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# SPRAY-PAINTING MOTION PLANNING AND QUALITY ANALYSIS IN POWDER COATING SYSTEMS

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Abstract: The paper reports results on the automation of the spray-painting process in industrial powder coating plants. The automation of the spray-painting process requires a painting model and the definition of appropriate metrics for painting task validation. Two main topics are addressed in the paper: motion planning of paint deposition and paint quality analysis. A paint quality function is formulated and results concerning experimental analysis are presented. *Copyright ©2002 IFAC*

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## 1. INTRODUCTION

As the global economy becomes more competitive, industrial production requires more automation along with process optimization and increasing of plant availability. However, in most cases, rather than to pursue complex automation to achieve complete autonomous systems, balanced automation and anthropocentric technological development concepts should be adopted in order to follow within a sustainable development.

The paper extends the theoretical and practical results reported in (Nunes, et al., 2001) concerning the Electrostatic Paint Robot project (EP-Robot) whose aim is to develop a semi-automatic/automatic spray-painting machine, for powder coating plants, able to paint objects with different and *a priori* unknown shapes moving in an aerial conveyor. It can, in many cases, perform the automatic painting alone or in other cases where the human intervention is unavoidable, e.g. in painting complex shapes, to reduce significantly the operator efforts. This automation introduces flexibility to the process and can contribute to the improvement of the quality of painting, costs reduction, and to a better knowledge of the process. This project has being developed by a consortium composed by a research institute (ISR-Coimbra) and an industrial partner (FIMEL, manufacturer of industrial powder coating systems).

## 2. EP-ROBOT MACHINE

Fig. 1 shows the typical sequence of phases involved in an electrostatic powder coating system. A dedicated aerial conveyor moves the workpieces. Only for large batches of workpieces an acceptable performance is achieved with rigid spray-painting systems, e.g. systems of one or two axis with pre-programmed movements. Only with an automatic spray-painting machine with capacity to adjust itself to the shape of the workpieces is possible to make the system more flexible and more efficient to small batches. Pre-commercial prototypes were developed and tested in a laboratory environment (see Fig.2) and in an industrial environment (see Figs 4 and 5). The main elements of a complete EP-Robot system are: two Cartesian 2-axis robots actuated by AC servo motors carrying the spray guns, arranged in the way that one is facing the other with the conveyor in the middle, a sensor ring system using laser technology, and a PLC based control system with Profibus to provide communications among the different modules. The sensor ring gives online a crude estimate of the object shape, more precisely an estimate of the parallelepiped envelope that entirely encloses the workpiece.

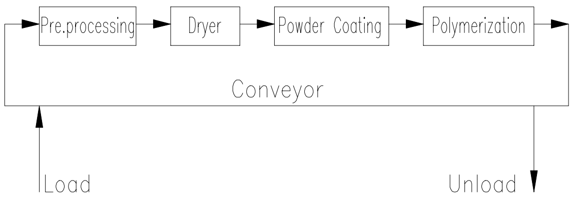


Fig. 1. Sequence of phases of a powder coating system.


Fig.2. An EP-Robot prototype in a laboratory environment with an aerial conveyor to completely simulate the motions involved in the spray-painting.

The horizontal axis positions the guns in an appropriate distance from the workpieces and the vertical axis adjusts the vertical motion of the spray-gun automatically to the piece height (see Fig.3). The sensor ring is not lined up, it is before the EP-Robot actuation axes (see Fig.5), allowing the anticipated estimation of the shape and the calculation of the spray-gun trajectory. In order to have appropriate coating trajectories, the machine should adapt itself online function of the conveyor velocity and workpiece dimensions, always having in view the guarantee of good quality of the painting. For that purpose a model of the process is an essential tool for the design of the EP-Robot machine.

## 3. SPRAY-PAINTING PROCESS MODELING

In this section the motion variables of the spray-painting process, as used in the EP-Robot, are defined. For that, we use the nomenclature presented in Table I.

Table I

| Variable | Description |
|---|---|
| $x$ | Horizontal position |
| $z$ | Vertical position |
| $y$ | Longitudinal position (conveyor) |
| $h$ | Workpiece height |
| $d$ | Spraying distance |
| $a$ | Spray projection diameter |
| $b$ | Path width |
| $\varnothing$ | Spray cone angle |
| $v_z$ | Vertical velocity (spray-gun's velocity) |
| $v_y$ | Conveyor velocity |
| $v_x$ | Horizontal velocity |

### *3.1 Process variables*

In order to optimize the deposition of paint onto the surface, the spray-gun should be properly positioned and oriented relatively to the surface.

