Optimization of Robotic Trajectories for Thermal Spray Shape Deposition

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Abstract

Thermal spray shape deposition is a new process for fabricating net-shape parts by incremental material build-up of cross-sectional layers. This paper presents an approach for spraying thin, flat layers using a robotic spray system. Asymmetries of the spray distribution are first corrected by tilting the spray torch based upon a computer model of the measured spray distribution. The path of the torch is then found using heuristics which are based upon the estimated standard deviation of the corrected distribution. For example, thick arc sprayed coatings (i.e. ~ 4mm) have been deposited using this method with the resulting standard deviation from the mean thickness between 20 to 30 /im. To demonstrate the shape deposition process, a layered prototype turbine blade shape was built using these optimized trajectories.

Keywords: **Thermal Spray, Robotic Spraying, Net Shape Fabrication.**

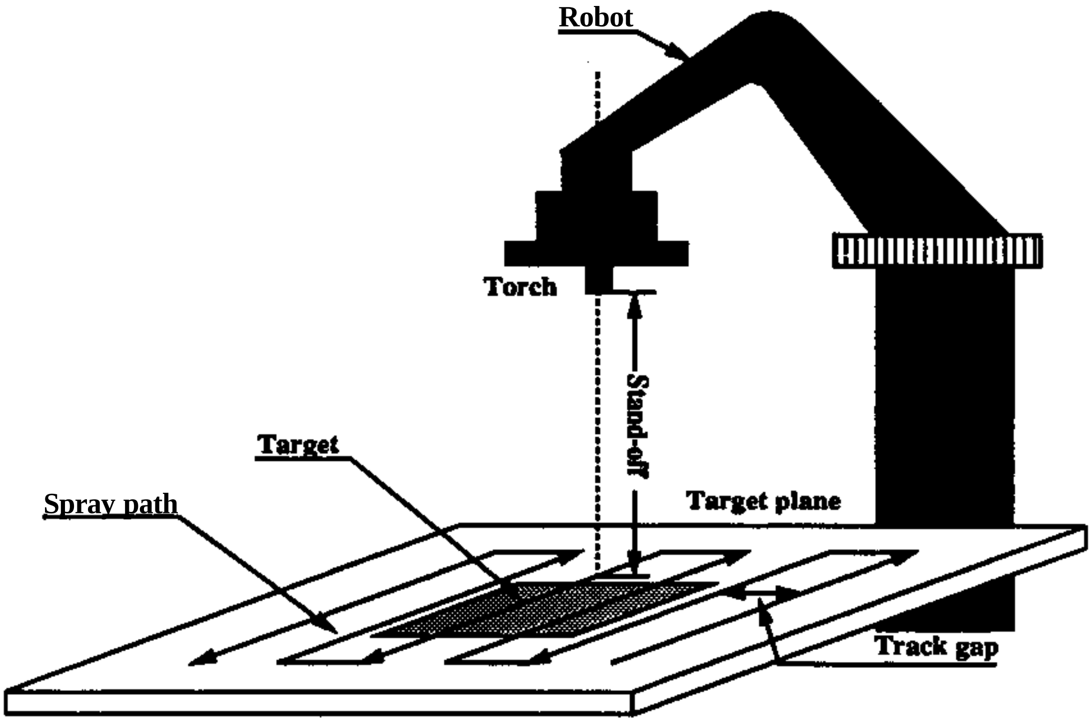

Figure 1: The spray torch is moved with constant stand-off and constant track gap

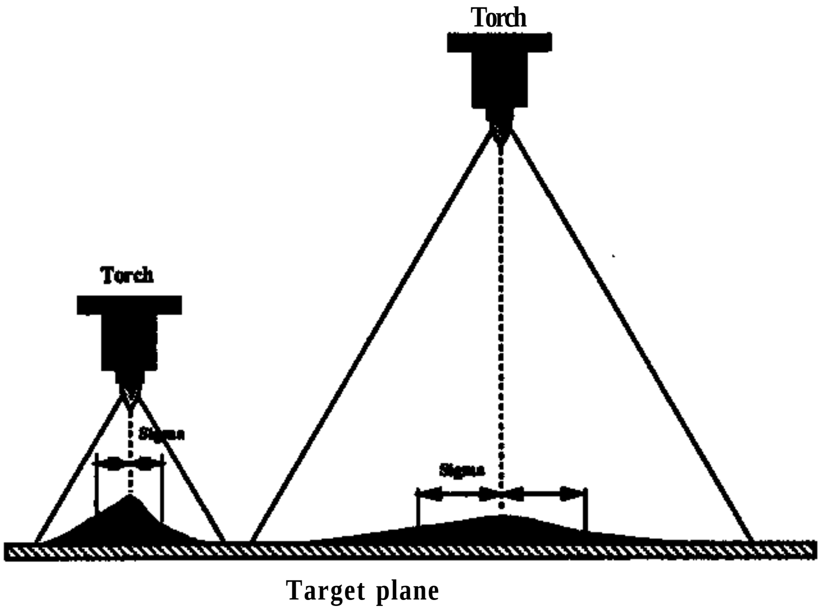

Figure 2: The standard deviation depends on the distance torch-target

asymmetries of the deposited material distributions reduce coating uniformity. The factors which contribute to asymmetries, including imperfect mass-flow control, torch geometry, and gas turbulence cannot always or easily be changed to alter the distribution. Poor alignment of the torch with the substrate also contributes to asymmetry. The distribution, however, can easily be affected by tilting the torch. The goal, therefore, is to develop strategies for spraying thick uniform coatings (i.e. ~ 4mm) by modifying the robot trajectories, including tilt angle and path. This report describes an approach to optimize robot trajectories to maximize coating flatness based upon measured distribution asymmetries.

