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Detection of production relevant deviations in paint sprays

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Abstract Spray painting is still a poorly manageable process due to the complex interaction of physical, chemical and environmental influences like turbulent air flows, strong electrostatic fields, complex viscosity of paints and paint booth conditions. Consequently, many important properties of the painted film, like thickness, color, surface structure and the efficiency of the process are not controllable in an adequate manner, despite the enormous economic ramifications of poor quality control in high volume applications, such as in the automotive industry. This study shows how novel, online spray monitoring can instantaneously generate characterizing quantities from the spray to detect harmful deviations in the process. In this study, several minute changes have been experimentally imposed on a paint system, such as changed paint viscosity or pigmentation, deviations in air flow and paint flow rates, and defective or used and worn equipment parts. It will be shown that all these deviations lead to features which allow a clear distinction from the intact and reference cases. Additionally, it is shown that most of the deviations, if not detected, would have led to quality issues of the paint coating.

Keywords Paint sprays - rotary bell, Defects, Drop sizing, Production monitoring

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Introduction

It is now well accepted in the paint industry that electrostatic spraying rotating bell (ESRB) atomizers are capable of achieving high transfer efficiencies while maintaining uniform coatings, thus making them especially suitable in the automobile industry, where the coating process represents a significant cost of the total production equipment investment.[1] Understandably there have therefore been significant efforts invested into modeling and numerically predicting the entire paint process using ESRB atomizers, in an effort to facilitate thickness calculation and planning of robot trajectories, whereby a large number of parameters are available for optimization.[2,3] These include, for example, spraying distance, robot traversing speed, as well as parameters demanding more complex models, such as voltage, shaping air flow rates, paint flow rates, rotation speed, paint rheology, purge air etc. Although significant progress has been made in this domain of prediction, there remain numerous factors under actual operating conditions, which cannot be adequately controlled to a degree sufficient to ensure that the process aligns with the employed prediction models. Indeed, in many cases the sensitivity of the final coating features (thickness uniformity, gloss, color, etc.) to deviations of these factors is not completely known or physically understood to the extent that these influencing factors can be modeled in predictive codes. Difficulties arise already in predicting the

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atomization process itself, since this involves film formation, ligament formation and drop formation, all of which involve complex hydrodynamics and hydrodynamic instabilities with boundary conditions definable and known only on a macro, possibly a micro scale, but definitely not on a nanoscale, at which instabilities are often initially excited. The practical approach to overcoming this modeling challenge has therefore been to investigate the influence of various factors experimentally,[4,5] whereby the experiments are conducted under well-controlled laboratory conditions. Very recent investigations also incorporate electrohydrodynamics to model the electric effects during the droplet formation.[6] Such studies deliver models or metamodels which can then be incorporated into prediction codes.

The present study takes a somewhat different approach, postulating that regardless of the predictive accuracy achieved in numerical models, there will always remain varying factors in actual production lines, that will lead to unwanted deviations and/or defects in paint quality. At most a numerical prediction of the influence of such deviations in operating parameters can be retroactive and off-line, by which time defects in the painting result have already occurred, incurring additional costs and lost time. The hypothesis which is to be tested in this study is whether a selective online monitoring of the atomization process is sufficient to detect production relevant deviations in the final coating. If so, this would allow a correction prior to the next work piece to be painted on the production line, thus reducing costly mitigating steps in coating repair. Such an approach is wholly dependent on having a device available, which is capable of online monitoring of spray characteristics and for this purpose an instrument based on the time-shift principle to measure drop size has been considered.

Equipment and methods

This description of the experimental facility and methods is subdivided into three parts: the rotary bell atomizer, the spray measurements, and the evaluation of the coated film.