*Assumption 1:* A simplified model assuming that the workpiece has a parallelepiped shape, which completely encloses the workpiece, is adopted in this work.

*Assumption 2:* the solution space is constrained by assuming that the spraying is carried out at a constant distance and keeping the nozzle axis orthogonal to the plane surface.

Under these assumptions, the robot $x$-axis does not move while it paints the same workpiece. Changes in the $x$ position can only occur during the transition time between workpieces. So in the sequel analysis we ignore the horizontal motion. The spraying performed at a constant speed ensures a nearly uniform film thickness. This fact leads us to analyze the spraying motion problem under the constraint

$$v = v_0 = \text{constant} \quad (1)$$

where $v$ denotes the speed of the spraying motion and $v_0$ a constant subject to the restrictions

$$v_0 \geq \max(v_y, v_z) \quad (2)$$

$$v_{\min} \leq v_0 \leq v_{\max} \quad (3)$$

where $v_y$ and $v_z$ are the conveyor and the vertical speeds respectively. The inequality (3) states that the spraying speed is confined to a certain interval of values so that the coating thickness be within an admissible band about the desired value. The spraying speed is related with the coating time that depends on the kind of powder, its flux of spraying through the spray-gun and the raw material of the workpieces. A minimum time of coating exists above which the spray-painting should be done so that the workpiece areas can be homogeneously coated. On the other hand, if the coating time is too long, the

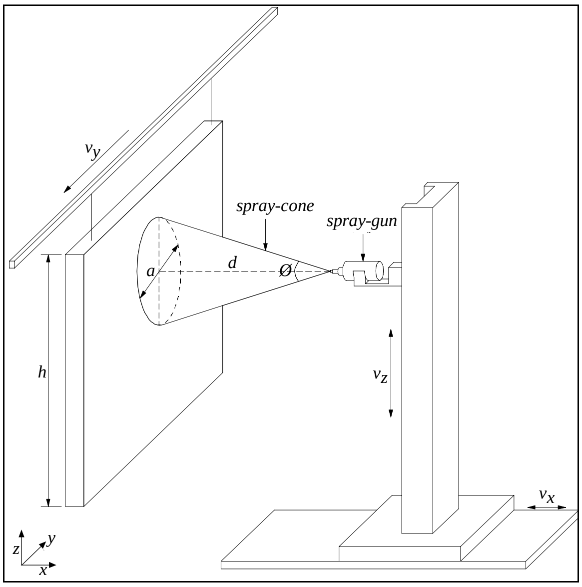

Fig. 3. Figure shows: a)-spray-painting task geometry assuming a plane surface; b)-spray-cone model as a simplified model of the powder spray cloud.

odds is that the powder may be detached. Due to the electromagnetic characteristics of the process, the spray-guns will have to keep a compulsory distance from the workpiece never less than 50 mm, once that in smaller distances there is the risk of electric arcs. For a high transfer efficiency the distance should be less than 300 mm. A spray-cone model is assumed as a simplified model of the powder spray cloud, as depicted in Fig.3. The spray projection diameter $a$ depends on the spraying distance $d$ and spray-cone angle $\phi$ :

$$a = 2d\, tg(\phi / 2) \qquad (4)$$

The spraying trajectory projected onto the workpiece surface is a periodic function, of period $b$ , as shown in Fig.4. This period is designated Path width. Its value is settled from the knowledge of the system parameters $d$ and $\phi$ , and should be in the range

$$0 < b \leq a \qquad (5)$$

so that it does not remain any area of the surface without being coated. Fig.4 shows the particular case for which the path width is equal to the spray projection diameter (i.e. $b = a$ ). In this case the surface is completely covered with the minimum of paint overlapping. Without considering the non-linearities of the motion at the workpiece extremities (see (Nunes, et al., 2001)) , due to the reversal of the direction of the motion, the vertical speed is related with the height of the workpiece, conveyor speed and path width as follows

