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# Discussion

## Process planning for multi-directional laser-based direct metal deposition

R Dwivedi and R Kovacevic, *Proc. IMechE, Part C: J. Mechanical Engineering Science*, 2005, **219**(C7), 695–707.

### S Agrawal

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The authors claim in the conclusion of their paper that the process planning algorithm for multi-directional metal deposition is developed and implemented. However, the derivations given in section 4.1 for multi-directional deposition are incorrect. Section 4.1, on inverse kinematics, does not present the inverse kinematic relationship for multi-directional deposition. The authors do not seem to have a clear understanding of the underlying transformations. The derivations and the paper mislead the readers and prospective researchers in performing process planning for multi-directional deposition.

### AUTHOR'S RESPONSE

Due to the length of the paper, many details are ignored and therefore the paper may not elaborate various details fully. However, queries are answered in detail in the sections below. I would like to thank the reviewer for bringing up this matter and will ensure that communications in future are detailed and well described.

### S Agrawal

The sub-heading of section 4.1 is 'Inverse kinematics for machine input'. However, no inverse kinematic relation has been presented. All three transformation equations (equations (8), (11), and (12)) correspond to forward kinematics. Nor have authors the suggested how the inverse kinematic relation will be derived. In inverse kinematics, the joint positions are found as a function of the end-effector position and orientation. The authors do not seem to have clarity on forward and reverse kinematics of robot motion and thus the paper is misleading to prospective researchers.

### AUTHOR'S RESPONSE

Contrary to a typical system with joints, where various kinematic (tilt, rotary, etc.) parameters vary simultaneously, this system is based on a 5-axis platform where different parameters are varied in steps. The same has been elaborated in equation (11) as a set of

distinct steps. Inverse kinematics essentially suggests the kinematic parameters required to obtain a desired configuration of a kinematic chain. Section 4.1 suggests the steps required to obtain a given configuration in a simplified manner. The text, as well as the equations, suggests a desired configuration is obtained through a set of five intermediate configurations. The steps described in equation (11) depict how the same was implemented in the CNC code. Derivation of the steps in reverse order,  $T_5 \rightarrow T_4 \rightarrow \dots \rightarrow T_1$ , is a very trivial exercise therefore I did not express it as an exclusive 'inverse kinematic' equation. However, the discussions in section 4.1 provide the guideline for any researcher to derive an exclusive 'kinematic relationship' for any other system that they might use for multi-directional deposition.

Section 4.1, as such, describes how the parameters are obtained for the 5-axis table to arrive at a desired configuration and hence, in my opinion, the sub-heading 'Inverse kinematics for machine input' looks reasonable.

### S Agrawal

Equation (11) implies that the transformation  $T_1$  is the tilt  $\theta$  of the platform about the  $x$ -axis and  $T_2$  is the rotation  $\phi$  of the rotary table about the  $z$ -axis. This is because the angles  $\theta$  and  $\phi$  are changing during transformations  $T_1$  and  $T_2$ , respectively, in equation (11).

However, the paragraph following equation (11) says that  $T_1$  is the rotation about the  $z$ -axis and  $T_2$  the rotation about the  $x$ -axis which is the opposite of what equation (11) implies.

### AUTHOR'S RESPONSE

It is a typing error and I do apologize for the error. However, when referred to the equations as well as Fig. 17, the typing error becomes obvious. I will certainly be extremely careful in future communications.

### S Agrawal

Moreover, this paragraph also says that both the transformations  $T_1$  and  $T_2$  correspond to the rotation of

the rotary table. The rotary table can only rotate about the local  $z$ -axis and not the  $x$ -axis. The authors seem to be unable to grasp the underlying transformations and subsequently perform the transformations.

### AUTHOR'S RESPONSE

Section 4.1 elaborates the details in context to Fig. 17. On referring to this figure and text (which says 'T1 corresponds to the rotation of the rotary table about the  $z$ -axis of local coordinate system. The T2 corresponds to the rotation of rotary table about the  $x$ -axis of the local coordinate'), the section exclusively described the transform T2 corresponding to the vertical axis passing through the plant of rotary table and the transform T1 to the horizontal axis passing through the plane of the rotary axis.