Rotary bell atomizer

The measurements were performed in a paint booth with a well-defined climate, i.e., 65% relative humidity at 21°C temperature and 0.3 m/s homogeneous downdraft. As paint applicator, a rotary bell (SAMES PPH 707, EC50) unserrated bell shape atomizer (diameter 50 mm) was chosen, which is widely used in the automotive industry and as pictured in Fig. 1. The paint is fed to the bell, accelerated by the centrifugal force of the rotation, and redirected to the work piece

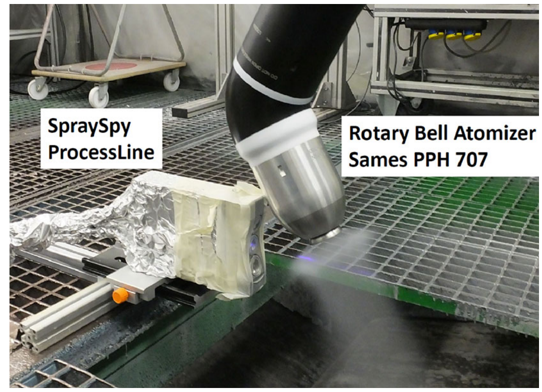

Fig. 1: Measurement setup in paint booth

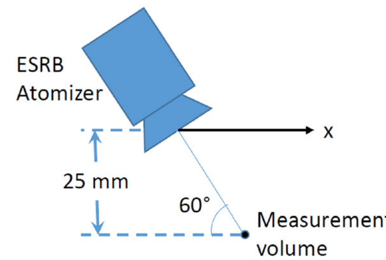

Fig. 2: Depiction of atomizer traverse with respect to measurement volume

by two shaping air configurations, consisting of a straight shaping air 1 and a swirled shaping air 2 to stabilize the spray cone.[2] The atomizer is traversed linearly using a 6-axes robotic arm (Fanuc P250-iB.) with the velocity of 1 mm/s along the x axis, as depicted in Fig. 2. Typical industrial painting parameters were chosen for the reference state: paint flow rate of 230 ml/min, shaping air 1 flow rate 300 sl/min (liters at standard temperature and pressure conditions), shaping air 2 200 sl/min and rotational speed of 50,000 rpm. No high voltage was applied in this study.

Malfunctioning of the paint process was invoked in three manners:

- operational parameters were varied up to approx. 20% to represent malfunctioning pumps, valves, controls, as well as operator errors.
- used and worn equipment was acquired from operating paint lines, for example worn bell cups (less sharp edge at the point of atomization) and worn shaping air rings with deviations in direction or homogeneity of the air flow.
- the commercial, waterborne automotive paint material was diluted or added with additional pigments to simulate batch differences.

The different operating conditions were given a classification between A (reference case) and G, as outlined in more complete detail in Table 1.

Table 1: Definition of the introduced deviations

A1-6	Reference case	See above
B1-2	Paint flow	180 and 280 ml/min
B3-4	Air flow	240/160 sl/min; 360/240 sl/min
B5-6	Rotation speed	40,000 rpm; 60,000 rpm
B7	Alternative brush	All values changed
C1-3	Bell cup defects	Worn bell cups
D1-3	Shaping air defects	Worn drillings
E1-2	Viscosity	Dilution with 2%; 10% DI water
G1	Effect pigmentation	Adding 0.5% aluminum flakes

For the operating parameters both lower and higher values were used compared to the reference case

Spray measurements

For online monitoring of the spray, the SpraySpy ProcessLine© from AOM-Systems has been employed. This instrument utilizes the time-shift measurement principle[7] and has been specially developed for 24/7 inline quality monitoring and process automation of industrial coating processes. The goal of this system is to ensure higher machine availability;[8] hence, higher throughput. The sensor operates equally well with all liquids and also with electrostatic sprays or with explosive solvents.[9–12]

The time-shift technique is a point measurement instrument, in which the scattered light of the individual droplets is detected by photodetectors and is converted into a time resolved signal, which provides specific signal signatures, depending on the size, velocity and composition of the droplet.[7] In the monitoring system, signal signatures are assigned to individual droplets and are continuously recorded. During the actual spray monitoring, the evaluation unit then uses the signal signatures that have been recognized as being valid, and checks their plausibility to determine a diagnostic parameter for the spray process.[9] This diagnostic parameter can then be used in a control or regulation system.

