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● *Paper*

ECONOMIC ANALYSIS OF ROBOTIC OPERATIONS: A CASE STUDY OF A THERMAL SPRAYING ROBOT

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There is growing interest in the industrial applications of computer-integrated manufacturing (CIM) and robotic technology. The economic analysis methods which are currently available to assess the cost effectiveness of robotic systems are, however, limited. This paper presents a methodology to address this issue. To demonstrate the methodology, a case-study is presented which uses a thermal spraying robot in a rapid tool manufacturing system. The interdependencies between tolerance, robot accuracy, and the probability of a successful spraying operation are demonstrated. The economic effects of using robots in the spraying process are analyzed. Analytical models are developed to estimate the productivity of components without any defects and the improvement in tool life attributable to robotic spraying. The economic analysis method presented in the paper is also applicable to other operations such as robotic assembly and robotic welding.

INTRODUCTION

During the past decade, the successful integration of robotics with CIM (computer-integrated manufacturing) technology has become one key to global competitiveness. CIM is a systems issue which involves rethinking many manufacturing activities. One such activity is the manufacture of tooling such as dies and molds required for the high-volume production methods that generate most of our manufactured products. Therefore, reducing the time to manufacture tools and to identify problems earlier is essential to shorten the design cycle and thus gain a competitive edge by achieving a faster response time to market demands. Rapid tool manufacturing technology is currently one of the most challenging areas of CIM.[1]

A rapid tool manufacturing system is being developed at Carnegie Mellon University which utilizes robotic thermal spraying. A critical step in the implementation of a robotic system is to perform an economic analysis for cost justification. The economic analysis methods which are currently available to assess the cost effectiveness of robotic systems are, however, limited.[2–4] These methods are based upon traditional capital investment techniques and do not account for strategic benefits of robotic systems such as higher productivity, improved product quality, and reduced defect rate. Many firms often invest in robotic technology in the absence of analytical methods to determine the best economic choice for a given task.[5–7] Without any economic objectives, any disruption in the production process can be mistakenly identified as a problem associated with the new robotic system.

Another factor that aggravates this problem is the lack of concurrent information exchange between experts in engineering and computer science disciplines and the economics and accounting disciplines during the process of new technology development. In most organizations the expertise in tool design and product design reside in different groups. As a result, new product development or product modification implies a series of expensive and time-consuming iterations for both product designers and toolmakers since some designs may not be readily manufacturable. Consequently, economic performance measures of the system do not become a vital part of the development of a new technology. Particularly, the trade-offs between the specified robot performance (e.g. accuracy, speed and resolution) and its ability to perform a given manufacturing task are not well understood within an economic context. This paper presents an approach to address this issue. To demonstrate the methodology, a case study is presented based on the robotic thermal spray process of the rapid tool manufacturing system. The relationship between the specified task tolerance, the robot accuracy, and the probability of keeping the robot gun at a prespecified position are derived. Then, the probability of a successful spraying operation is converted to a measure of productivity impacts and improvement in expected tool life.

The rapid tool manufacturing system considered here integrates stereolithography and thermal spraying into a complete CAD/CAM environment.[8] With stereolithography apparatus (SLA), plastic prototype models are built directly from liquid photopolymers by laser scanning. Thermal spraying is then used to incrementally deposit metal onto the SLA models to build the tool. The quality of the spraying operation is highly dependent upon accurate and consistent execution of spray paths. Manual spraying by a skilled technician is tedious and can result in poor deposition quality; robotic sprayers have the potential to achieve superior results.

The development of the rapid tool manufacturing system included the identification of a series of economic measures of the performance of a robot for different process requirements. One issue to consider in the introduction of a robot into the spraying operation is the interdependence between robot accuracy and the quality of the spray deposition. The objective of this case study is to investigate these interdependencies through a formal framework of economic analysis. The conditions required to select the most cost effective robot and the economic effects of using robots in the spraying process are developed using analytical models to estimate the productivity of tools and the improvement in tool life. The economic analysis method presented in the paper is also applicable to other operations such as robotic assembly and robotic welding.

In Section 2, a brief description of the sprayed metal tooling system is provided. Section 3 proceeds with the development of a model of robotic spraying. In Section 4, the relationship between spraying features and robot accuracy is demonstrated by considering different alternatives of spraying specifications and accuracy levels to improve the probability of a successful spraying operation. Then the economic implications of robotic spraying is assessed by two methods: productivity of components without any defects, and improvement in tool life.

2. SPRAYED TOOLING

The robotic spraying process considered in this paper is part of a unified CAD/CAM tool manufacturing system. In this system, both prototype and tooling fabrication are based upon compatible shaping deposition processes, stereolithography apparatus (SLA) and arc spray equipment, while the underlying geometric and process models share a common representational scheme. Stereolithography is a process which creates plastic models directly from a vat of liquid photocurable polymer by selectively solidifying it with a scanning laser beam.[9] As the laser beam draws on the liquid surface it creates cross-sections of the solid shape. Complete three dimensional shapes are built-up by drawing cross-sections on top of each other with each new layer being lowered into the vat by an elevator mechanism. SLA is excellent for rapidly producing plastic prototype models. The next step uses arc spraying to create an injection mold tool directly from the prototype.