Section 2 of this report describes the measurement procedure and characterization of the actual spray distribution. Section 3 describes a simple method to symmetrize the material deposition by tilting the spray torch. The resulting distributions are at least symmetric with two perpendicular axes. The equivalence of the distributions with respect to these two axis depends upon the properties of the spray torch and cannot be influenced by this method. It turns out that a small asymmetry of the distribution has a negligible effect on the coating uniformity if the spray path is chosen properly; it is more important to find the optimal spray path as described in section 4.

2 Measurement of deposition symmetry

In order to derive the optimal tilt angles and spray path, an accurate model of the deposited material distribution is required. In particular, it is essential to determine the distributions along two perpendicular axes; the x and y axes in Figure 3. The measurement of one distribution is produced by first moving the torch along a straight line above and parallel to the x-axis with the geometric axis of the torch approximately normal to the target plane. In order to keep the measurement simple and to obtain a reasonable time average of the material build-up, we have observed that the height of the peak of the deposited material should be allowed to accumulate at least 2mm. The profile of a perpendicular cross section in the middle of the deposited material is then measured[1] (dotted curve in Figure 3). Depending on the shape of the measured cross section, the spray torch can then be rotated about the x-axis by a, as will be described in section 3, to compensate for any asymmetry.

A typical cross section is shown in Figure 4. The sample was produced by spraying zinc onto a sand-blasted steel plate with a two-wire electric arc spray system. Figure 5 shows the measured data from that sample distribution. The accuracy of the measurements lies within ± 0.005mm, which is in the order of magnitude of the sprayed particle sizes. The procedure is repeated in y-direction in order to determine the second distribution.

Next a method is required to characterize the symmetry of a two dimensional data array such as is shown in Figure 5. For this purpose, a statistical variable 7 is used [3]:

$$\gamma = \frac{\sum_{i=1}^{n}(y_i - \mu)^3 \cdot z_i}{\sigma_y^3}$$

and

$$\sigma_y^2 = \sum_{i=1}^{n}(y_i - \mu)^2 \cdot z_i; \qquad \mu = \sum_{i=1}^{n} y_i \cdot z_i$$

where y_i and Z{ are the coordinates of the i-th measured point of the cross section, and <J is the standard deviation. The expected value, /i, of the distribution is that point on the baseline of the cross section which a single particle emanating from the torch hits with the highest probability. The function 7 turns out to be a very accurate indicator of the tilt of a curve if the data is measured in equidistant steps; the value of 7 is zero if the data array is symmetric with respect to its maximum (/i), it is less than zero if the data curve is tilted to the left, otherwise it is positive. Figure 6 depicts example curves for these three cases.

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[1] For this measurement, an electronic contact depth gage is used which is fixed in the shaft of a milling machine. The sample is affixed to the x-y table of the milling machine such that the x and the y spray path align with the **x** and y **axes** of the milling machine, respectively. The distribution is then measured in equidistant steps of lmm or smaller.

