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Optimal robot spray painting process parameters are specified using a modified Taguchi approach in multi-objective optimization

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Abstract Improvements in quality, productivity, and environmental cleanliness can be achieved through the application of robot spray painting processes, while also minimizing labor and costs. This technique finds application in various sectors including automobiles and home appliances. The enhancement of paint coating quality hinges on the specification of optimal spray painting process parameters. Performance indicators such as thickness variation, surface roughness, and film adhesion are considered crucial in this pursuit.

In this context, a modified Taguchi approach is introduced, serving as a straightforward alternative to the Taguchi orthogonal array and gray rational analysis. The objective is to determine optimal spray painting process parameters (e.g., distance, pressure, and speed) that result in minimal thickness variation, reduced surface roughness, and maximized film adhesion. Empirical relations are established to predict thickness variation, surface roughness, and film adhesion. The acquired test data closely align with or fall within the anticipated range.

Keywords: ANOVA; Automated paint; Distance; Film adhesion; Pressure; Speed; Surface roughness; Thickness variation."

1. INTRODUCTION

The utilization of the spray painting process is widespread, finding application in various sectors such as automobiles and home appliances. This technique involves atomizing liquid paint and depositing it onto the intended surface [1]. The quality of this process hinges on factors like spray coverage and the thickness of the coating layer.

The automation of this spray painting process through robots has the potential to enhance quality, productivity, and environmental cleanliness, all while minimizing costs and labor [38, 36]. The effectiveness of the paint quality is influenced by factors such as transfer rate, pressure, gun travel speed, viscosity, surface preparation, paint composition, and temperature. Notably, while chemical and environmental properties remain relatively constant, the pressure, distance between the gun and the surface, and the gun travel speed play pivotal roles in affecting performance indicators [2].

Researchers, including From and Gravdahl [3], have proposed techniques to expedite the painting process carried out by standard industrial manipulators. Abdellatif [4] has detailed the design and functionality of an automated wall painting robot machine. Thakar and Vora [39] have provided insights into component manufacturing and paint requirements for rust

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protection in small and medium-scale industries. Keerthanaa et al. [5] have introduced a procedure involving infrared transmitters and flame receivers to identify wall appearance. They employ a microcontroller unit to regulate DC motor movement for automated wall surface painting. Bhalamurugan and Prabhu [6] have investigated the performance characteristics of an industrial robot ABB-IRB1410 in developing an automated painting process. They have employed Taguchi orthogonal array (OA) and gray relational analysis (GRA), converting the multi-objective optimization problem into a single objective and carrying out optimization using GRA. Their study includes a comparison of results with manual painting using an HVLP gun.

The Taguchi approach, a systematic statistical methodology, utilizes orthogonal arrays to suggest a limited number of experiments that yield the data necessary for a full factorial design of experiments [7]. This approach is cost-effective and minimizes the time and resources required for trial run experiments. It has found successful application in various industrial contexts, optimizing solutions for challenges such as drilling-induced damages in composites, performance of plate heat exchangers, and stage and satellite separation processes in space launch vehicles [8].

Bhalamurugan and Prabhu [9] have devised an experiment for the robot spray painting process, utilizing Taguchi's L9 orthogonal array to identify optimal process parameters. These parameters include distance, pressure, and speed, each with three levels. The goal is to optimize the robot spray painting process parameters based on performance indicators encompassing thickness variation, surface roughness, and film adhesion. The study incorporates gray rational analysis (GRA) to optimize a multi-objective problem involving the three performance indicators. Analysis of variance (ANOVA) is performed after applying signal-to-noise (S/N) transformations to yield a single value for each test run output response, namely thickness variation, surface roughness, and film adhesion. The S/N ratio transformations, as recommended by Taguchi, consolidate the scatter in test data into a single value. While this method provides a deterministic output response from mean values, the present study employs a modified Taguchi approach to estimate the output response range for specified robot spray painting process parameters. This estimation is then compared with test data, and it's worth noting that the S/N ratio transformation adopted by Bhalamurugan and Prabhu introduces additional computational complexity. Nevertheless, the test results align within the estimated range.