In arc spraying, metal wire is melted in an electric arc, atomized, and sprayed onto a substrate surface (Fig. 1) such as plastic created with SLA. On contact,

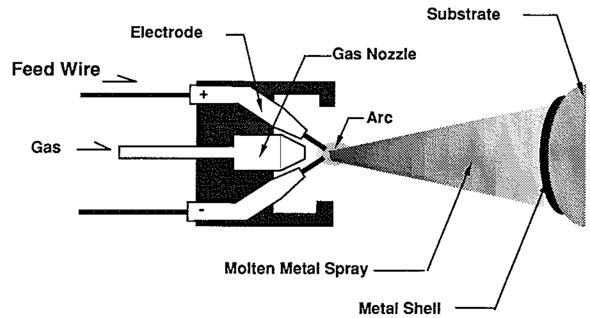

Fig. 1. Electric arc spraying.

the sprayed material solidifies and forms a surface coating. Spray coatings are repeatedly applied to incrementally deposit multiple fused layers. The layers, when separated from the substrate, form a free-standing shell with the shape of the substrate surface. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tooling can be fabricated. Relative to conventional machining methods, the sprayed metal tooling approach has the potential for fast and cost effective production of tools, particularly for those parts with complex shapes or large dimensions. Thus, with SLA an initial part shape or prototype is quickly created. Thermal spraying is then used to make tools based on the part shapes produced by SLA.

For example, consider a conventional machined injection mold shown in cross section in Fig. 2. The holes represent cooling channels, and the injection geometry is that of a simple sprue gate. Alternatively, the fabrication steps for buildings sprayed mold using SLA patterns are depicted in Fig. 3.

The steps are:

- *Step* 1: Build SLA pattern used to make one mold half. This pattern is the complement of the interior of this mold half. In this example, the mold pattern includes the partial part shape, a parting plane, and sprue gate.
- *Step* 2: Apply a water soluble release agent onto the plastic pattern, such as polyvinyl alcohol (PVA), to facilitate separation of metal from plastic.
- *Step* 3: Place a metal frame onto the pattern.
- *Step* 4: Spray metal onto the pattern and around inside edge of frame. Alloyed zinc compositions are used for this particular process because of their relatively low residual stress. A process for depositing steel is currently being developed. Sprayed

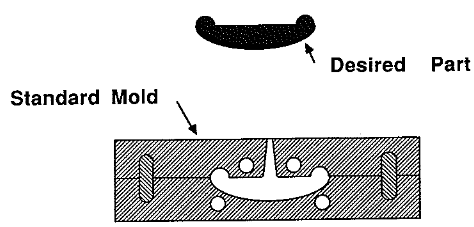

Fig. 2. Conventional mold.

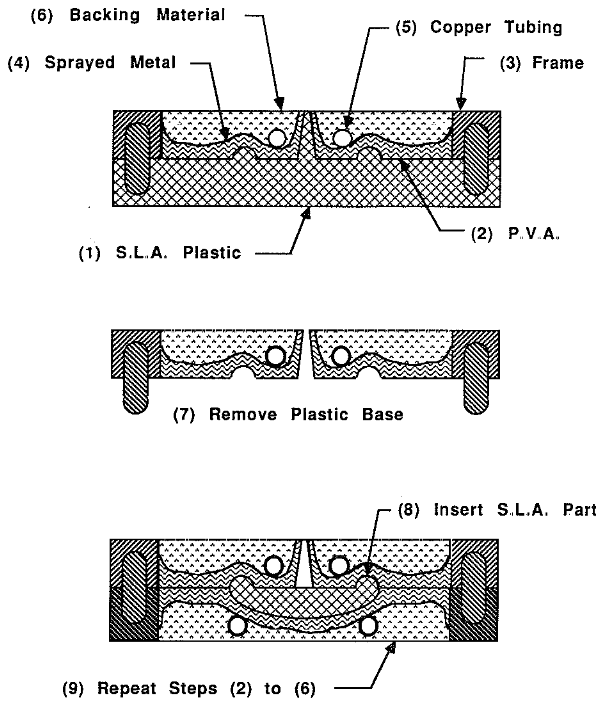

Fig. 3. Sprayed tool process.

shell thicknesses are typically on the order of 2–7 ml.

- *Step* 5: Lay in place copper tubing for heating and cooling channels for the injection mold process. Additional injection mold components, such as prefabricated ejector pin assemblies (not shown), can be added in Step 1 and sprayed in place in Step 4.
- *Step* 6: Pour in a backing material to support the metal shell. Typical backing materials include epoxy mixed with aluminum shot.
- *Step* 7: Separate the substrate pattern from the mold half. This is aided by dissolving the PVA in water. This completes the fabrication of the first mold half.
- *Step* 8: With SLA, build a model of the whole part to be molded, including runners and gates, and insert the model into the first mold half. This forms the pattern for spraying the second mold half.
- *Step* 9: The second mold half is completed by repeating Steps 2–7.