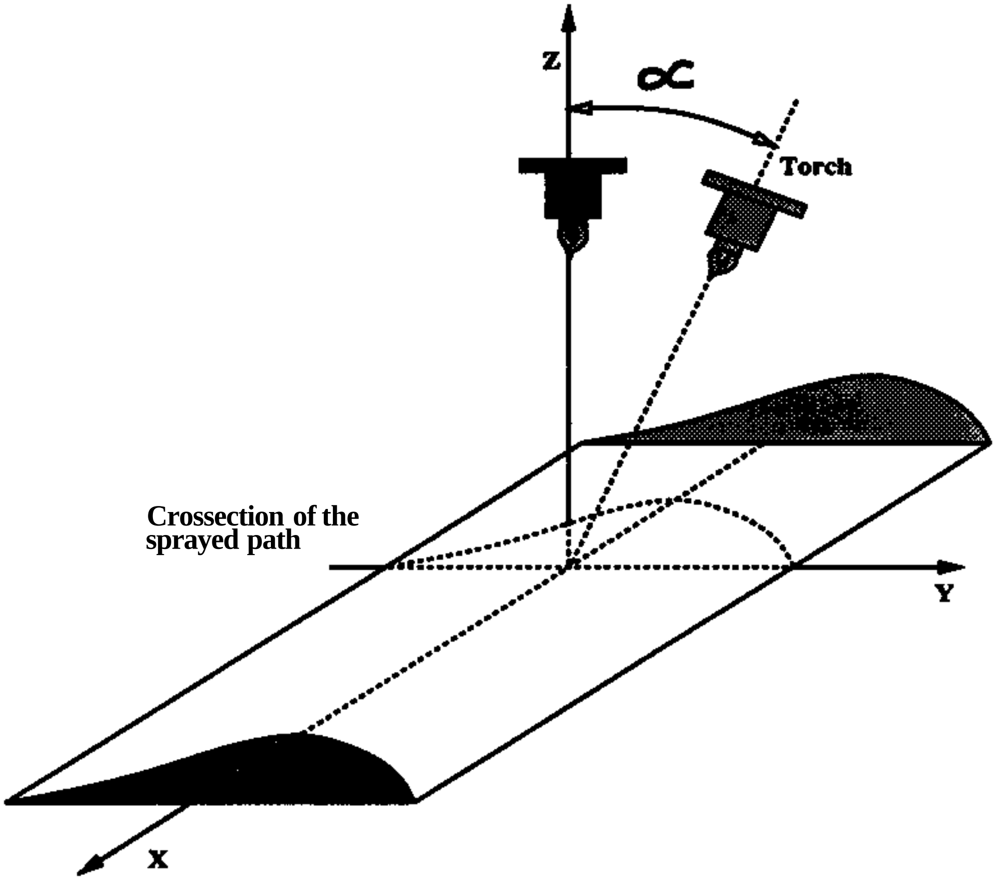

Figure 3: Asymmetric distributions can be symmetrize by tilting the torch

Figure 4: Zinc sprayed onto steel

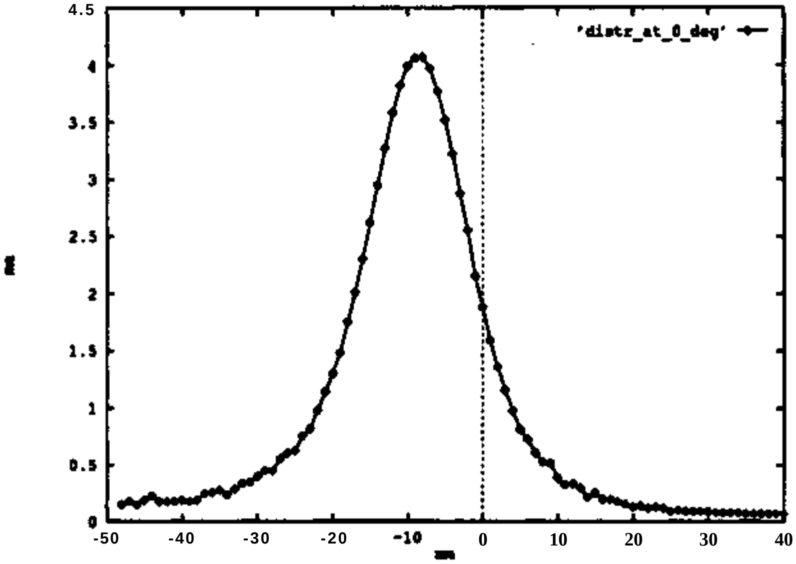

Figure 5: Measured data array

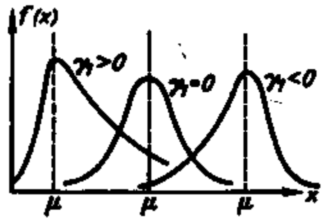

Figure 6: The function 7 is used to determine the tilt of a curve

The following section describes a method for determining the optimal tilt angle about an axis using the corresponding data array and by minimizing the function 7.

3 Torch tilt angle optimization

The redistribution of the measured data array when the torch tilted by an arbitrary angle, a, is first derived. For this derivation, the torch is assumed to be fixed while the target plane is tilted. Figure 7 shows how a point (A) from the horizontal plane is transformed to a point (A') on the tilted plane. A mass of particles leaves the torch at an angle ¥. The amount of mass is proportional to the distance />, and this same amount of mass must also precipitate on the tilted plane at the same angle ¥. Given the position of the spray torch relative to the target and given the coordinates of the measured data points on the untilted plane, the distance *p* can be calculated. With a given tilt angle, a, the measured data point (A) can be transformed to (A^9) on the tilted plane by intersecting the beam emanating from the torch at an angle ¥ with the tilted plane.

The new data array must then be rotated back to the horizontal plane because, in practice, the torch is tilted while the target is fixed. This can be done using the rotation matrix T:

$$\vec{x} = \mathbf{T} \cdot \vec{x'}$$

$$T = \begin{pmatrix} \cos(\alpha) & \sin(a) \\ -\sin(a) & \cos(a) \end{pmatrix}$$

where x^7 is a point in the tilted coordinate system and £ is a point in the horizontal system. When tilting the torch, it is essential that the torch still points to the same point on the target plane and that the distance between torch and target is kept constant.

With this transformation and with the previously defined function 7, it is simple to find the optimal tilt angle without additional spray experiments. Nu-