Six signal features/signatures (labeled simply P_1, P_2,..., P_6) are available from the SpraySpy device.[13] In particular P_1 is equal to the number of drops collected within the measurement interval; P_2 corresponds to the mean drop diameter of transparent particles; P_3 gives the drop diameter of all non-transparent particles; P_4 is the mean drop velocity of transparent particles, P_5 is the mean velocity of all non-transparent particles, P_6 is equal to the mean time-shift of between peaks on the two detectors generated by second-order refraction. Not all of these signals are of high relevance in the present application, in particular the signatures related to non-transparent particles. A full description of their computation can be found in reference (7).

The rotary bell atomizer is traversed at a rate of 1 mm/s away from the time-shift device, starting with the measurement location positioned on the axis of the rotary bell cup. This is illustrated in Fig. 2, showing the x axis, along which measurements were performed between $0 < x < 54$ mm. Thus, the total time for traversing through the spray amounts to 54 s. The angle of the measurement line with respect to the axis of the atomizer is 60°; thus, the droplets traverse the measurement volume approximately normal to the x axis. Sampling the time-shift signals at 5 Hz translates into measurements acquired at 0.2 mm intervals along the measurement line, allowing profiles of various quantities across the spray to be captured. To confirm repeatability and to estimate the overall uncertainty of the reference measurement (A1), this measurement was repeated six times on different days after reassembling the equipment.

Coated film measurements

To determine the impact of the simulated process malfunctioning on the final quality of the paint finish, panels have been coated according to the parameter variations outlined in Table 1. The panels were painted with a speed of 100 mm/s and at a painting distance of 200 mm. On these panels the paint film thickness was measured with a magnetic-inductive probe. The total deviation has been defined as the integrated quadratic deviation over the spray pattern.

For the color measurement the multi-angle photo spectrometer BycMac was used, after additionally painting the panels with a clear coat. This device outputs the color distinguished between lightness (L*), green–red (a*) and blue–yellow (b*). The sample is illuminated at a 45° angle and the reflected light is detected at -15°, 15°, 25°, 45°, 75° and 110° with respect to the gloss spot angle. For the cases B1-6 in Table 1, the color of the reduced parameter setting is subtracted from the increased setting, so the sign of the change can be depicted; for the other cases the maximum deviation from the reference case is calculated.

Data processing

The SpraySpy device provides a time series of each of the six parameters, comprising a value arising from each individual droplet passing through the optical detection volume. An example of such a time trace of signal signature P_1 is shown as a black curve in Fig. 3. A mean time series is obtained by averaging over all six trials under reference conditions and is designated $\overline{f_{\mathrm{ref}}}(t_i)$. Note that this can be computed for each of the six signature values and furthermore, the mean at different times t_i corresponds to a mean at different positions in the spray, according to the traversing speed given above.

To evaluate how a certain deviation of the operational parameters (case = B1-G1) can be detected in the time-shift signatures, a standard deviation from the reference case can be computed for any of the six signal signatures as follows, the sum for P2 to P6 running of the region were significant droplets detected as we know from signature value P1:

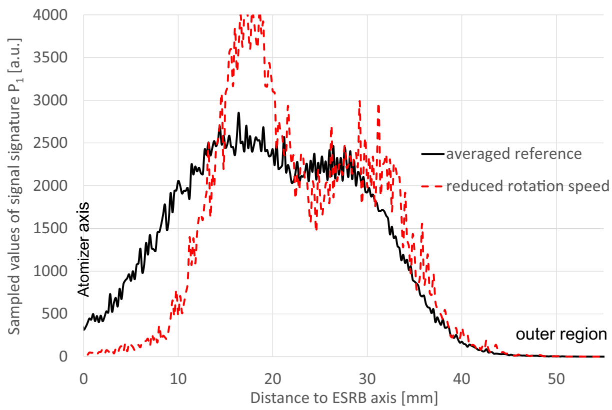

Fig. 3: Comparison of signal signature P_1 for case B5 (red curve) to the averaged reference case (black curve). The B5 case is taken as a reduced bell speed from 50,000 rpm to 40,000 rpm, abscissa according to Fig. 2

$$\sigma_{\text{case}} = \frac{1}{(N-1)}\sqrt{\sum_{i=1}^{N}\overline{\left(f_{\text{case}}(t_i) - \overline{f_{\text{ref}}}(t_i)\right)^2}} \tag{1}$$

The calculated deviations σ_{case} were then normalized with the standard deviation obtained from the six repetitions of the reference case, i.e.,

$$\hat{\sigma}_{\text{case}} = \frac{\sigma_{\text{case}}}{\sigma_{\text{ref}}} \tag{2}$$

In this way, the natural variations and uncertainties in equipment operation are accounted for when evaluating the standard deviation. Values of $\hat{\sigma}_{\text{case}}$ smaller than 1 denote no significant change compared to the reference case: values larger than one indicate statistically significant deviations of the spray compared to the reference case.

Parameter P_1 correlates closely to the rate of particle detection, so this parameter is reasonable to examine in regions of the spray with both low and high particle densities. For the other parameters P_2 to P_6, which correspond approximately to mean values, like droplet size or velocity, it is better to utilize their statistics only in spray regions exhibiting higher particle densities in order to ensure statistical significance. In terms of the traversing time in this experiment, these regions occurred in the time frame 15 s to 45 s after beginning of the traverse on the centerline of the rotating bell (see Fig. 2), reflecting the fact that the particle density directly below the bell cup is low.

Spray monitoring

In Fig. 3 we show as an example, a typical profile of signal signature P_1 obtained when the bell speed has been altered from the reference speed (deviation B5). The curves depict the typical behavior of an ESRB

Deviation	P1	P2	P3	P4	P5	P6
Ref.	0,4	0,5	0,5	0,5	0,3	0,5
Ref.	0,5	0,7	0,5	0,5	0,3	0,5
Ref.	0,3	0,5	0,5	0,5	0,4	0,6
Ref.	0,6	0,6	0,6	0,6	0,4	0,5
B1	0,8	1,1	0,6	1,0	1,3	1,2
B2	0,8	0,8	1,7	0,8	1,4	0,8
B3	2,8	2,9	3,2	1,6	1,0	2,1
B5	1,6	1,5	1,5	2,8	2,2	2,9
B6	1,8	3,0	2,7	2,2	0,8	1,7
B7	2,8	2,7	1,2	4,6	4,3	4,4
Ref.	0,7	0,9	0,7	0,9	1,0	1,0
C1	1,2	1,0	0,9	1,2	1,0	1,2
C2	1,1	0,8	0,9	1,0	0,8	1,2
C3	1,2	0,9	1,2	0,9	0,8	0,9
Ref.	1,0	1,0	1,0	1,0	0,6	0,9
D1	3,3	2,3	2,7	1,7	1,3	1,7
D2	2,8	1,8	1,7	1,4	0,9	1,4
D3	1,9	2,0	1,5	1,5	0,9	2,0
E1	2,0	2,5	1,3	2,7	1,3	1,6
E2	1,7	1,4	1,3	1,3	0,8	1,1
G1	3,5	4,5	7,5	5,2	5,4	2,1

Fig. 4: Normalized standard deviation according to Eq. (2) of the six signal signature values for all deviations (A-G) as defined in Table 1. A value of unity corresponds to a standard deviation as found in the reference case. The color indicates the severity of the effect: dark green - low; red - high

atomizer. In the inner part, close to the axis of the atomizer, only a very low number of droplets are found, consisting of very small particles at low positive or even negative speeds.[14] In each measurement interval the signature value P1, corresponding to the number of droplets, falls to very small values in the outer regions (at 0 mm resp. 50 mm).