The mold fabrication is completed by removing the SLA insert.

The potential effect of combining thermal spraying with SLA to build tooling is enhanced by automating the thermal spray process with robotics. Tooling manufacture by thermal spraying is currently a labor intensive manual art-form. Shifting emphasis to robotic spraying, driven by an off-line trajectory and process planner, improves tooling quality by achieving consistent and predictable performance of the sprayed metal shell.[10] In particular, such process control capability will be crucial for building sprayed steel tooling. The fabrication of sprayed steel tooling requires uniform deposition over the entire substrate surface. Such spray control is difficult to achieve with manual techniques.

Automated thermal spraying requires the scheduling of the arc spray parameters and the selection of the robot trajectory. Trajectory planning involves determining the relative path of the spray on the part. While the arc parameters (e.g. wire feed rate, arc voltage, etc.) directly affect the sprayed shell quality, the path of the gun is equally important. For example, to minimize the porosity of the deposited material, and thus increase material strength, particle trajectories should align with the surface normals to assure maximal splattering of the molten particles. As the angle between the particle trajectory and surface normal increases, shell porosity increases. There is also an optimal distance between the gun and the substrate which maximizes particle velocity, further minimizing porosity. Thus, there is interdependence between the accuracy of the robot, spraying specifications, and the quality of the sprayed part.

3. MODELING OF ROBOTIC SPRAYING

In this section, a model is developed to relate the predicted performance of spraying operations to spraying specifications, such as task tolerance, and to the accuracy levels of different thermal spraying robots. *Tolerance* is defined as a specified permissible magnitude of error from the prespecified position/orientation of the spray gun relative to the surface. The main factors that affect tolerance are limits of the *accuracy* of the robot and the requirements for obtaining a successful deposition process.

During the spraying process, the distribution of sprayed particles approximates a Gaussian distribution.[11,12] As depicted in Fig. 4, a prespecified length of overlap of two adjacent spray areas is necessary to obtain a uniform sprayed surface. This requires that the gun is kept at a specified vertical distance from the surface and also makes the precise specified horizontal motion. These conditions are demonstrated in Fig. 4. The model developed here assumes that the gun orientation is normal to a flat substrate, and is useful for aproximating robot performance with more complex geometries. The case for convex and concave surfaces and cavities is the subject

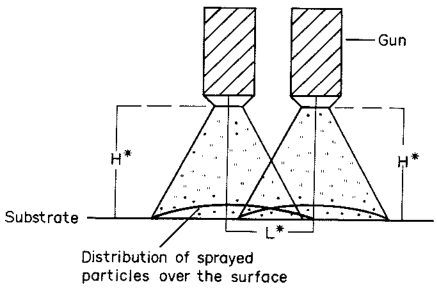

Fig. 4. The conditions for a successful spraying operation.

of future research. The flat substrate model is appropriate for another thermal spray process being developed at Carnegie Mellon University.[12]

As can be seen in Fig. 4, in order to achieve a successful spraying operation, the distance of the gun from the surface should be H^*. In addition, the spray gun has to make the precise horizontal movement L^*.

Define:

H—actual distance of the spray gun from the surface
h_{min}—a minimum allowable tolerance for an acceptable spraying operation
h_{max}—a maximum allowable tolerance for an acceptable spraying operation
L—actual horizontal distance of the spray gun from one spray point to the next
l_{min}—a minimum allowable tolerance for an acceptable spraying operation
l_{max}—a maximum allowable tolerance for an acceptable spraying operation

The conditions for a successful spraying operation are:

$$h_{min} \leq |H^* - H| \leq h_{max}$$

and

$$l_{min} \leq |L^* - L| \leq l_{max}.$$

The distributions of H and L can be represented by h and l with the following mean and standard deviation:

$$\mu_h = \frac{\text{minimum height} + \text{maximum height}}{2}$$

$$\mu_l = \frac{\text{minimum length} + \text{maximum length}}{2}$$

$$\sigma_h = \frac{\text{tolerance}_h}{6}$$

$$\sigma_l = \frac{\text{tolerance}_l}{6}.$$

Defining the variable

$$y_h = |H^* - H|$$

with mean and variance

$$\mu_{y_h} = \text{tolerance}_h$$

$$\sigma_{y_h}^2 = (\sigma_h)^2.$$

Defining the variable

$$y_l = |L^* - L|$$

with mean and variance

$$\mu_{y_l} = \text{tolerance}_l$$

$$\sigma_{y_l}^2 = (\sigma_l)^2.$$

Under manual spraying, the condition for a successful spraying operation is:

$$Y_h \geq 0 \text{ and } Y_l \geq 0.$$

The following variables can be defined in order to analyze robotic spraying:

d—the displacement from H^* and L^*,

X_A—the accuracy of the robot.