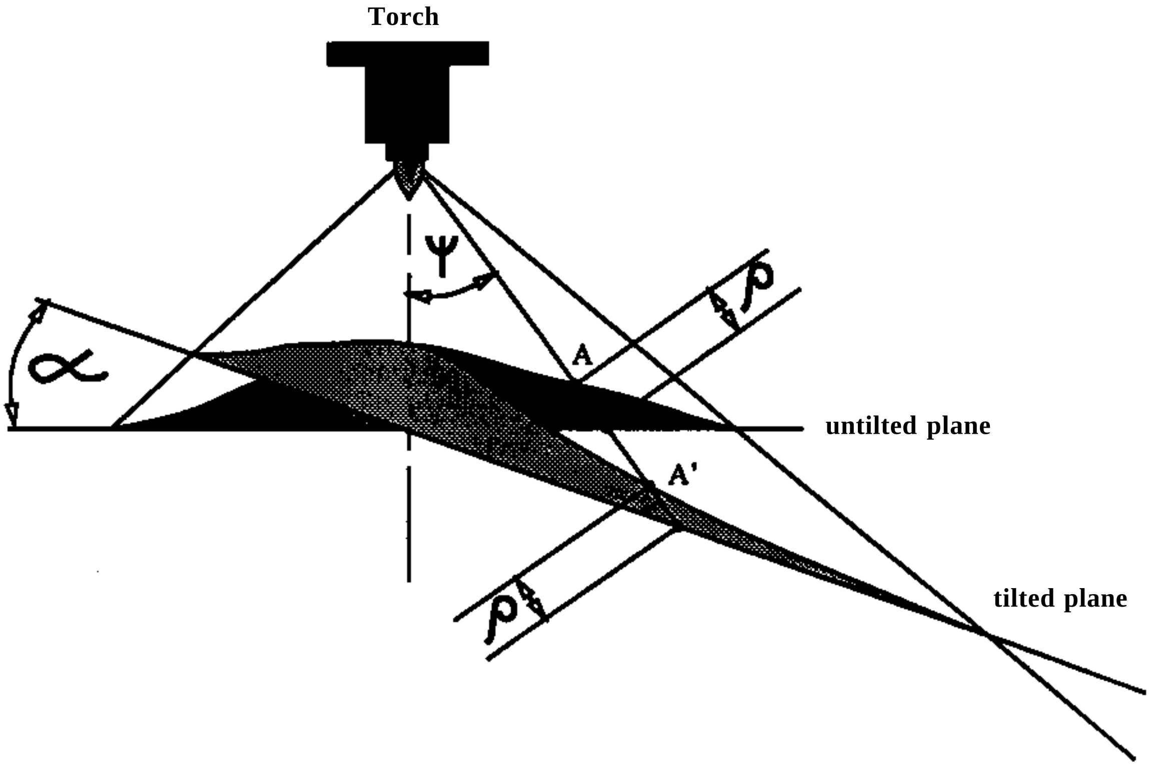

Figure 7: Transformation of the measured data array

merical optimization is used to find the tilt angle which minimizes the function 7 using the following hill climbing algorithm [2]:

```
WHILE ( abs(gamma) > Epsilon ) {
   Alpha = Alpha + Delta;
   tilt measured data array about Alpha degrees;
   calculate Sigma;
   gamma_old = gamma;
   determine gamma( tilted data array );
   IF ( (abs(gamma_old) - abs(gamma)) < 0 )
       Delta = (-0.5)*Delta;
   }
```

Once the correction angle *a* for the x-axis is found, the procedure is repeated to find the correction angle for the y-axis.

The reliability of this method can be tested by measuring and calculating the optimal tilt angle for two distributions; one produced by holding the torch perpendicular to the target plane, the other with an arbitrary angle. The resulting optimal angle between the normal vector of the target plane and the spray torch should be the same for both distributions. For example, Figure 8 shows the measured data array for the cross section in Figure 9 where the torch was tilted 30°. This data array was used as input for the numerical optimization program. The optimal tilt angle was calculated by the program to be 4°. This approximately corresponds with the optimal tilt angle of 6° calculated for the perpendicular cross section in Figure 4.

This optimization algorithm assumes that the deposition efficiency is independent of the angle of impingment of the sprayed particles; that is, the particles impinging normal to the surface stick as well as the particles hitting the target at an acute angle. The effects due to gas turbulence have also been neglected. In practice, if a is too large (i.e., approximately greater than. 25°), then the deposition efficiency drops and the mechanical properties of the coating also degrade. The typical corrections which are required in our spray system is on the order of 10° degrees or less; for these cases the optimization algorithm is valid.

The next step is to determine the best spray path based upon the optimized distributions.

4 Spray path selection

While the symmetry of the distribution is important, we have observed that proper selection of the spray path is more critical. As stated earlier, the spray torch is moved by the robot along parallel lines in the in x and y directions. The torch should move with a constant velocity along these lines, while over the target, to maintain a constant deposition rate. The spray path is defined

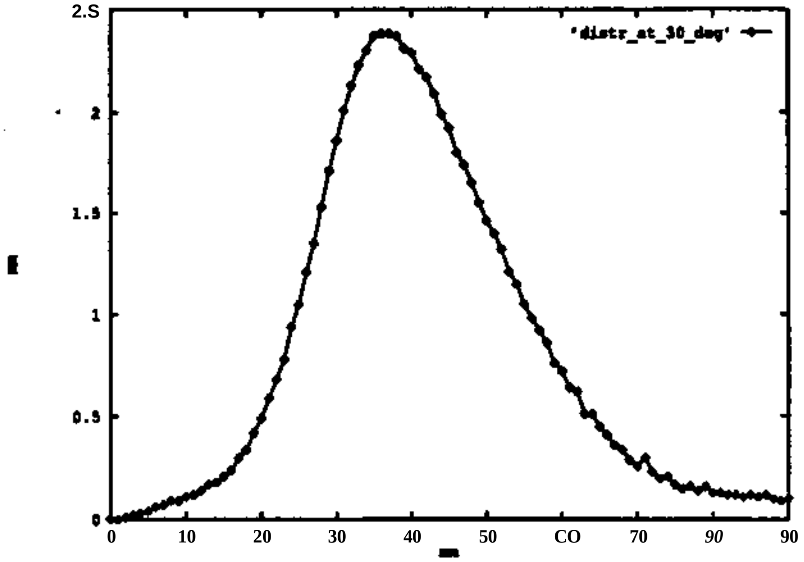

Figure 8: Measured data array of cross section in Fig.9.

Figure 9: Zinc sprayed onto steel at an angle of 30°.

