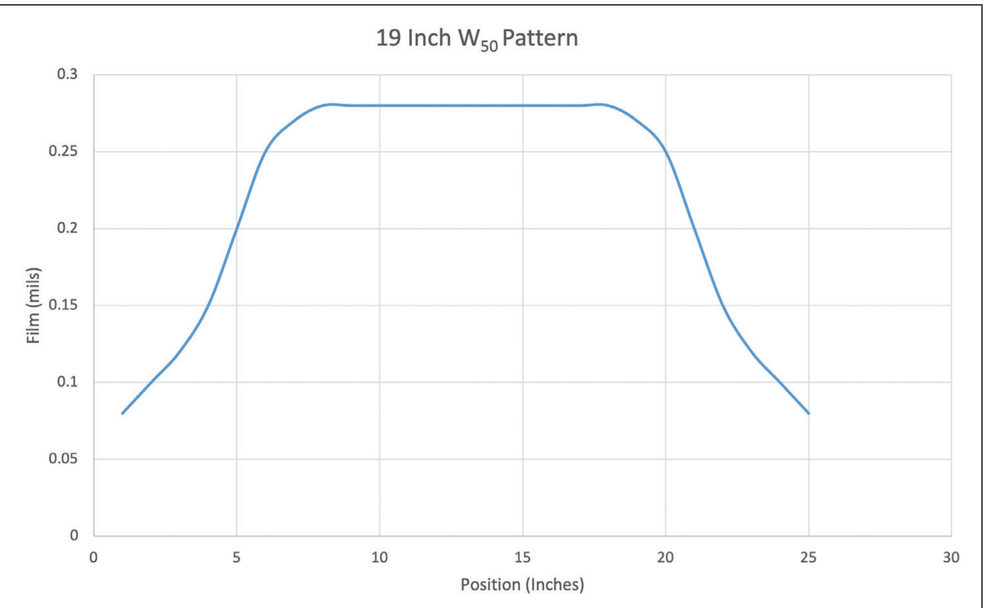


FIGURE 12—Spray Pattern Overlap, Narrow Index

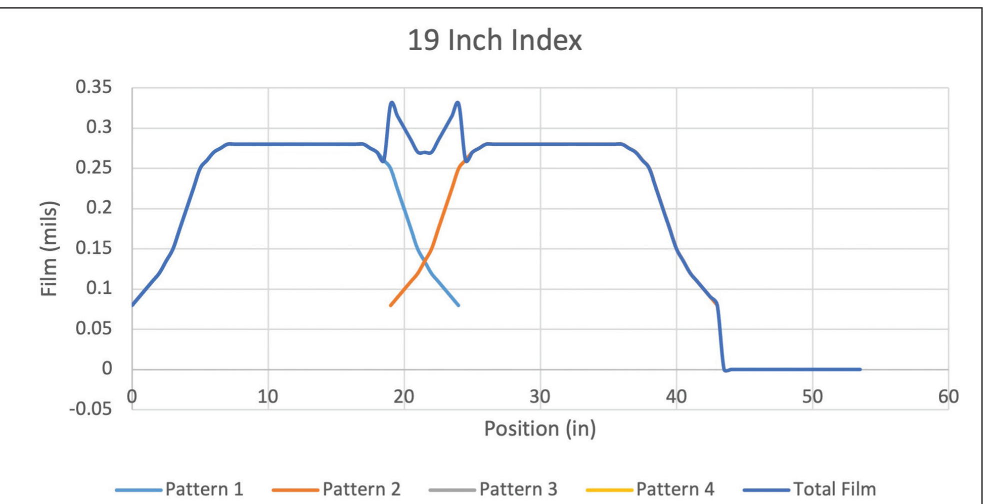
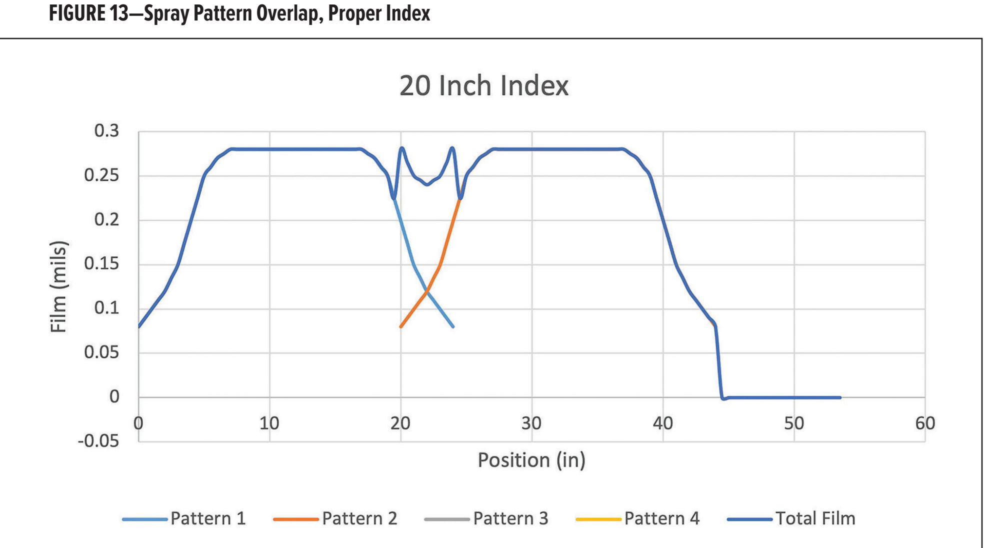