Then the *displacement*, d, is a random variable in the range:

$$-X_A \leq d \leq +X_A.$$

Since displacement in any direction will result in an unsuccessful spraying operation, the following conditions must be satisfied:

$$d \leq 0.5|L^* - L|$$

and

$$d \leq 0.5|H^* - H|$$

where L and H are in the range of a specified permissible magnitude of error (i.e. tolerance) from L^* and H^*.

Representing:

$$|L^* - L| = D_L$$

$$|H^* - H| = D_H.$$

3.1. *Normally distributed clearance and robot accuracy*

The distributions of L and H can be represented by l and h, which can be approximated by a normal distribution with mean μ_l, μ_h, and variance $(\sigma_l)^2$, $(\sigma_h)^2$.

Similarly, the distributions of D_L and D_H can be represented by d_L and d_H with the mean and standard deviation:

$$\mu_{d_L} = \frac{\text{minimum length} + \text{maximum length}}{2}$$

$$\mu_{d_H} = \frac{\text{minimum height} + \text{maximum height}}{2}$$

$$\sigma_{d_L} = \frac{\text{tolerance}_L}{6}$$

$$\sigma_{d_H} = \frac{\text{tolerance}_H}{6}.$$

The 6σ limit encompasses an area of 0.997 under the normal distribution and is a very close approximation.

Redefining the variable $y_L = 0.5\, D_L$ with mean and variance:

$$\mu_{y_L} = 0.5\, \mu_{d_L}$$

$$\sigma_{y_L}^2 = 0.5^2\, (\sigma_{d_L})^2.$$

Redefining the variable $y_H = 0.5\, D_H$ with mean and variance:

$$\mu_{y_h} = 0.5\, \mu_{d_H}$$

$$\sigma_{y_H}^2 = 0.5^2\, (\sigma_{d_H})^2$$

where μ_{y_L} and μ_{y_H} are the mean values of the clearance range, and $\sigma_{y_L}^2$ and $\sigma_{y_H}^2$ are the variances of the clearances. Since displacement both to the right and to the left has to be considered in calculating the probability of a successful spraying operation, clearance is defined as double the size of tolerance.

It is assumed that the overall robot accuracy X_A has a probability density function of $f(X_A)$. If c represents the distribution of clearance and t represents the distribution of accuracy, then the probability of obtaining L^* or H^* is:

$$P(C \geq T) = \int_{C=0}^{C_{\max}} \int_{T=0}^{C} f(t) f(c) \, dt \, dc.$$

Assuming that $f(X_A)$ has a uniform distribution:*

$$P(C \geq T) = \frac{1}{X_A} \left\{ \mu_y - \sigma_y \theta(X_A) - \mu_y \left[1 - \int_{-\infty}^{X_A} \theta(c) \, dc \right] \right\} + \left[1 - \int_{-\infty}^{X_A} \theta(c) \, dc \right]$$

where:

$$\theta(c) = \frac{1}{\sqrt{2\Pi}\sigma_c} \exp\left[-\frac{1}{2} \left(\frac{c - \mu_c}{\sigma_c} \right)^2 \right].$$

A successful spraying operation requires that both L^* and H^* are obtained. Since H^* and L^* are independent, the probability of a successful spraying operation $P(S)$ for normally distributed clearance and uniformly distributed accuracy is:

$$P(S) = [P(C \geq T)]_{H^*} \cdot [P(C \geq T)]_{L^*}.$$

The methodology is demonstrated through an example. As can be seen in the Appendix, using a robot with an accuracy level of 0.04, the probability of a successful spraying operation for tolerance level of 0.06 on H^* and a tolerance level of 0.07 on L^* is 66%. In this example, different tolerance levels on H^* and L^* have been selected for illustrative purposes. Usually tolerance levels on H^* and L^* should be equal.

3.2. *Uniformly distributed clearance and robot accuracy*

The distribution of robot accuracy and clearance usually follows a uniform distribution. Therefore, the results obtained above can be extended to the case of uniformly distributed clearance and robot accuracy:

If $Y_{\max} > X_A$, then,

$$P(C \geq T) = \int_{C=0}^{X_A} \int_{T=0}^{C} f(t) f(c) \, dt \, dc + \int_{X_A}^{Y_{\max}} f(c) \, dc$$

$$P(C \geq T) = \int_0^{X_A} \int_0^{C} \frac{1}{X_A} \frac{1}{Y_{\max}} \, dt \, du + \int_{X_A}^{Y_{\max}} \frac{1}{Y_{\max}} \, du$$

$$P(C \geq T) = \int_0^{X_A} \frac{c}{X_A} \frac{1}{Y_{\max}} \, dc + \frac{Y_{\max} - X_A}{Y_{\max}}$$

$$P(C \geq T) = \frac{[X_A]^2}{2X_A Y_{\max}} + \frac{Y_{\max} - X_A}{Y_{\max}}$$

$$P(C \geq T) = \frac{2Y_{\max} - X_A}{2Y_{\max}}.$$

If $Y_{\max} \leq X_A$, then,

$$P(C \geq T) = \int_{C=0}^{Y_{\max}} \int_{T=0}^{C} f(t) f(c) \, dt \, dc$$

$$P(C \geq T) = \int_{C=0}^{Y_{\max}} \frac{c}{X_A} f(c) \, dc$$

$$P(C \geq T) = \frac{[Y_{\max}]^2}{2X_A Y_{\max}}$$

$$P(C \geq T) = \frac{Y_{\max}}{2X_A}.$$

In the following section economic implications of robotic spraying will be investigated for uniformly distributed robot accuracy and clearance.