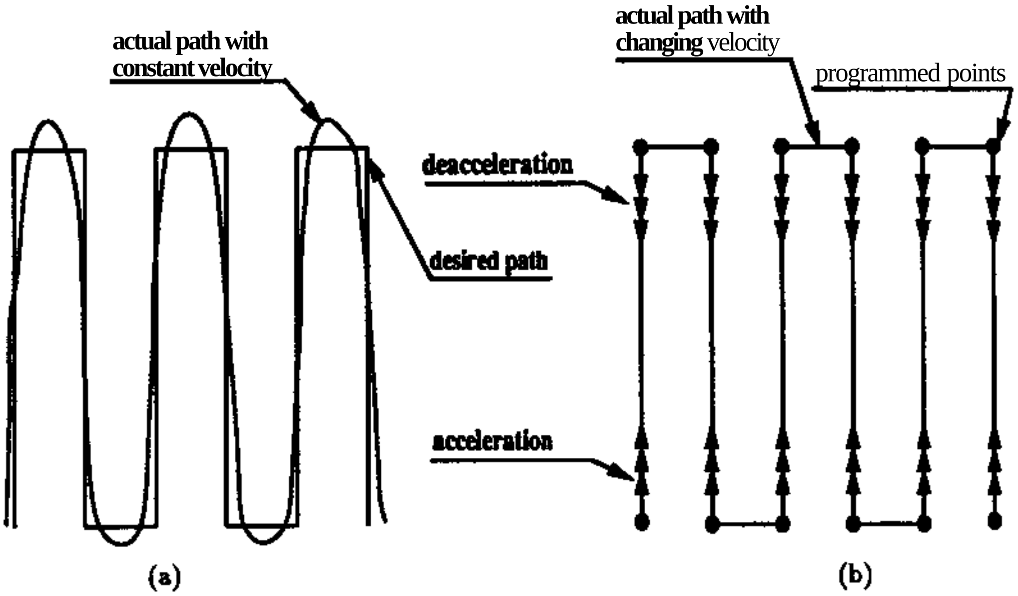

Figure 10: Movement of the spray torch

by a set of points along these lines. The robot operating system provides two motion control alternatives to execute the path; either movement with constant linear velocity (i.e. $|\vec{v}|$ = *constant)* along the path, where the actual path of the torch will deviate from the programmed spray path as a function of the commanded velocity, or movement exactly from programmed point to point using a series of accelerations and decelerations along the path. These two cases are illustrated in Figure 10. Both types of motion detract from the uniformity of the coating. Whether to move with constant velocity or to move exactly along the programmed lines depends on the dynamic behavior of the robot system. If point-to-point motion is selected, then the length of the path must be chosen such that the deviations occur outside the working target area; this approach wastes material. Alternatively, the robot can be commanded to move with a low constant velocity, so that the programmed trajectory can be followed more accurately. If the robot moves too slow, however, the substrate gets too hot and the coating too thick.

For electric arc spraying application, we have observed that good deposition uniformity can be achieved by specifying constant velocity motion with a track gap distance of one standard deviation *(a)* of the corrected distribution. The expected standard deviation is determined empirically from the simulation program in Section 3. For the movement in x-direction, the y-space between two tracks should be cr_y> and for the movement in y-direction, the x-space should

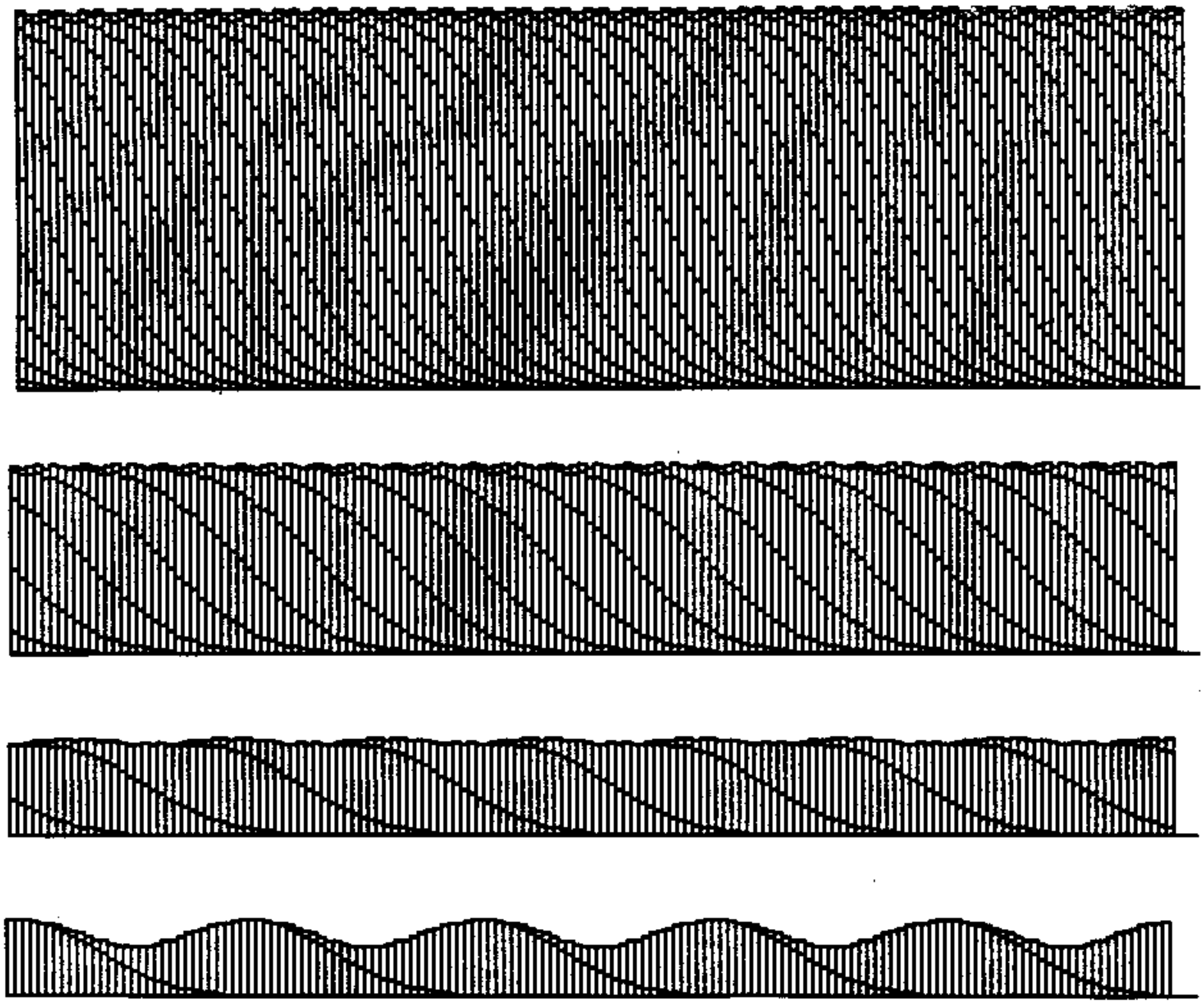

Figure 11: Simulation of the first layer as a function of the track gap for the equal to 0.5, 1.0, 2.0 and 3.0 <*r*).

be $<r_x$. Figure 11 depicts an example which shows the first layer as a function of space between the tracks (i.e. track gap). The simulation was based on a symmetric Gaussian distribution and shows a cross section normal to the sprayed lines. For other symmetric distributions, the "one standard deviation" rule-of-thumb still gives good results. Only if the track gap gets bigger than one standard deviation, the difference in the evenness between Gaussian and non-Gaussian coatings can be significant.