$$v_z = \frac{2hv_y}{b} . \qquad (6)$$

The spraying is performed at the linear speed

$$v = \frac{v_z}{\cos\theta} . \qquad (7)$$

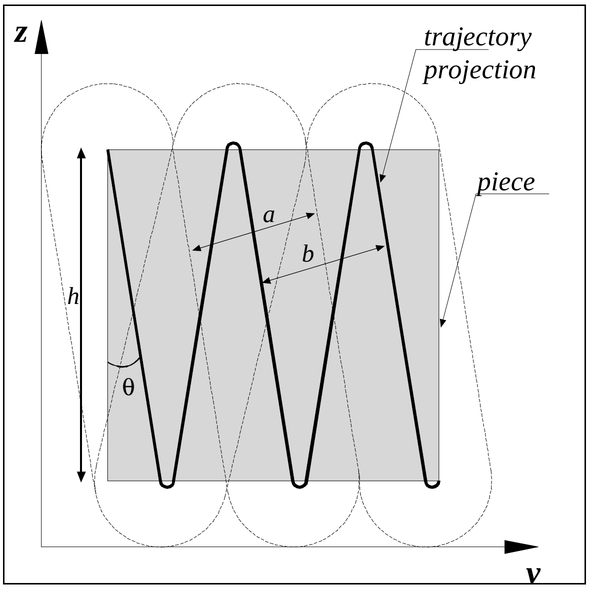

Fig. 4. Painting trajectory: the rectangle represents the workpiece surface and in the same figure is superimposed the spray-gun trajectory. In the figure is shown the particular situation in which the spray projection diameter is equal to the path width: $a = b$.

with

$$\cos(\theta) = \sqrt{1 + \left(\frac{b}{2h}\right)^2} \qquad (8)$$

3.*2 Motion Planning*

Under condition (1), the motion of paint deposition onto the surface describes a periodic trajectory as depicted in Fig.4, which is traversed at the constant linear velocity $v = \sqrt{v_y^2 + v_z^2} = v_0$. If the speed of the conveyor increases the vertical speed must decrease to maintain valid the condition (1). The angle $\theta$ defined in Fig. 2 increases in this case. Herein, we assume that $0 \leq \theta \leq \pi / 2$ . The upper bound $\theta = \pi / 2$ defines the state $\{ v_y = v; v_z = 0 \}$, for which the spraying is done only in the horizontal with the conveyor reaching the prescribed spraying speed (note that the motions are in opposite directions). On the other hand, $\theta = 0$ occurs whenever the conveyor is stopped and the vertical axis moves at the prescribed spraying speed: $\{ v_y = 0; v_z = v \}$. The speed of the conveyor, which is normally unchanged for long periods of time, is not a control variable for us but an input to be taken into account when calculating online the speed of the vertical axis. Now we can state the trajectory-planning problem as we faced it in the EP-Robot project.

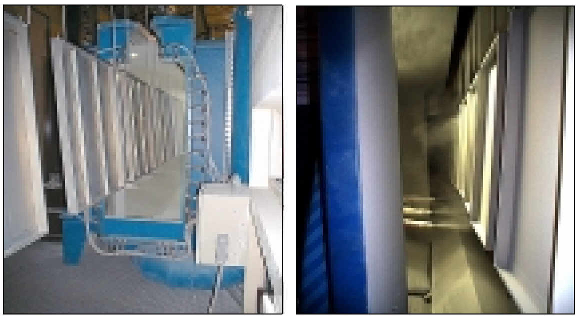

Fig.5. Left)- Sensor ring of an EP-Robot prototype installed in an industrial plant; Right)- EP-Robot carrying three spray-guns horizontally line-up.

*Problem:* Given an admissible conveyor speed $v_y = v_{y_0}$ determine the vertical speed $v_z = f(h, b, v_{y_0})$ where $h$ and $b$ are the workpiece height and path width respectively.

To analyze the problem consider the case depicted in Fig.4 with $b = a$. If the height increases the vertical speed must increase proportionally so that the surface continue to be completely covered. This implies that the spray-painting speed increases too. In order to maintain the coating thickness within the tolerance limits, and as much as possible with values in the vicinity of the desired value, a plausible solution would be to increase the delivery volume of the injectors, in order words to increase the flux of powder. The automatic control of the flux is not practicable with the actual devices incorporated in the powder coating systems produced by the factory. So, given this constraint we can only aspire to achieve thickness values within an admissible band about the desired value. Now, two approaches to the trajectory-planning problem are formulated.