Although both curves exhibit two peaks at approximately the same measurement positions, they also show significant differences. One apparent difference is that the B5 case exhibits a much lower drop density immediately underneath the bell. Presumably, the reduced bell speed of 40,000 rpm instead of the reference case of 50,000 rpm leads to larger drops overall and these are less susceptible to being sucked in to the low pressure zone created immediately below the bell (due to the swirl), due to their larger inertia. These larger drops have more ballistic like trajectories and lead to a higher first peak in Fig. 3. The remainder of the profile remains relatively unchanged.

In Fig. 4 the normalized standard deviation for all six signal signatures and for all deviation cases (B1 - G1) are tabulated. It is apparent that many of these values are less than unity, meaning that this particular defect or material change has little influence on that particular signal signature. On the other hand, certain values lie far above unity, indicating a strong influence of that particular operational defect or material change on the spray. Several examples of such deviations will be briefly discussed. Note however, that the standard deviations for the A series, i.e., the reference condition, all lie below unity, indicating that the variations from

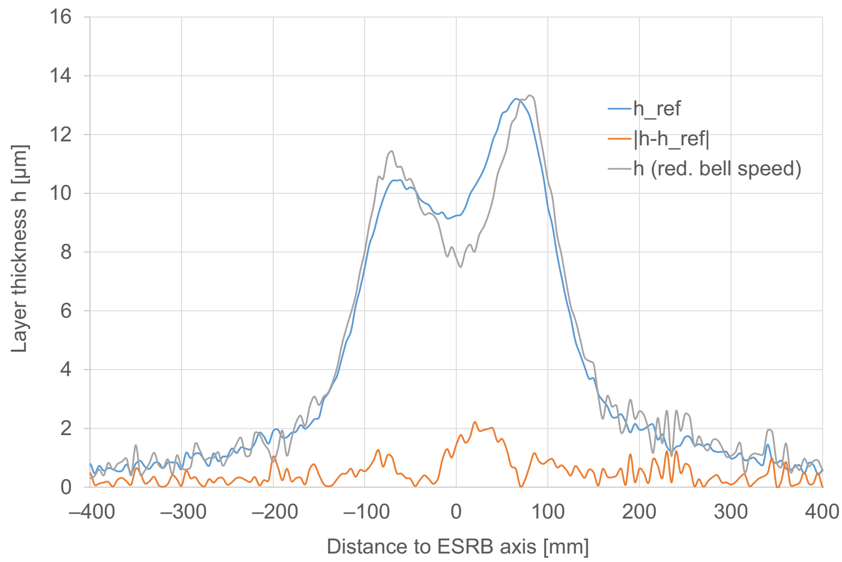

Fig. 5: Example for the spray pattern h_{ref}, h for reduced bell speed and $|h(x) - h_{ref}(x)|$ of the painted film

one repetition to the next are minimal, confirming the high reproducibility of the reference measurement.

Changing the paint flow rate (B1-B2) results in little change of the normalized standard deviation. This is a result also observed by reference (15) using laser diffraction measurements. The reduced air flow parameter (B4) could not be measured due to contamination of the lenses by the wide spray cone. Changing the rotational speed (B5-6) influences the spray strongly in signature profile form (as discussed above), and is related to droplet velocity and size. The different brush (B7) used in the industrial application for producing a strong metallic effect can easily be distinguished, especially by the signal signatures $P_4 - P_6$. Defects at the bell (C1-3) only show minor effects, similar to the minor deviations in film thickness and color measured on the painted panels (see section "Coated film measurement"). In contrast, defects in shaping air (D1-3) have a massive impact on the spray cone, similar to the parameter deviation B3. Modifying the paint material properties influences the spray strongly, especially the pigmentation.