FIGURE 13—Spray Pattern Overlap, Proper Index



referred to as the path index distance, or "index," and is typically measured in millimeters or inches. The index distance by itself does not directly convey any information about the width or the shape of the spray pattern. The proper index to use for an application should be determined by the spray pattern.

The W_{50} for a given fluid flow and application parameters provides a rough approximation of how far apart these strokes should be, but does not consider the shape of the pattern. Knowing what the slope is on each edge of the pattern is crucial in obtaining a uniform film.

Consider a hypothetical applicator with a spray pattern that is approximately a trapezoid in shape with a W_{50} pattern size of 19 inches shown in *Figure 11*. If we make the index 19 inches, the same as the W_{50} pattern size, we get an overlap that looks like *Figure 12*. Note the spike of nearly 25% in the total film where the tails of the pattern meet. A slight change in the slope of the pattern or the index between strokes can reduce the variation in total film.

Increasing the index to 20 inches reduces the variation of a single pass film in the example shown in *Figure 13*.

The peaks are at 0.28 mil with valleys at 0.24 mil; a range of 0.04 mil.

If the index is set too wide for a given applicator pattern, a stripe of thin film can occur in between each stroke. From these examples it should also be clear why collecting the pattern film measurements at the smallest practical resolution can provide a better understanding of the pattern shape and can speed the process of finding the optimal index spacing.

WHAT IS AN OVERLAP?

It is rare that an applicator has a perfectly flat plateau around the pattern's maximum film. It is much more common for the pattern to be a slightly uneven curve or even have multiple film thickness "bumps" within the pattern.

Different types of applicators also tend to have slightly different characteristic curves. To minimize the variation caused by an imperfect pattern, a sound paint application strategy is to apply the same total film thickness with multiple strokes that are strategically shifted.

Consider the same applicator pattern shown in *Figure 11* with a W_{50} of

19 inches. It is obvious that if the index were adjusted to 9.5 inches based only on the W_{50} value, twice the amount of film would be deposited. If the robot tip speed were to also double, the film thickness would be reduced by approximately half (or if one were to find the same W_{50} pattern shape at half of the fluid flow). The result would resemble *Figure 14*.

The film plateau ranges from the peaks of 0.305 mils to valleys of 0.27 mils with a standard deviation of .0107 mils. Note the high peak films resembling those in *Figure 12*.

Altering the index to 10 inches instead of 9.5 inches would help reduce the variation resulting in the film profile shown in *Figure 15*.

For a 10-inch index, the film plateau ranges from 0.28 mil at the peaks to 0.256 mil in the valleys with a range of 0.024 mil. The standard deviation of the plateau improves to 0.0085 mil, indicating a more uniform film. While this may not sound like a large number, often coatings are applied at four times this thickness (or more) and consequently the variation between high and low points would quadruple. If one is not careful, the variation in pattern stack-ups can have a large impact on the standard deviation of the dry film thickness even before booth, part, and material variation are considered.

The above examples demonstrated an overlap of 50% and 47%, but overlaps around 66% and 75% are also quite common depending on the profile of the applicator pattern. They also demonstrate the importance of including overlap strokes around the edges of parts to achieve the full paint film over the entire intended surface.