*Approach I:* a constant path width is prescribed which implies a range of values to the spraying speed function of a range of workpiece heights:

$$\begin{aligned} &\text{Set } \; b = b_0, \quad \text{with } b_0 \le a \\ &for \;\; h \in [h_{\min}, h_{\max}] \Rightarrow v \in [v_1, v_2] \end{aligned} \tag{9}$$

Notice that the spraying speed values are in practice upper bounded (Eq. (3)) so that a minimum admissible film thickness can be guaranteed. Obviously this implies in its turn also an upper bound value to the workpiece heights, which is with great probability less than $h_{\max}$.

*Approach II:* a constant spraying speed is prescribed which implies a range of values to the path width function of the range of workpiece heights:

$$\begin{aligned} &\text{Set } \; v = v_0, \\ &for \;\; h \in [h_{\min}, h_{\max}] \Rightarrow b \in [b_1, b_2] \end{aligned} \tag{10}$$

Since in any circumstance $b$ can be higher than $a$, this means that the workpiece height may be in practice upper bounded by a value less than $h_{\max}$. Both approaches can lead to limitations in the maximum value allowed to the workpiece height (above $h_{\max}$). In practice this problem is surpassed by using three spray-guns lined up either vertically or horizontally (see Fig. 5 that shows an image of the spray-guns configuration used in a prototype installed in an industrial plant). The horizontal arrangement gives rise to three trajectories with the same period but out of phase. The optimal distances among the guns are determined function of the other motion variables of the spray-painting process.

## 4. PAINT QUALITY FUNCTION

The quality of a coated surface is a function of the following aspects: uniformity of the film thickness and absence or excess of paint. The uniformity of the film thickness is very important in order to maintain the physical characteristics all along the piece's surface. The absence or excess of paint should be prevented once this leads to undesirable characteristics. A homogeneous film thickness surface is not reachable; normally a painted surface is composed with a wide range of areas with different film thickness values. To quantify the painting quality, taking into account those considerations, a paint quality function based on the formulation given in (Potkonjak, et al., 2000) is defined as follows.

*Definition 1:* A surface $S$ ($S \subset \Re^3$) is well painted if a minimum variation in film thickness $F(s)$ ($s$ denotes a point at the surface $S : s \subset S$) with respect to desired (ideal) value $F_d$ is achieved all over the surface.

We complement the definition with the following consideration:

*Remark 1:* An excessive presence or absence of paint at any surface area should be prevented.
The painting quality function $J_q$ can be formulated as a combination of two performance indices:

- mean-square root error in film thickness:

$$V = \sqrt{\frac{\sum_{n=1}^{N} (F(n) - F_d)^2}{N}}, \tag{11}$$

  where $N$ is the number of sampled surface points.
- maximum deviation from the desired thickness:

$$L = \max_{n=1,..N} (|F(n) - F_d|) \tag{12}$$

The function $J_q$ should be normalized to the $[0,1]$ interval. Value 0 indicates that the painting quality is unacceptable, while value 1 results only when the thickness at all sample points is equal to $F_d$. Now we derive boundary values of indices $V$ and $L$:

$$\begin{aligned} &\exists n \in [1,..N] : F(n) = 0 \vee F(n) > F_{\max} \\ &\Rightarrow V_{\max} = F_{\max} - F_d, \, L_{\max} = F_{\max} - F_d \end{aligned} \tag{13}$$

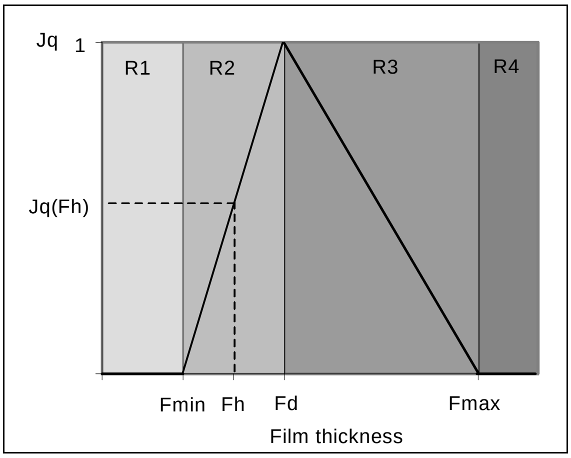

Fig.6: The four regions for the paint quality function.

$$\forall n \in [1,..N]: F(n) = F_d \Rightarrow V_{\min} = 0,\ L_{\min} = 0\,. \quad (14)$$