### S Agrawal

The derivation of equation (12) is also wrong. If the expressions are derived according to equation (11) and, therefore, the second transformation is the rotation  $\phi$ , then  $\phi$  should appear in the expressions for  $p_x^2$  and  $p_y^2$  but not in the expression for  $p_z^2$ , as given below

$$\begin{aligned}[T_1] &= \text{Rot}(x, \theta), \\ [T_2] &= \text{Rot}(z', \phi), \\ [T_3] &= \text{Trans}(\text{Base}, x, y, z)\end{aligned}$$

The position vector  $\{p^1\}$  is given by

$$\begin{aligned}\begin{Bmatrix} p_x^1 \\ p_y^1 \\ p_z^1 \\ 1 \end{Bmatrix} &= \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} + [T_1] \begin{Bmatrix} r \\ 0 \\ h \\ 1 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta & 0 \\ 0 & \sin \theta & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &\times \begin{Bmatrix} r \\ 0 \\ h \\ 1 \end{Bmatrix} = \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} + \begin{Bmatrix} r \\ -h \sin \theta \\ h \cos \theta \\ 1 \end{Bmatrix}\end{aligned}$$

and the position vector  $\{p^2\}$  is given by

$$\begin{aligned}\begin{Bmatrix} p_x^2 \\ p_y^2 \\ p_z^2 \\ 1 \end{Bmatrix} &= \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} + \begin{bmatrix} \cos \phi & -\sin \phi & 0 & 0 \\ \sin \phi & \cos \phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &\times \begin{Bmatrix} r \\ -h \sin \theta \\ h \cos \theta \\ 1 \end{Bmatrix} \\ &= \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} + \begin{Bmatrix} r \cos \phi + h \sin \theta \sin \phi \\ r \sin \phi - h \sin \theta \cos \phi \\ h \cos \theta \\ 1 \end{Bmatrix}\end{aligned}$$

If equation (12) is derived as per the explanation in the paragraph following equation (11) and, therefore, the second transformation is the rotation  $\theta$  about the  $x$ -axis, then the angle  $\theta$  should appear in the expressions for  $p_y^2$  and  $p_z^2$  but not in the expression for  $p_x^2$ .

This section derives the angles needed for multi-directional deposition. Multi-directional deposition, the objective of this paper, depends upon the angles derived in section 4.1. The authors do not understand the transformations involved and are not capable of performing multi-directional deposition with the transformation presented in section 4.1.

### AUTHOR'S RESPONSE

The equation (12) is described as per the original location of the point under consideration. Following the rotations, the CNC table should adjust to arrive to the original  $x$ ,  $y$  and  $z$  location. Since any such adjustments will depend on a particular machine the details are not given. However, the reviewer has brought up a very important point that is not clarified well in the text. Therefore, the relationship in equation (12) should be described in the context to change in angles that is  $(\theta' - \theta)$  and  $(\phi - \phi')$ . The relationship described by the reviewer provides a better understanding with a modification and that is

$$\begin{aligned}[T_1] &= \text{Rot}(x, (\theta' - \theta)) \\ [T_2] &= \text{Rot}(z', (\phi' - \phi)) \\ [T_3] &= \text{Trans}(\text{Base}, x, y, z)\end{aligned}$$