4. ECONOMIC IMPLICATIONS OF ROBOTIC SPRAYING

If the probability of a successful spraying process is not adequate, other alternatives can be considered to improve the process. Improving the accuracy of the robot may be one option. However, the cost of spraying would increase since a robot with an improved accuracy level would cost more. Another option may be to increase tolerance at the cost of reducing the tool quality. Thus, there is a trade-off with each option. In this section two evaluation criteria are presented to assess the desirability of each alternative: productivity impacts and improvement of tool life. The relationship between tolerance, robot accuracy, and the probability of keeping the robot gun at a prespecified position are demonstrated. Then, the probability of keeping the robot gun at a prespecified position and the probability of a successful spraying operation are converted to a measure of productivity impacts and improvement in expected tool life.

First increasing allowances for H^* was considered. As can be seen in Table 1, the clearance range has increased by 8 in., from 2.44–2.56 in. to 2.40–2.60, when the tolerance level has increased from 0.06 to 0.10 in.

Table 2 shows the probability of maintaining H^* or L^* [i.e. $P(C \geq T)$] for various robot accuracies and tolerance levels. As can be seen in the table, to achieve $P(C \geq T) = 0.75$ for a tolerance level of 0.01, a robot with an accuracy level of 0.01 is needed. However a robot with an accuracy level of 0.03 is needed to achieve the same level of probability for a tolerance level of 0.04.

Similarly, if the most accurate robot that can be obtained has an accuracy level of 0.07, the probability of a successful spraying operation increases from 14.3 to 80.6, by increasing tolerance from 0.01 to 0.09 through design modifications. The probability level,

* See Appendix for details.

Table 1. Alternatives of spraying features

Tolerance	Clearance range	μ_y
0.06	2.44–2.56	0.030
0.07	2.43–2.57	0.035
0.08	2.42–2.58	0.040
0.09	2.41–2.59	0.045
0.10	2.40–2.60	0.50

however, can be as high as 97.2 with a robot accuracy level of 0.01.

Figure 5 demonstrates that for more precise spraying operations, the probability of obtaining successful spraying is highly affected by robot accuracy level. The probability of successful spraying, however, is less affected by robot accuracy level for tolerance levels 0.06 and higher.

4.1. *Productivity implications*

The probability level of holding the spray gun at H^* and L^* can be converted to an output rate of components without any defects. Assuming that sequential operations of individual spraying operations on an SLA mold patterns are independent and that the production of parts without any defects are directly affected by the quality of the spraying operation on the mold, the productivity rate is given by:

$$P_r = P(C \geq T)\frac{1}{ct}.$$

The output per hour of components without any defects for a cycle time of 45 s is shown in Table 3. As can be seen in Table 3, the probability level of 97.2 for holding H^* or L^*, can be converted to an average productivity rate of 78.6 units per hour.

Similarly, the probability of a successful spraying operation $P(S)$ can be converted to a productivity rate

$$P_r = P(S)\frac{1}{ct}$$

where:

$$P(S) = P(C \geq T)_{H^*} \times P(C \geq T)_{L^*}.$$

The values for $P(C \geq T)_{H^*}$ and $P(C \geq T)_{L^*}$ can be obtained from Table 2.

Assuming that sequential operations of individual sprays on an SLA mold part are independent and that the production of parts without any defects are directly affected by the quality of spraying operation on the mold, Table 4 shows the productivity effect of a

Table 2. The probability of holding the robot gun at a prespecified position for various combinations of robot accuracy and tolerance level

Tolerance	Robot accuracy (X_A) 0.07	0.06	0.05	0.04	0.03	0.02	0.01
0.01	0.143	0.167	0.200	0.250	0.333	0.500	0.750
0.02	0.286	0.333	0.400	0.500	0.625	0.750	0.875
0.03	0.423	0.500	0.583	0.667	0.750	0.833	0.917
0.04	0.563	0.625	0.688	0.750	0.813	0.875	0.938
0.05	0.650	0.700	0.750	0.800	0.850	0.900	0.950
0.06	0.708	0.750	0.792	0.833	0.875	0.917	0.958
0.07	0.750	0.786	0.821	0.857	0.893	0.929	0.964
0.08	0.781	0.813	0.844	0.875	0.906	0.938	0.969
0.09	0.806	0.833	0.861	0.889	0.917	0.944	0.972