And then results the following normalized values:

$$V_{norm} = \frac{V_{\max} - V}{V_{\max} - V_{\min}} = \frac{F_{\max} - Fd - V}{F_{\max} - Fd}\,, \quad (15)$$

$$L_{norm} = \frac{L_{\max} - L}{L_{\max} - L_{\min}} = \frac{F_{\max} - Fd - L}{F_{\max} - Fd}\,. \quad (16)$$

As in (Potknojak, 2000), to met both constraints of definition 1 and remark 1, a function of weighted disjunctive-conjunctive means is used to combine normalized indices (15) and (16):

$$J_q = \left[\alpha V_{norm}^p + (1-\alpha) L_{norm}^p\right]^{-p} \quad (17)$$

The function assumes conjunctive or disjunctive behavior by means of parameter $p$. The disjunctive behavior is reached when $p$ increases above zero. In our case another remark should be introduced:

*Remark 2:* It is more critical the deviations below the ideal film thickness $F_d$ than above that same value.

Taking into account remark 2 $J_q$ can be reformulated defining the four regions depicted in Fig.6.

*Definition 2:* surface points with thickness less than $F_{min}$ belong to region R1.
*Definition 3:* surface points with thickness $F(n)$ in the range $F_d > F(n) \geq F_{\min}$ belong to region R2.
*Definition 4:* surface points with thickness $F(n)$ in the range $F_{\max} \geq F(n) \geq F_d$ belong to region R3.
*Definition 5:* surface points with thickness $F(n) > F_{\max}$ belong to region R4.

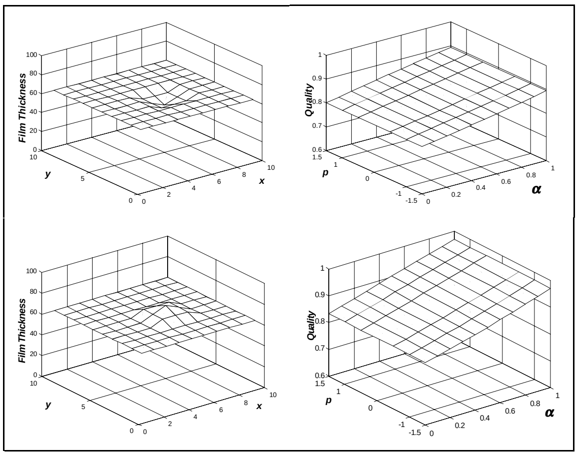

Fig.7: Top) underpainting situation; Bottom) overpainting situation.

Thus for R2

$$V_{normR2} = \frac{Fd - F_{\min} - V}{Fd - F_{\min}}\,,\ L_{normR2} = \frac{Fd - F_{\min} - L}{Fd - F_{\min}}$$

and

$$J_{qR2} = \left[\alpha V_{normR2}^p + (1-\alpha) L_{normR2}^p\right]^{-p}$$

In a similar way for R3

$$V_{normR3} = \frac{F_{\max} - Fd - V}{F_{\max} - Fd}\,,\ L_{normR3} = \frac{F_{\max} - Fd - L}{F_{\max} - Fd}$$

and

$$J_{qR3} = \left[\alpha V_{normR3}^p + (1-\alpha) L_{normR3}^p\right]^{-p}.$$

Finally we formulate $J_q$ as follows:

$$\exists n \in [1,..N]: F(n) \in R1 \vee F(n) \in R4 \Rightarrow J_q = 0$$

$$\forall n \in [1,..N]: F(n) \in (R2 \bigcup R3) \Rightarrow$$

$$J_q = \left[\beta J_{qR2}^p + (1-\beta) J_{qR3}^p\right]^{-p} \quad (18)$$

A possible value for $\beta$ is to make it as a function of the distribution of the number of points in R2 and R3:

$$\beta = \frac{N_{R2}}{N}\,,$$

where $N_{R2}$ is the number of sample points with film thickness inside R2 and $N$ is the total number of sample points.

The quality function gives a numerical value that depends of the two performance indices as stated above. Fig.7 shows the behavior of the function for two examples. As expected for the underpainting situation, the quality values are lower than in the other case. Additionally we can observe the influence of the $\alpha$ parameter. By increasing $\alpha$ the result of the quality function increases because it is given more weight to the mean-square root error.