The position vector  $\{p^1\}$  is given by

$$\begin{aligned}\begin{Bmatrix} p_x^1 \\ p_y^1 \\ p_z^1 \\ 1 \end{Bmatrix} &= \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} + [T_1] \begin{Bmatrix} r \sin \phi \\ h \cos \phi + r \cos \theta \sin \phi \\ h \cos \phi - r \cos \theta \cos \phi \\ 1 \end{Bmatrix} \\ &= \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta' - \theta) & -\sin(\theta' - \theta) & 0 \\ 0 & \sin(\theta' - \theta) & \cos(\theta' - \theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &\times \begin{Bmatrix} r \sin \phi \\ h \cos \phi + r \cos \theta \sin \phi \\ h \cos \phi - r \cos \theta \cos \phi \\ 1 \end{Bmatrix} = \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} \\ &+ \begin{Bmatrix} r \sin \phi \\ (h \cos \phi + r \cos \theta \sin \phi)(\cos(\theta' - \theta)) \\ -\sin(\theta' - \theta)(h \cos \phi - r \cos \theta \cos \phi) \\ (h \cos \phi + r \cos \theta \sin \phi)(\sin(\theta' - \theta)) \\ +\cos(\theta' - \theta)(h \cos \phi - r \cos \theta \cos \phi) \\ 1 \end{Bmatrix}\end{aligned}$$

and the position vector  $\{p^2\}$  is given by

$$\begin{Bmatrix} p_x^2 \\ p_y^2 \\ p_z^2 \\ 1 \end{Bmatrix} = \begin{Bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{Bmatrix} + \begin{bmatrix} \cos(\phi' - \phi) & -\sin(\phi' - \phi) & 0 & 0 \\ \sin(\phi' - \phi) & \cos(\phi' - \phi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{Bmatrix} r \sin \phi \\ (h \cos \phi + r \cos \theta \sin \phi)(\cos(\theta' - \theta)) \\ -\sin(\theta' - \theta)(h \cos \phi - r \cos \theta \cos \phi) \\ (h \cos \phi + r \cos \theta \sin \phi)(\sin(\theta' - \theta)) \\ + \cos(\theta' - \theta)(h \cos \phi - r \cos \theta \cos \phi) \\ 1 \end{Bmatrix}$$

### S Agrawal

The example taken for Fig. 18 is a simple example of branched structure. There is no collision detection needed and the direction of deposition can be determined in a very straightforward manner, that is, along the direction of branches. The authors do not seem to have applied automated C-space modelling and collision detection.

### AUTHOR'S RESPONSE

The C-space modelling is done. Please note the second step in Fig. 18, for each slice there is another contour that incorporates the C-space modelled slice geometry. It obviously doesn't show a collision. I would like to insist that for many objects that have rather simple geometry, unless the fabrication is initiated, the prospective collisions are not detected. For example, in Fig. 11 the geometry is simple and in the first look it is difficult to visualize any chances of collision. Therefore it is suggested that the C-space modelling and collision detection is done *a priori*. To convey the principle idea of the paper, three cases are elaborated. In the first, there is collision; the second, no collision; whereas the

third elaborates the effectiveness of the method in fabricating rather complex non-linear geometry of helix.

### S Agrawal

The conclusion says the process planning algorithm is developed and implemented. No algorithm for automation has been presented in the paper. No automation has been done for C-space modelling and multi-directional deposition. The process planning for multi-directional metal deposition has not been implemented.

### AUTHOR'S RESPONSE

The paper is written with mainly the manufacturing and mechanical engineering community in mind. Sections 2.1, 2.2, 3, and 4.1 describe the approach. I strongly believe that the descriptions in relevant sections should guide any researcher to successfully implement the method. I do agree that an algorithm in a formal 'flow chart' or 'pseudocode' or 'pidgin code' is not provided; however, in most of the communications pertaining to the manufacturing/mechanical engineering community an insistence on these formal expressions is not there. Apart, for C-space modelling there are many different approaches available, such as roadmap methods, potential field, and so on. C-space modelling and collision detection are fields of very agile research and every now and then newer methods are introduced. Certain approaches may or may not suite other researchers. C-space modelling or collision detection are very important components of the paper and our automation was based simply on the offset of the polygons obtained by slicing the part, which many other researchers may not find very efficient. The crux of the paper being the 'process planning for multi-directional laser-based direct metal deposition', the paper addresses the automation of C-space modelling and collision detection in brief sections.