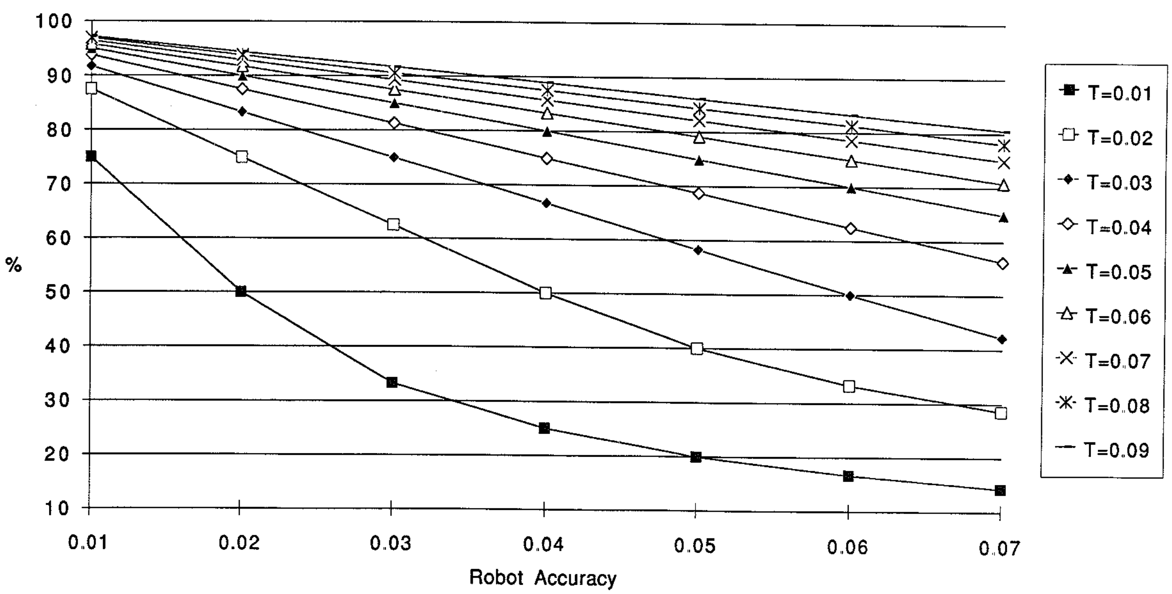

Fig. 5. The relationship between probability of successful spraying and robot accuracy for various levels of tolerance.

Table 3. Productivity implications of holding the robot gun at a prespecified position

Tolerance	Robot accuracy (X_A)						
	0.07	0.06	0.05	0.04	0.03	0.02	0.01
0.01	11.4	13.3	16.0	20.0	26.7	40.0	60.0
0.02	22.9	26.7	32.0	40.0	50.0	60.0	70.0
0.03	34.3	40.0	46.7	53.3	60.0	66.7	73.3
0.04	45.0	50.0	55.0	60.0	65.0	70.0	75.0
0.05	52.0	56.0	60.0	64.0	68.0	72.0	76.0
0.06	56.7	60.0	63.3	66.7	70.0	73.3	76.7
0.07	60.0	62.9	65.7	68.6	71.4	74.3	77.1
0.08	62.5	65.0	67.5	70.0	72.5	75.0	77.5
0.09	63.8	64.4	66.7	68.9	71.1	73.3	78.6

Table 4. Productivity implications of various combinations of robot accuracy and tolerance level

Tolerance	Robot accuracy (X_A)						
	0.07	0.06	0.05	0.04	0.03	0.02	0.01
0.01	1.63	2.22	3.20	5.00	8.89	20.0	45.0
0.02	6.53	8.89	12.8	20.0	31.3	45.0	61.3
0.03	14.7	20.0	27.2	35.6	45.0	55.0	67.2
0.04	25.3	31.3	37.8	45.0	52.8	61.3	70.3
0.05	33.8	39.2	45.0	51.2	57.8	64.8	72.2
0.06	40.1	45.0	50.1	55.6	61.3	67.2	73.5
0.07	45.0	49.4	54.0	58.8	63.8	69.0	74.4
0.08	48.8	52.8	57.0	61.3	65.7	70.3	75.1
0.09	51.9	55.6	59.3	63.2	67.2	71.4	75.6

successful spraying operation for various combinations of robot accuracy and tolerance levels. The productivity effect has been calculated based on the assumption that tolerance levels on H^* and L^* are equal.

4.2. *Improvement in tool life*

The quality of the spraying operation affects tool life. If the spraying is non-optimal, then the sprayed shell is non-uniform in thickness and more porous. For example, an injection mold tool may require uniform heating throughout the tool. If the sprayed surface of the tool is not uniformly thick, then the injected part may not solidify at the same rate over its surface. Increased porosity accelerates the rate at which the tool loses tolerance, due to surface wear, eventually reducing the tool life.