Coated film measurement

Panels have been painted and the quality has been measured, concentrating on the film thickness and the color, as these are typically the quality features most relevant in industrial applications. The film thickness is the most important quality parameter in all paint shops and is responsible for most paint defects, such as boiling, sagging, color mismatch or thin films. Here, we can use as a criterion for the thickness deviation the integral of the spray pattern absolute thickness difference from the reference thickness along a line h perpendicular to the traversing direction (denoted x direction), see Fig. 5 as an example:

$$\Delta h = \int_{-\infty}^{\infty} |h(x) - h_{\mathrm{ref}}(x)| dx \tag{3}$$

This integrated thickness Δh has the units of mm^2 if h and x are evaluated in mm. This corresponds to the conventional method of expressing thickness variations achieved by such atomizers.[2] This quality measure captures all feature differences in the spray pattern, such as the total integral due to the transfer efficiency, maximum height, width, etc.

The results of this thickness measurement are shown in Fig. 6. The strongest influencing factors on the paint layer thickness are the paint flow rate and maladjustment of the shaping air. The paint flow rate influence is intuitive and has an approximately linear influence on the thickness; however, the strong influence of shaping air was not expected *a priori*, although it is in good accordance with the spray measurements.

The color deviation dL*25[16] is discussed here, since for the silver metallic color investigated, the lightness close to the specular angle is the quantity most strongly impacted by the paint application. This is due to the fact that the orientation of the effect pigments influences this value.

The color is influenced in nearly all trials deviating from the reference case (see Fig. 7). The increased paint flow rate yields higher layer thickness, lower evaporation rates of water from the film, and poorer orientation of the effect pigments; hence, a reduction of dL*25. Increasing the air flow and especially the rotational speed of the bell, leads to the opposite effect, i.e., faster water evaporation during the flight of the paint droplet, consequently a better orientation of the pigments. The defects on the bells are of low

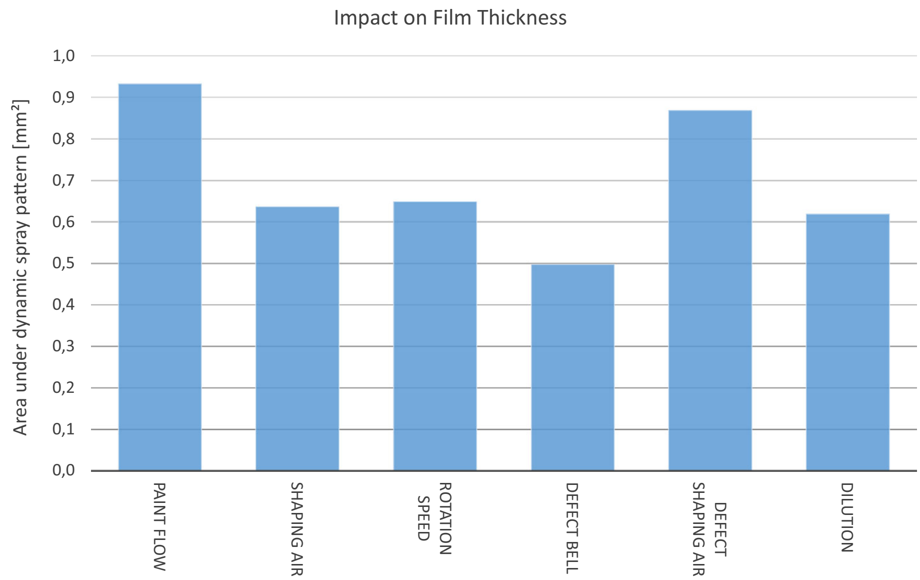

Fig. 6: Impact of the various operational deviations (see Table 1) on the integrated thickness Δh (equation (3)) of the painted film. Averaged values are shown for all repetitions of each of the six parameters