Figure 12 illustrates how the geometric quality of the surface improves with tilt and path optimization. The coating in the first example (Figure 12a) was sprayed with the torch held at a right angle to the target plane. The track gap was 1.2 standard deviations. This sub-optimal trajectory produced a wavy, uneven coating. In the second example, the material distribution was symmetrized using the aforementioned tilt procedures, and the track gap was set to 1.0 standard deviations. There is a clear improvement in coating uniformity. The mean thickness of the coating is 3.93mm and the measured standard deviation from the mean thickness lies between 20 to 30 *pm,* which is in the range of the particle size distribution.

Theoretically, the best coating uniformity can be produced by allowing the track gap to approach zero. In this case the center of the torch moves over every point of the target plane, thus the coating would be perfectly even. This is valid for any shaped distribution. While smaller track gaps produce more uniform coatings, the coatings become thicker and the substrate hotter. In cases where thin and even coatings are required, the torch speed must therefore be increased as the track gap is reduced. This is limited by the dynamic properties of the robot.

Thick even coating can be achieved by systematically depositing and accumulating thin uneven layers. For this approach, the first layer is sprayed as usual in x and y directions with a track gap of one standard deviation. The starting points of subsequent layers are then selected to lie between the first two lines of the first trajectory. Figure 13 illustrates how the starting points of the subsequent eight layers, for example, would be chosen. The starting points are distributed between the first two lines of the first layer so that the starting points of $(2^n — 1)$ layers will fill the track gap with equidistant steps. The 2^n-th layer will start at the same point as the first layer. The higher the number n, the more even the surface becomes after n layers have been deposited. Staggering the layers in this way has the advantage that the unevenness of the growing coating is always smaller than or equal to the unevenness of one single layer

Figure 14 shows the improvement in uniformity for an increasing number of layers achieved by choosing the starting points according to the illustration in Figure 13. A large track gap was selected for emphasis. In another example, the same starting points were used for the asymmetric distribution in Figure 15 which also shows the first and the eighth layer of the coating. Even for this highly asymmetric case, the coating uniformity improves with an increasing number of layers.

5 Discussion

In summary, to spray uniformly thick coatings it is necessary to first determine the properties of the deposited material distribution. The distribution symmetry can then be symmetrized by properly tilting the spray torch. This is important for spraying thin coatings which consist of only a few layers. As a rule-of-thumb, the distance between two sprayed lines, the track gap, should be equal to or smaller than one standard deviation of the material distribution. For thick coatings, however, the small unevenness of each layer can be compensated for by systematically shifting the starting points of each layer. Thick coatings can

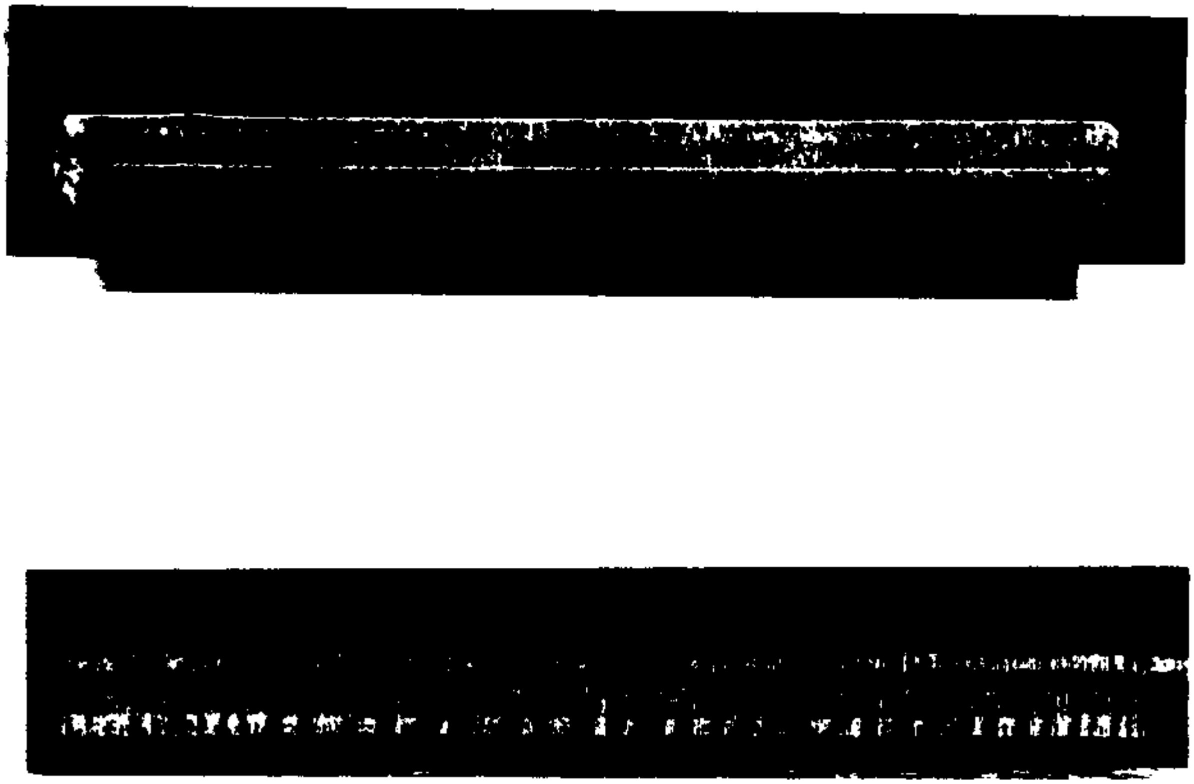

Figure 12: A properly aligned torch improves the geometric quality of the surface