Overlap Terminology

Within the technical paint community in the United States, overlap is usually specified in terms of a percentage of the pattern value. A 50% index for a 19-inch pattern would be 9.5 inches; 50% of the second stroke is overlapped onto the first stroke. The general formula for percent overlap is:

$$1 - \frac{Index}{W_{50}} = \%Overlap$$

An alternate method to specify overlap is in terms of multiples of overlaps or "times overlap" and is more prevalent among the European paint technical community. The general equation for times overlap is:

$$\frac{W_{50}}{Index} = Times\ Overlap$$

Although both methods of specifying overlap do so as a function of W_{50}, remember that pattern shape and not the width of the pattern should determine the proper index.

WHAT IS AN OFFSET?

Many paints are applied in two or more coats to achieve target films. If a second coat is applied with exactly the same robot path and exactly the same application parameters, the inherent variation in the total film will increase. Effectively, the film peaks are again applied on top of the previous peaks, and the valleys are applied on top of the previous valleys. In order to minimize this stack-up, it is beneficial to shift the robot application path between coats by a pre-determined distance. The distance the path is shifted between coats is referred to as the offset.

The normal method to offset a path is by half of the optimized index being used on the part. For example, we found that our optimal index from the previous example was 10 inches, so the offset should be 5 inches between the first and second pass. The robot path