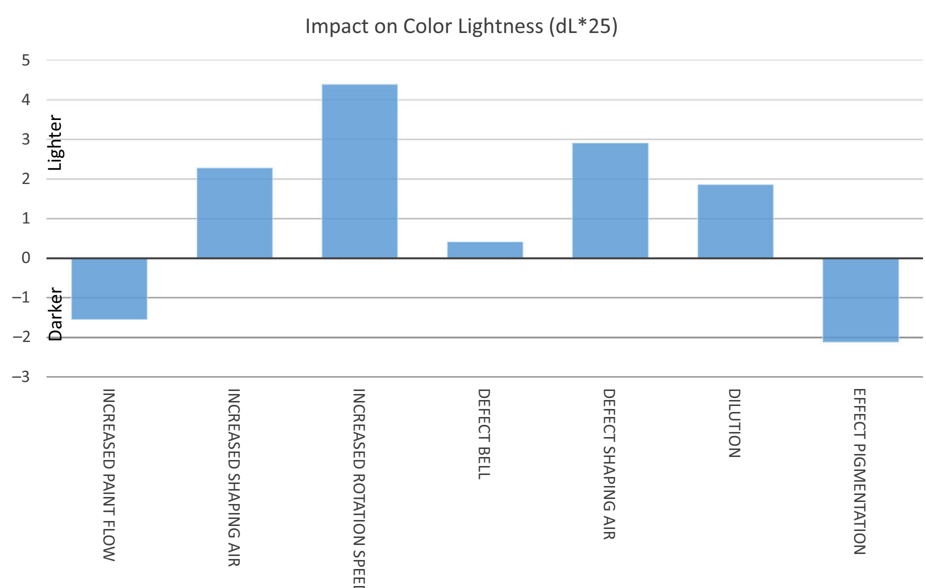

Fig. 7: Impact of the deviations (see Table 1) on the color (lightness at the detection angle of 25°) of the painted film, as described at the end of section 3.2

significance; this is valid also for the color. The remaining parameters again influence the evaporation, and with that the color.

Discussion and conclusions

A systematic investigation of the impact of variations in operating parameters or equipment conditions in the spray coating process on the paint coating has been performed. All relevant variations occurring in practical industrial painting processes have been considered, namely operating parameter variations, defects in the equipment, and modifications of the paint material. It has shown that these changes can be detected in the spray via an instrument operating on the time-shift measurement technique. Furthermore, it has been shown that the paint film quality is influenced by these variations. Small variations in the spray, like defects on the bell, lead to only minor variations in the quality.

It is not the purpose of this study to elucidate the physics of how each of the deviating operation parameters lead to variations in the two measured features of the coating—thickness and color. Rather, the purpose is to demonstrate that an indication of reduced coating quality can already be detected by monitoring certain features of the drops in the spray; in this case the signal signatures $P_1 - P_6$, and likely possible using only a subset of these signal signatures. This represents a significant practical step in quality control, since the time required for the measurement is the traversing time of approx. 1 min. Such a control measurement would be possible by directing the robot to the measurement station at regular intervals between production units.

Following this proof-of-principle demonstration, the next step is to more systematically investigate how variations of the signal signatures can best be correlated with operating deviations. This obviously is an ideal case for machine learning, in which the learning data set is generated in a laboratory campaign similar to what has been presented in this study, but more expansive in parameter variation and number of repetitions. This would also increase the statistical significance of any deductions. What remains to be revealed, is how universal the teaching data set will be for various ESRB atomizers, or to what extent additional teaching campaigns must be performed for each atomizer. This is the subject of on-going research with the equipment used in this study.

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Data availability All data have been presented in this manuscript, and no additional data needs to be attached in the supplementary. Data will be available upon request.

Conflict of interest The authors declare that they have no Conflict of interest.

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