If tool life is expected to be a constant number of parts, life expectancy of the tool reduces as a function of the probability of an unsuccessful spraying operation. This can be formulated as a linear function:

$$\text{ToolLife} = \text{ETL} \cdot P(S)$$

where:

ETL—expected tool life
$P(S)$—probability of a successful spraying operation given the tolerance and robot accuracy.

Table 5 demonstrates percentage reduction in tool life for various levels of tolerance and robot accuracy. Reduction in tool life can be as high as 98% for a tolerance level of 0.01 and robot accuracy level of 0.07. If robot accuracy is improved to 0.01, reduction in tool life is 43.8%.

Table 5. Percentage reduction in tool life for various combinations of robot accuracy and tolerance level

Tolerance	Robot accuracy (X_A)						
	0.07	0.06	0.05	0.04	0.03	0.02	0.01
0.01	98.0	97.2	96.0	93.8	89.0	75.0	43.8
0.02	91.8	88.9	84.0	75.0	60.9	43.8	23.4
0.03	81.6	75.0	66.0	55.6	43.8	30.6	16.0
0.04	68.4	60.9	52.7	43.8	34.0	23.4	12.1
0.05	57.8	51.0	43.8	36.0	27.8	19.0	9.8
0.06	49.8	43.8	37.3	30.6	23.4	16.0	8.2
0.07	43.8	38.3	32.5	26.5	20.3	13.8	7.0
0.08	39.0	34.0	28.8	23.4	17.9	12.1	6.2
0.09	35.1	30.6	25.9	21.0	16.0	10.8	5.5

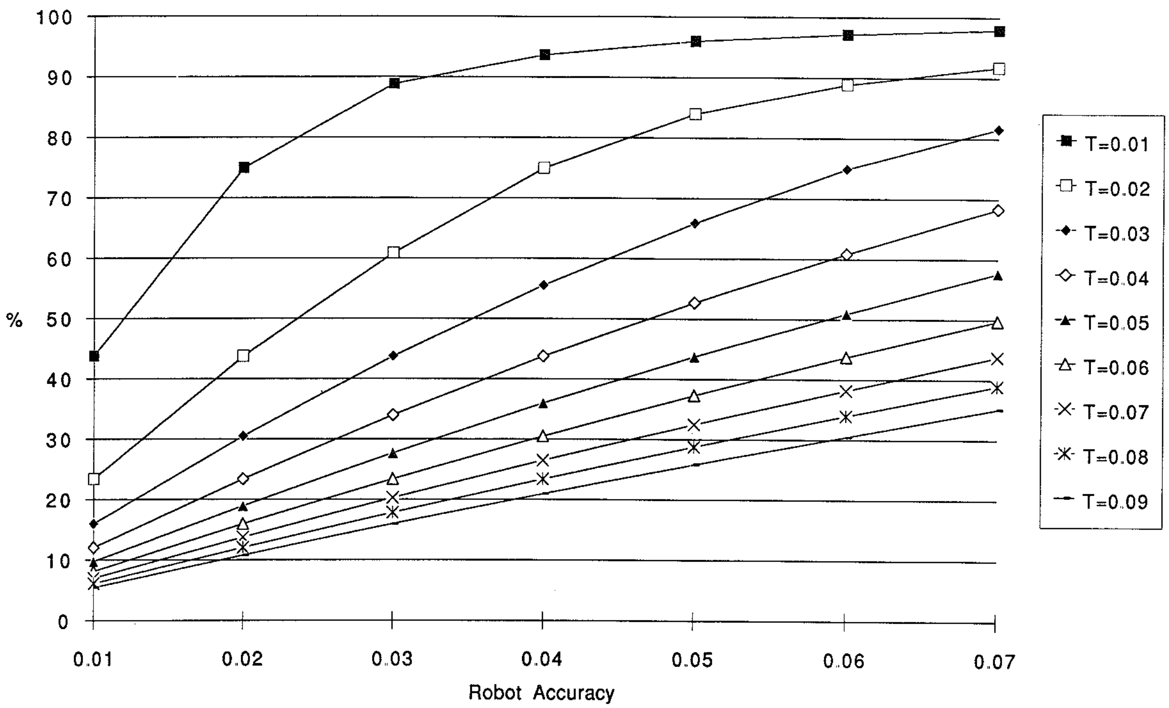

Fig. 6. The reduction in tool life for various levels of tolerance and robot accuracy.

Figure 6 exhibits the relationship between percentage reduction in tool life and various levels of tolerance and robot accuracy. As can be seen in the figure, for a tolerance level of 0.01, tool life is significantly improved if robot accuracy is improved from 0.03 to 0.02 or to 0.01. However, improving robot accuracy from 0.07 to 0.03 does not make a significant improvement in tool life. Reduction in tool life is 98% when accuracy is 0.08 and 89% when accuracy is 0.03. Only 9% improvement in tool life may not be worth the expense of buying a more accurate but more expensive robot. For a tolerance level of 0.03, however, tool life is improved by 38% when robot accuracy is improved from 0.07 to 0.03. As can be seen more clearly in Fig. 5, improvement of robot accuracy has different effects on tool life for different tolerance levels.