FIGURE 14—General Robotic Coating Application Setup Process

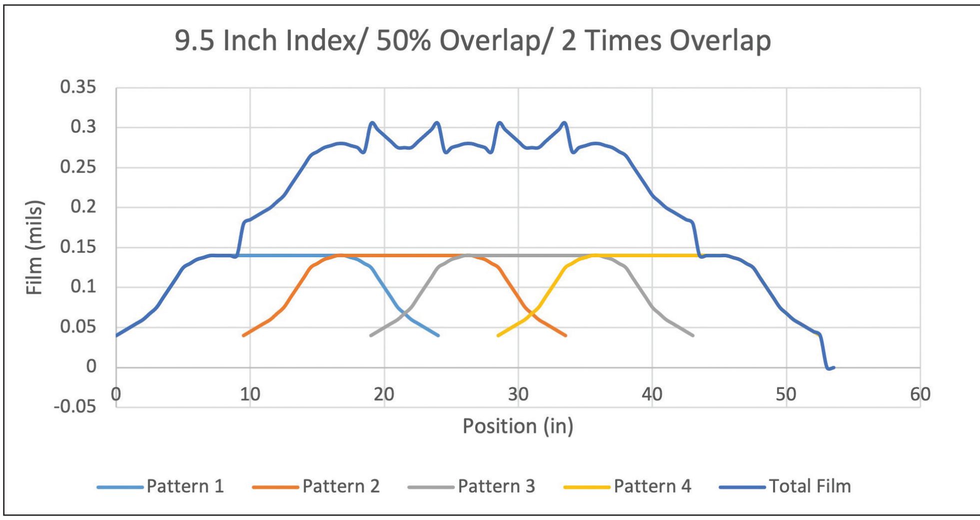


FIGURE 15—General Robotic Coating Application Setup Process

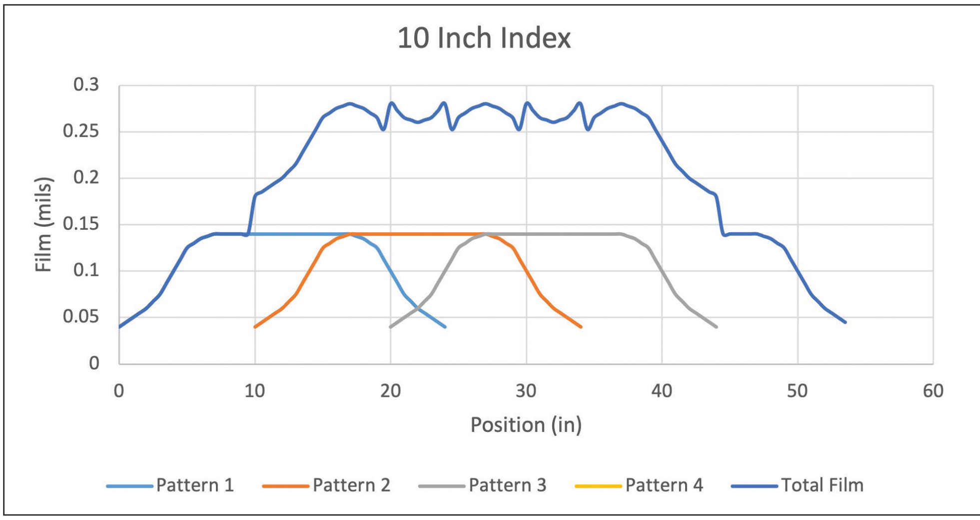
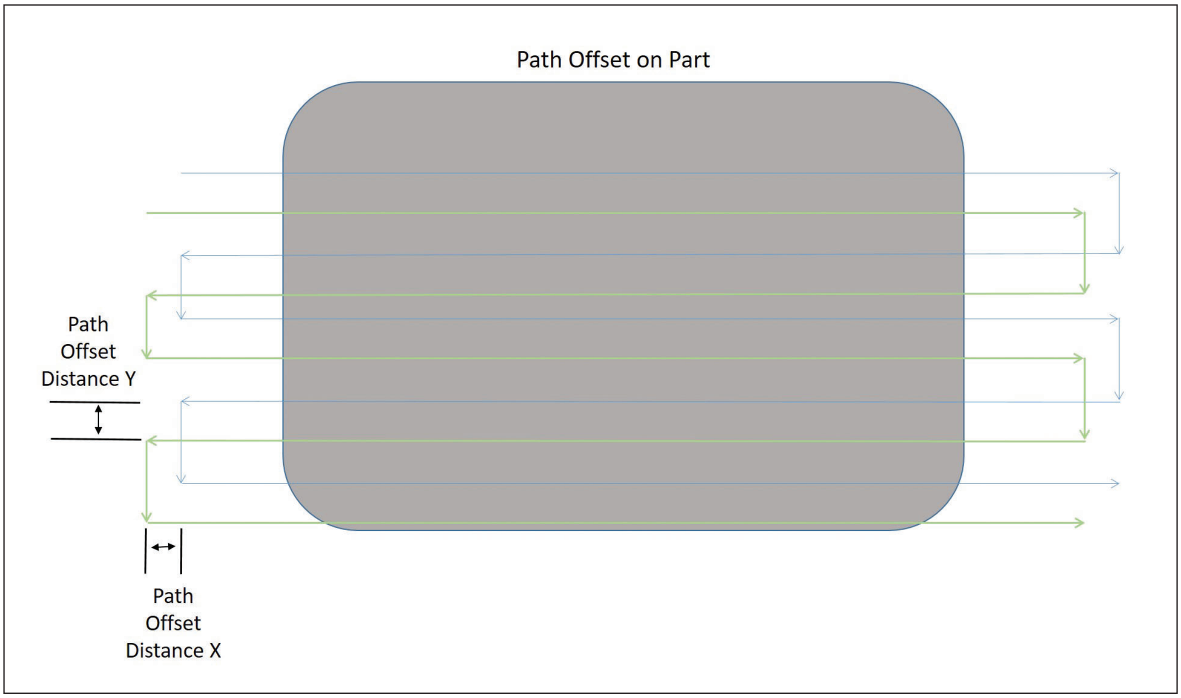


FIGURE 16—General Robotic Coating Application Setup Process



programmer could generate the ideal part path and then offset it by 5 inches on the second pass and add/remove strokes to achieve proper overlaps.

If the part geometry allows it, a more efficient method for programming the offset is to generate the ideal path as a theoretical baseline and then offset that baseline path 2.5 inches in one direction for the first pass and offset the baseline 2.5 inches in the opposite direction for the second pass. It is often beneficial to offset the path in both axes of the surface plane that is being painted, particularly when the applicator trigger-on and trigger-off must be on the part.

TRIGGERS

Triggering the applicator on and off is a necessary but problematic part of any automated painting process. Any experienced painter will advocate triggering an applicator off of the part whenever possible for good reason. Every time that the applicator is triggered on, it takes time for a stable plume of atomized paint to develop. Although this may appear instantaneous to the naked eye, the development of the pattern is often easily measurable in the film on the part surface when the applicator is moved at a smooth constant velocity. While it is not possible to completely eliminate this problem with most applicators, it is possible to minimize the effect by carefully tuning the trigger timing and fluid delivery pressures.