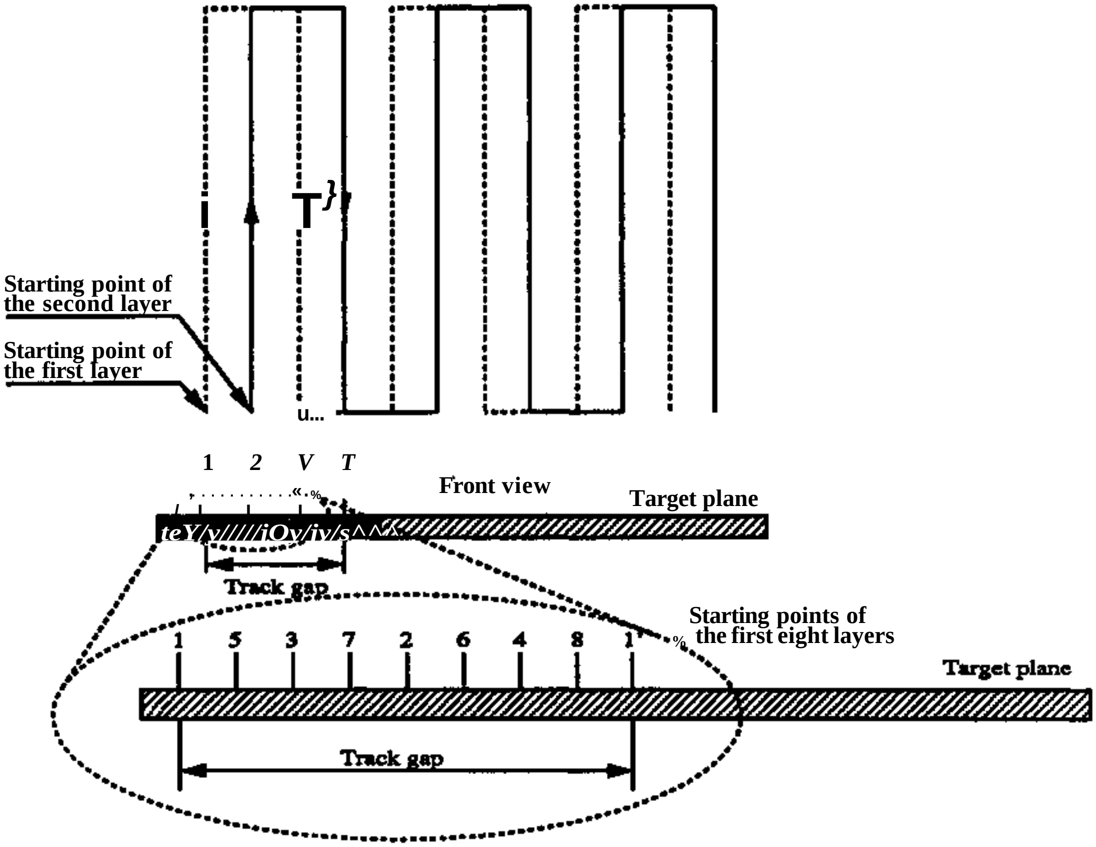

Figure 13: Shifting the starting points of subsequent layers in a systematic fashion compensates the small unevenness of each layer.