5. CONCLUSION

The decision to introduce a robot into a spraying operation requires a thorough understanding of the relationship between robot accuracy and productivity. One way of accomplishing this is to develop a probabilistic model of robot positioning accuracy and relating it to productivity measurements. This paper provided a framework of analysis to identify the best economic combination of alternative spraying specifications and thermal spraying robots with different accuracy levels. Application of the methodology was provided to demonstrate how the probability of a successful spraying operation can be improved by considering different alternatives of spraying specifications and robot accuracy levels. The economic effects were assessed by converting the probability of a successful spraying operation to a productivity rate of components without any defects and by assessing the improvement in tool life.

With slight modifications the methodology can be applied to other areas of manufacturing automation such as robotic assembly and robotic welding. In the case of robotic assembly, for example, tolerances for a mating operation would be different and down time for the robot would vary significantly.

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APPENDIX

1. *Obtaining* P(C ≥ T) ·

$$P(C \geq T) = \int_{C=0}^{C_{\max}} \int_{T=0}^{C} f(t) f(c)\, dt\, dc.$$

Assuming that $f(X_A)$ has a uniform distribution:

$$P(C \geq T) = \int_{C=0}^{X_A} \int_{T=0}^{C} \frac{1}{X_A} \theta(c)\, dt\, dc + \int_{X_A}^{\infty} \theta(c)\, dc$$

where:

$$\theta(c) = \frac{1}{\sqrt{2\Pi\sigma_c}} \exp\left[-\frac{1}{2}\left(\frac{c-\mu_c}{\sigma_c}\right)^2 \right]$$

$$P(C \geq T) = \frac{1}{X_A}\left\{ \int_{-\infty}^{\infty} c\theta(c)\, dc - \int_{-\infty}^{0} c\theta(c)\, dc - \int_{X_A}^{\infty} c\theta(c)\, dc] + [1 - \int_{-\infty}^{X_A} \theta(c)\, dc \right\}$$

$$P(C \geq T) = \frac{\mu_y}{X_A} - \frac{1}{X_A}\left[\int_{-\infty}^{0} c\theta(c)\, dc + \int_{X_A}^{\infty} c\theta(c)\, dc \right] + \left[1 - \int_{-\infty}^{X_A} \theta(c)\, dc \right].$$

The probability of $Y < 0$ is very small and

$$\int_{X_A}^{\infty} c\theta(c)\, dc = \sigma_y \theta(X_A) + \mu_y\left[1 - \int_{-\infty}^{X_A} \theta(c)\, dc \right],$$

$$P(C \geq T) = \frac{1}{X_A}\left\{ \mu_y - \sigma_y\theta(X_A) - \mu_y\left[1 - \int_{-\infty}^{X_A} \theta(c)\, dc) \right] \right\} 1 \left[1 - \int_{-\infty}^{X_A} \theta(c)\, dc \right]$$

where:

$$\theta(c) = \frac{1}{\sqrt{2\Pi\sigma_c}} \exp\left[-\frac{1}{2}\left(\frac{c-\mu_c}{\sigma_c}\right)^2 \right].$$

2. *Application*

Using $X_A = 0.04$ in. and the following spraying specifications, the probability of a successful spraying operation can be calculated as follows:

Distance of the spray gun from the surface $(H^*) = 2.50$ in.
Tolerance = ±0.06 in.
Range = 2.56 in. maximum to 2.44 in. minimum
Clearance = 0.12 in.
Horizontal distance of the spray gun between two spray points $(L^*) = 3.00$
Tolerance = ±0.07 in.
Range = 3.07 in. maximum to 2.93 in. minimum
Clearance = 0.14 in.

$$\mu_{d_H} = 0.06$$

$$\sigma_{d_H} = \frac{0.006}{6} = 0.001$$

$$\mu_{y_H} = 0.5\,\mu_{d_H} = 0.03$$

$$\sigma_{y_H} = 0.5^2\,\sigma^2 = 0.05$$

$$P(C \geq T)_{H^*} = \frac{1}{0.04}[0.03 - (0.05)(0.1476) - 0.03(1 - 0.9207)] + [0.9207] = 0.75$$

$$\mu_{d_L} = 0.07$$

$$\sigma_{d_L} = 0.07/6 = 0.0117$$

$$\mu_{y_L} = 0.5(\mu_L) = 0.035$$

$$\sigma_{y_L} = 0.5^2\,\sigma^2 = 0.00585$$

$$[P(C \geq T)]_{H^*} = \frac{1}{0.04}[0.035 - (0.00585)(0.1476) - 0.035(1 - 0.9207)] + [1 - 0.9207] = 0.873$$

$$P(S) = [P(C \geq T)]_{H^*} \cdot [P(C \geq T)]_{L^*} = 0.75 \times 0.8733 = 0.66.$$