In simple terms, a trigger point is the robot program command calling for paint application to begin at the start of a stroke and at the other end of the stroke a trigger-off event is commanded. When this occurs, the applicator main needle opens which starts the fluid flow and introduces the un-atomized paint to the aerodynamic drag forces which cause it to begin breaking into progressively smaller droplets.

During this transient period between when the fluid is turned on and when a steady and stable pattern is established, much larger and smaller droplets than normal are formed and typically distributed over a very small area within the spray plume. What results is a much higher propensity to create sag or run defects with this rapidly changing spray pattern shape. This is extremely difficult to counter with the index and offset methods previously discussed. The same conditions also occur when the applicator is triggered off.

Applicator "spit" defects of partially dried agglomerations of paint from a fluid tip, injector, air cap, high-voltage needle, or distribution disk are also highly correlated to applicator trigger events. For these reasons, trigger events should be programmed to occur off of the production part and far enough away for the pattern to fully develop if at all possible.

Often modern automated paint application systems rely on positive displacement fluid pumps that are capable of producing more than 1000 psi when dead-headed. This pressure far exceeds the safe working pressure of the paint fluid lines within the automation and can easily separate fluid fittings from the paint lines and fill the robot full of paint.

To prevent this messy failure mode, paint automation manufacturers include control logic that requires the main needle on the applicator to be open for fractions of a second before the gear pump can start pumping. The gear pump is also commanded to stop pumping fractions of a second before the main needle closes at a trigger-off event. This is referred to as the pump anticipator. The exact value of this lag/lead varies by the length of the line between the pump and the applicator, the shear properties of the material, and the pneumatic delay of the trigger opening or closing.

A different anticipator value is configured to account for the pneumatic delay of the applicator trigger to fully open. If the anticipation time is too short the automation will sense an over-pressure condition and fault, and if the time is set too long the triggers will not occur where intended on the part. If the time is set too long for basecoat materials containing effect pigments the flakes will be initially strained through the gear pump teeth, then compacted when the pump begins to turn, and result in defects of compacted agglomerations of effect pigment on the part near the trigger-on events. Applicator lead and lag times should not be used as an alternative for proper trigger point placement in the robot path.

ROBOT TIP SPEED WHILE PAINTING

The robot tip speed is directly proportional to the amount of paint applied to the part and can be an important tool to achieve a uniform and continuous film. Application tip speeds between 500 mm/sec and 1000 mm/sec are within the normal range for painting with a robot. Between 800 mm/sec and 1000 mm/sec the pattern typically begins to distort and at tip speeds beyond 1000 mm/sec the pattern is often so distorted that it is unusable. This would typically be referred to as a "blown" pattern.

The response time of the fluid-delivery system is much slower than the motion of the robot. From a practical standpoint, this means that a change in the fluid delivery parameters could take a second or more to take effect and for the pattern to become stable. The applicator will be changing state across a length of 0.5m to 1m. For that reason, it is often better to adjust the path velocity so that it is slightly slower or slightly faster over complex contours to achieve the target film. Additionally, by maintaining the same application parameters the pattern size and the particle size distribution within the pattern remains constant. It also reduces the number of applicator parameter presets or brushes that must be defined and maintained.

NEXT STEPS IN THE PROCESS

Defining application parameters requires a significant amount of work but a structured and data driven approach often saves days or weeks of frustration downstream. The parameters established will provide the robot programmer(s) with critical information needed to begin creating process paths using offline programming tools.

The offline paths will require some final tuning on setup components to adjust trigger points and slight tip speed modifications to account for booth airflow variations, but it is not uncommon for the first trial part to be uniform and within 15% of the targeted coating thickness. The application team will be armed with a solid understanding of the robotic applicator applying a particular coating. This baseline knowledge will make correcting application issues that do arise much faster and easier.

Initial application testing is perhaps one of the most confusing parts of the robotic paint application process. Some veterans in the industry may recognize the process (Braslaw, 1998). The steps outlined are more than the best practices of a single person or company. The approach has been honed over several decades through countless hours of work and refinement by engineers, chemists, technicians, programmers, and robot operators throughout the paint and coatings industry. The knowledge often passes by word and by practice from one professional to another across generations of automation technology. The reader is encouraged to use this collective knowledge to make a coating process better, improve upon the methodology, and pass it along to someone new to the field. ❊

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