2. Analysis

Experiments on the ABB IRB 1410 robot were conducted by Bhalamurugan and Prabhu. The experiments involved the utilization of specially designed end-effectors equipped with a pneumatically controlled spray gun. To manage air pollution stemming from the emitted fumes, a portable paint booth was constructed to secure the CRCA steel substrates (measuring 250×150×1.5mm) in a suitable position. For painting purposes, a Hi-Solids Poly Urethane (PU) with low volatile organic compounds (VOC) content was employed. The

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viscosity of the paint was measured using a Ford#4 cup. Path planning for the gun travel adopted a 50% overlapping approach. In a bid to enhance paint coating quality, the study considered thickness variation (ψ1), surface roughness (ψ2), and film adhesion (ψ3) as key performance indicators. These were evaluated against the backdrop of spray painting process parameters including distance (A), pressure (B), and speed (C), as depicted in Figure-1.

A three-level design was adopted for each of the three spray painting process parameters, namely A, B, and C. The specific levels for the process parameters and the corresponding performance indicators (ψ1, ψ2, and ψ3) were determined based on an L9 orthogonal array configuration. The minimum number of experiments, denoted as NTaguchi, was calculated in correspondence with the number of process parameters (np) and their assigned levels (nl) [26].

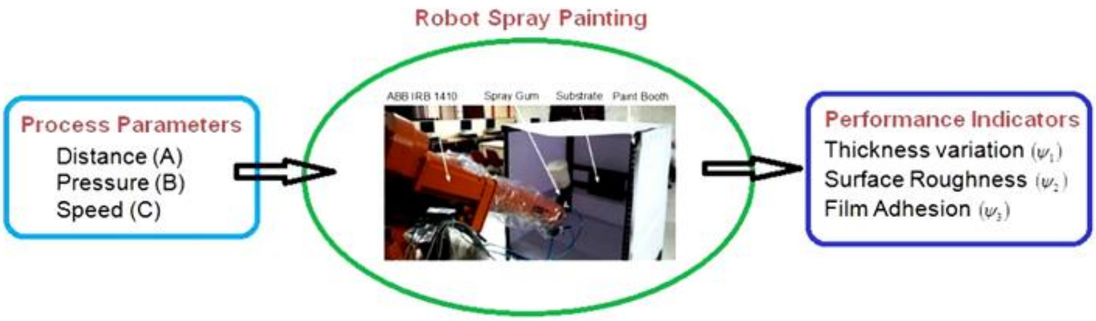

Figure-1: Robot spray painting process parameters and performance indicators [3]

In the context of the present L9 orthogonal array, where NTaguchi equals 9 and nl equals 3, equation (1) determines the number of process parameters, with np equal to 4, that can be accommodated. However, the study by Ref.focuses solely on three spray painting process parameters. As a result, a fictitious factor (D) is introduced into Table 1, similar to the approach.

Table-2 provides the ANOVA results, delineating the contributions of spray painting process parameters – namely distance (A), pressure (B), speed (C), and the fictitious parameter (D) – to the variations in thickness. Specifically, these parameters contribute 51.72%, 30.17%, 13.15%, and 4.96% to the variation in thickness, respectively. Similarly, concerning surface roughness, the contributions of spray paint process parameters A, B, and the fictitious parameter (D) amount to 18.23%, 74.31%, 6.92%, and 0.54%. In the case of film adhesion (ψ3), the contributions are distributed as follows: 47.08% for A, 30.2% for B, 19.54% for C, and 3.18% for D.

From the ANOVA results in Table-2, it can be inferred that the optimal spray painting process parameters for achieving minimum thickness variation (ψ1) correspond to A1B2C2, where the subscripts denote the respective levels of the process parameters. For minimizing surface roughness (ψ2), the optimal set of process parameters is A3B2C1, while the maximum film adhesion (ψ3) is achieved with process parameters A3B3C3.