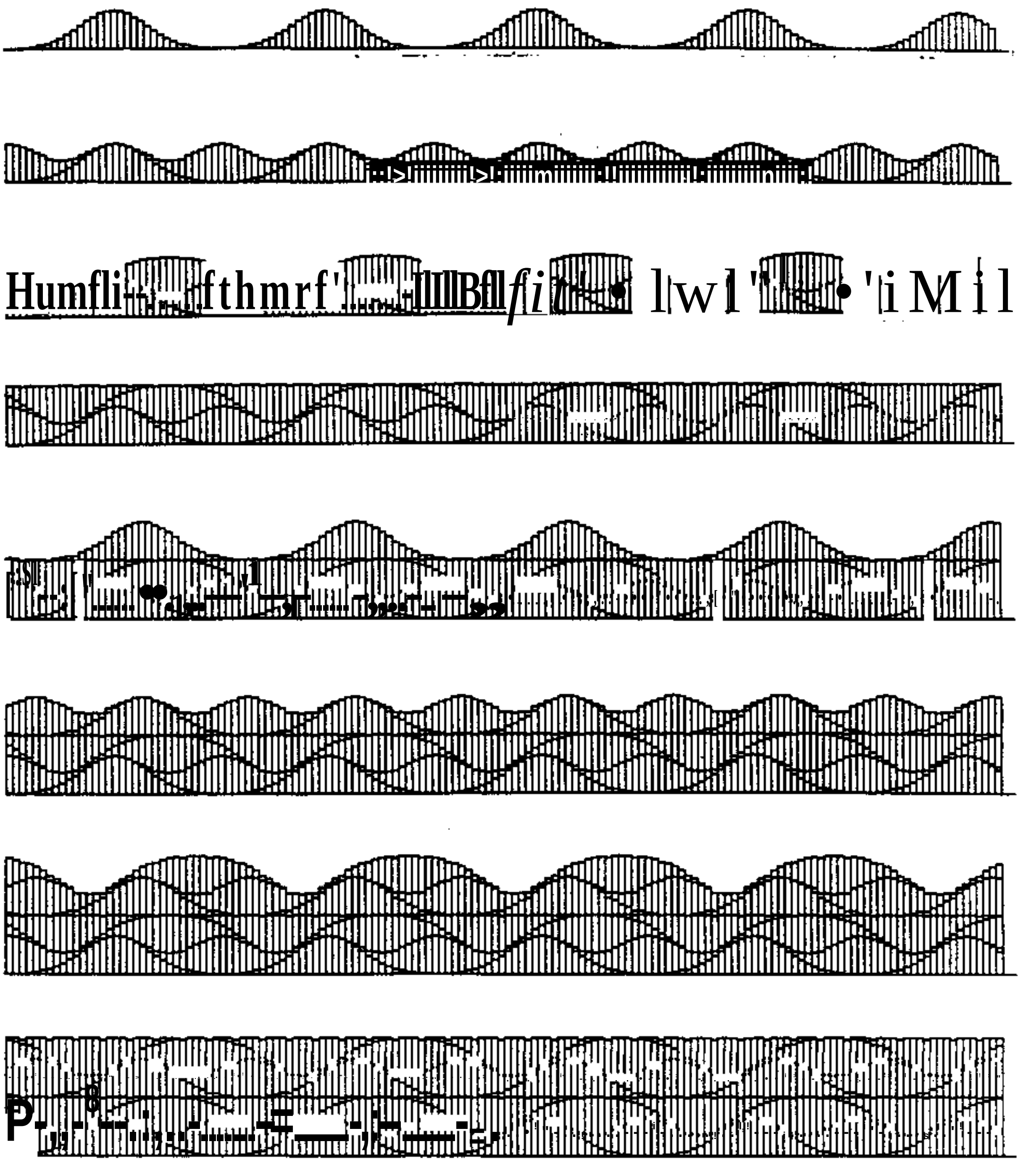

Figure 14: The evenness improves for an increasing number of layers by choosing the starting points according to Figure 13

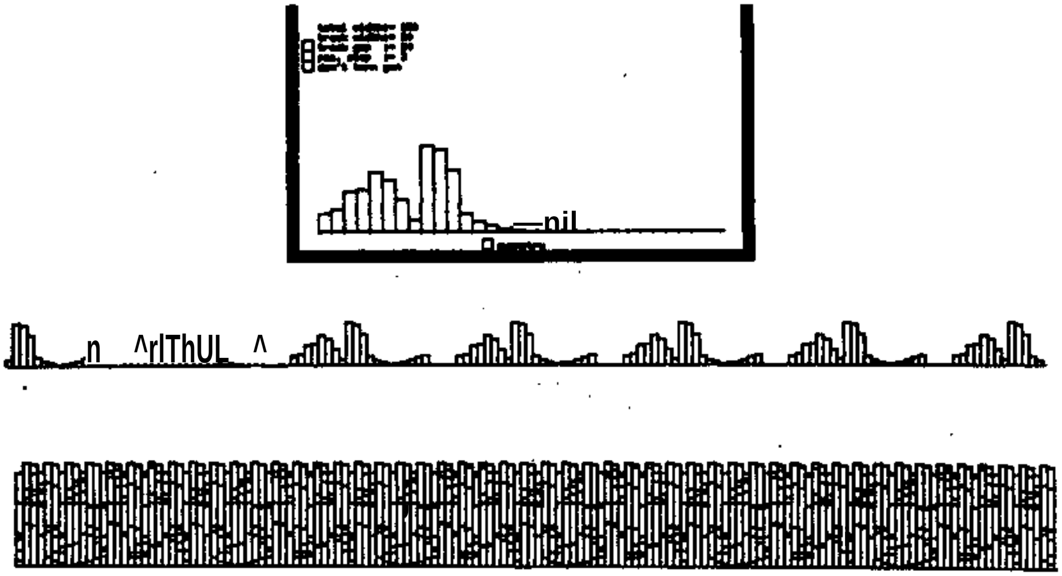

Figure 15: Simulation of the first and eighth layer of a coating using different starting points for each layer according to Figure 13, sprayed with an asymmetric distribution.

Figure 16: Sprayed turbine blade using the MD* process. The trajectories of the spray torch were optimized using the described method.

be deposited with a standard deviation from the mean thickness of 20 and 30 *pm* using the aforementioned spray strategy.

This strategy has been used in the MD* process. In this process, a part is manufactured by successively spraying cross sectional layers. To create a part, it's CAD geometric model is first sliced into cross-sectional layers. For each material in a layer, a mask is made that exposes the area where that material occurs and a thermal spray torch traverses the area exposed by the mask. Thus, each layer is formed by selective deposition of material and the complete part is formed by a vertical concatenation of thin, flat layers. A support material material, which can be melted out after completion, may also deposited to support the under-cuts. The accuracy of the whole part depends strongly on the accuracy of each deposited layer.

To demonstrate the MD* concept, a prototype zinc turbine blade was fabricated, as is shown in Figure 16, with a semi-automated system consisting of a $CO2$ laser mask-cutting station and an arc-spray robot. The robot is a GMF S-700, 6-axis articulated manipulator. The thermal spray system is a Miller customized two-wire electric arc with closed-loop wire feed control. The robot was commanded to move with a constant speed of approximately 50cm/s (Figure 10a) and with a distance between torch and target of 12cm. The masks were manually transferred on a fixturing plate to the robot and placed on top of the growing part with the aid of alignment pins. Layers were sprayed to approximately .005 inch thickness and the turbine blade was built along an axis with minimum height to minimize overall build time. In a fully automated system it is anticipated that .001 inch layers can be achieved.

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