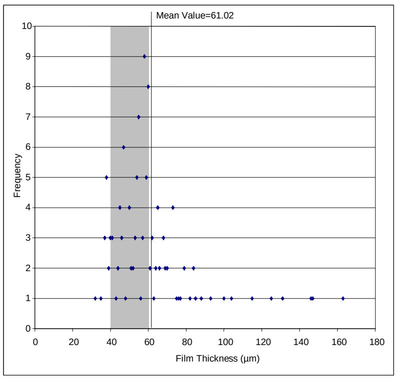


Fig. 8. Film thickness frequencies for manual painting.

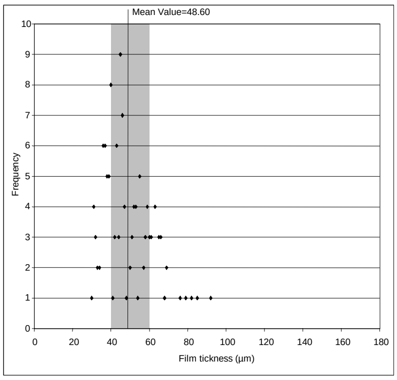


Fig. 9. Film thickness frequencies for automatic painting.

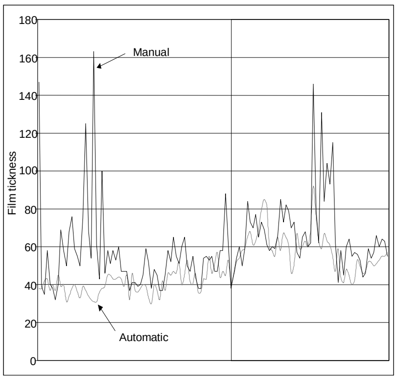


Fig. 10. Manual and automatic data superimposed. The data are shown in its index order of gathering.

## 5. EXPERIMENTAL RESULTS

A EP-Robot prototype was installed in a continuous working industrial powder coating plant in February 2001. Some results were acquired in full process of laboring, therefore suffering from imposed restrictions by the normal process of industrial production. The tests could not be destructive and the workpieces were imposed by the production. In this section an analysis concerning experimental data that was periodically acquired by the quality department is performed. The data concern to the painting of book-shelves (see Fig. 5) with an area of $1\times 0,3m^2$. The book-shelves are plane surfaces with salient borders which are difficult to paint due to the Faraday effect. The EP-Robot was equipped with three Corona spray-guns, horizontally lined up. The analysis is based on two experimental data sets composed by measures of the film thickness at the central point of the book-shelves (see Fig.5), taken during approximately three weeks ($\approx 150$ samples for each set). The beginning of the collection of data occurred just after the installation of the EP-Robot in the production line. One set is concerned with painting done by the EP-Robot and the other with manual painting. Film thickness frequencies of the manual and automatic painting are illustrated in Figs 7 and 8, respectively. The ideal film thickness is around $50\mu m$ and no part of the piece should have a thickness less than $30\mu m$. A major requirement is to achieve great uniformity of the film thickness. In manual production this feature depends on the operator's ability and experience in positioning, orientating, and moving the spray-gun smoothly and around a certain constant speed. From this set of results we cannot conclude in what concerns the film thickness along the surface. However, a better consistency in film thickness, around a reference value, results for the automatic painting. In both cases, about 57% of results lie within the desired band of $[40,60]\mu m$, however a tendency for overpainting and a greater number of too high thickness values occur in manual painting. An important benefit of the automatic painting is the possibility to make parameter adjustments with a gradual improvement of the painting quality and, at the same time, reducing costs. The knowledge of the process and the influence of its variables in the final result are made possible with the process automation. Fig. 10 shows the same data sets, but with the manual and automatic data superimposed and shown in its index order of gathering. During the data gathering time some adjustments were made in the process with the purpose of improving the thickness that was initially in the mean slightly below the ideal value. From Fig. 10 we observe a slight improvement in the thickness of robot painting. The data in the right window of Fig. 10 are more concentrated in the desired band of $[40,60]\mu m$ which contains about 63% of the results.

## 6. CONCLUSIONS AND FURTHER WORK

To capture online more general piece shapes, other solutions will be investigated by fusing data from other sensor modalities, namely vision systems. The global aim is to develop an automatic spray-painting machine that improves the quality of painting and at the same time leads to the reduction of the production and maintenance costs. In order to compete, a company should continue the automation of their production lines. In doing so, hazard identification and control, and online malfunction detection, have become increasingly important to protect costly systems, ensure the safety of personnel and guarantee the quality of the production. This is another line of research being pursued in the EP-Robot project.

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