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The process designer seeks to identify a set of spray paint process parameters that collectively ensure minimum thickness variation (ψ1), minimal surface roughness (ψ2), and maximal film adhesion (ψ3). The test data extracted from ANOVA Table-2 reveals distinct optimal process parameters for ψ1, ψ2, and ψ3. In instances such as this, where multiple objectives are to be optimized simultaneously, a multi-objective optimization approach needs to be employed.

Table-1: Design factors and the performance indicators (viz., thickness $variation(\psi_1)$, surface $roughness(\psi_2)$, and film $adhesion(\psi_3)$) as per L_9 orthogonal array.

Design factors	Designation	Level-1	Level-2	Level-3
Distance (mm)	*A*	100	125	150
Pressure (bar)	*B*	2	2.25	2.5
Speed (mm/s)	*C*	75	90	105
Fictitious	*D*	d_1	d_2	d_3

Test Run	Levels of design factors				Performance indicators					
					Thickness variation, $\psi_1(\mu m)$		Surface roughness, $\psi_2(\mu m)$		Film adhesion, $\psi_3(\%)$	
	A	*B*	*C*	*D*	Test [10]	Eq.(2)	Test [10]	Eq.(2)	Test [10]	Eq.(2)
1	1	1	1	1	9	9	0.102	0.102	96.5	96.5
2	1	2	2	2	2	2	0.110	0.110	95	95.0
3	1	3	3	3	9	9	0.162	0.162	98.5	98.5
4	2	1	2	3	5.5	5.5	0.104	0.104	97	97.0
5	2	2	3	1	5.5	5.5	0.096	0.096	97.5	97.5
6	2	3	1	2	18	18	0.130	0.130	98.5	98.5
7	3	1	3	2	18	18	0.083	0.083	98.9	98.9
8	3	2	1	3	14	14	0.070	0.070	98.5	98.5
9	3	3	2	1	18	18	0.137	0.137	98.9	98.9

Since ψ_1, ψ_2 and ψ_3 are three different output responses, they must be functionally represented in non-dimensional form. For this purpose the maximum values of ψ_1, ψ_2 and ψ_3 evaluated from the ANOVA table-2 using the additive law (2) are: $\psi_{1max} = 25\ \mu m$, $\psi_{2max} = 0.1653\ \mu m$and $\psi_{3max} = 100.6\%$. Using the additive law, one can estimate the output response $(\widehat{\Psi})$ [26]:

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Design Factors	1-Mean	2-Mean	3-Mean	Mean	Sum of Squares	% Contribution
Thickness variation, $\psi_1(\mu m)$						
A	6.667	9.667	16.667	11	158	51.72
B	10.833	7.167	15	11	92.17	30.17
C	13.667	8.5	10.833	11	40.17	13.15
D	10.833	12.667	9.5	11	15.17	4.96
Surface roughness, $\psi_2(\mu m)$						
A	0.1247	0.1100	0.0967	0.1104	1.177E-03	18.23
B	0.0963	0.0920	0.1430	0.1104	4.798E-03	74.31
C	0.1007	0.1170	0.1137	0.1104	4.469E-04	6.92
D	0.1117	0.1077	0.1120	0.1104	3.489E-05	0.54
Film adhesion, $\psi_3(\%)$						
A	96.67	97.67	98.77	97.7	6.62	47.08
B	97.47	97.00	98.63	97.7	4.25	30.20
C	97.83	96.97	98.30	97.7	2.75	19.54
D	97.63	97.47	98.00	97.7	0.45	3.18

3. Concluding Remark

The extensive use of robot spray painting processes in the automotive industry has prompted a pursuit for enhanced paint coating quality. This entails the specification of optimal spray painting process parameters. The present study addresses this imperative by considering key performance indicators, namely thickness variation, surface roughness, and film adhesion. To achieve this, a straightforward modified Taguchi approach is adopted.

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