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A kinematic simulation software for additive manufacturing metal deposition processes

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Abstract

This paper proposes to define a kinematic simulation of the DMD process to predict the evolution of the real velocity (V) of the nozzle, the main parameter of the process control with the laser power (P) and the powder flow (F). Beyond the production time, the kinematical model allows to detect deceleration zones, which are likely to present excess material leading to the appearance of porosities. The proposed approach is generic enough to apply to any type of machine and allows to simulate movements with limited acceleration or limited jerk. The approach makes it possible to process very long trajectories commonly observed in this process.

Keywords: Additive Manufacturing, Direct Metal Deposition, Kinematic behaviour, Tool path simulation

1. Introduction

While additive manufacturing processes are in full development, decision-making software to establish manufacturing strategies is not widely available. This is particularly the case for the Direct Metal Deposition (DMD) process executed on structures such as 5-axis machines or 6-axis anthropomorphic robots. CAM software uses programmed velocity to calculate manufacturing times and does not take into account machine slowdowns to compute trajectories. In reality, the machine slows down along the path according to its own kinematic capabilities. Thus, the powder deposition rate varies and consequently the width and height of the tracks vary accordingly, the cooling rate is slower which is likely to generate coarser microstructures and the production times are largely exceeded [1].

While works have consisted in developing closed-loop process control to compensate for accelerations and decelerations [2], it is also necessary to be able to simulate these velocity variations upstream of the process to indicate the slowdown zones and manufacturing times in order to help the user to choose the best strategy or identify part quality problems.

An elementary building time model based on feedrate slowdowns at corners has been proposed in [3] to obtain the optimal tool-path zig-zag inclination during filling operations in extrusion-based technology. However, it

doesn't consider constraints due to maximal kinematic constraints, contour error or cycle time interpolation.

The model developed therefore aims to produce the following results as depicted in figure 1:

- the programmed geometry representing the trajectory with the associated nominal time;
- the simulated manufacturing time taking into account the machine kinematic constraints and the execution;
- the result of the feedrate planning, i.e. the evolution of the position along the toolpath, velocity, acceleration and jerk over time, with technological parameters such as laser status (on/off).

In order to achieve this objective, it is necessary to dispose of a temporal interpolation model of the trajectories that adapts to all kinds of articulated mechanical structures that execute this process. The method which is particularly used in numerical controllers is the limited jerk model [4]. An iterative implementation of this type of control for 5-axis machines has been proposed in [5] but requires computation times at least as long as the execution time of the trajectories on the machine. A filter-based approach has been proposed by [6] to reduce calculation times. Indeed, it is based on an analytical model with limited acceleration that is faster to implement but which nevertheless presents difficulties in transitions between blocks. Also, the proposed method is based on the one developed in [7] with some simplifying assumptions that ensure a good compromise between the relevance of the results and the calculation time.

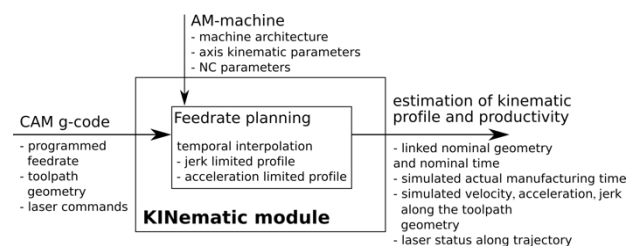


Figure 1. Functional description of the developed module

The objective of this article is thus to propose an off-line kinematic simulation software based on limited jerk

constraints from machine kinematical characteristics and on nominal toolpath feed by G-code. In this paper, the 3-axis implementation of the method is proposed. The model and its experimental validation are exposed in sections 2 to 4, numerical investigations are carried out in section 5 and section 6 is dedicated to the conclusion and future work.

2. Path pre-processing

Path pre-processing consists in analysing the geometry of the path to deduce kinematic constraints, especially feedrate drops, which are inevitable during its follow-up. Since the trajectory is made of linear segments, the analysis is done on each segment connecting two consecutive programmed points, and between two consecutive segments [8][9].

2.1. Linear segments analysis

From each programmed point P_i on the path from G-code, the norm of each linear segment is determined as the variation of the curvilinear abscissa s along the path:

$$\Delta s_i = \|P_i - P_{i-1}\| \quad (1)$$

An orthonormal local base $(\mathbf{f}, \mathbf{n}, \mathbf{t})$ is built on the trajectory consisting of a locally tangent vector \mathbf{f} , a transverse vector to displacement \mathbf{t} and a normal vector to the plane of deposition \mathbf{n} . The tangent vector \mathbf{f} gives the local direction of motion and is determined as follows:

$$\mathbf{f}_i = \frac{P_i - P_{i-1}}{\|P_i - P_{i-1}\|} \quad (2)$$

Given the maximum speeds of the machine's X, Y and Z axes $(V_X^{\max}, V_Y^{\max}, V_Z^{\max})$, it is possible to determine the maximum speed achievable along each segment V_f^{\max} by saturating the most solicited axis relative to its maximum speed:

$$V_{f,i}^{\max} = \min\left(\frac{V_X^{\max}}{|\langle \mathbf{f}_i, \mathbf{x} \rangle|}, \frac{V_Y^{\max}}{|\langle \mathbf{f}_i, \mathbf{y} \rangle|}, \frac{V_Z^{\max}}{|\langle \mathbf{f}_i, \mathbf{z} \rangle|}\right) \quad (3)$$

In the same way, the equivalent equations for acceleration A_f^{\max} and jerk J_f^{\max} can be determined. Although it is possible, the maximum velocity that can be reached during the execution of the trajectory is limited again by the programmed velocity on each segment V_f^{prog} :

$$V_{f,i}^{\max} = \min(V_{f,i}^{\max}, V_{f,i}^{\text{prog}}) \quad (4)$$

At this stage, all necessary kinematic quantities along each segment are determined for future temporal interpolation.

2.2. Analysis of transitions between segments

The kinematics simulation model is based on the assumption of tangential connection of each segment to ensure continuity of the forward movement along the path. The deviation from the programmed path (or interpolation tolerance) is small enough with respect to the segments to assume that the geometric modification is

very local on the transitions between segments. By installing an arc-based connection, it is possible to determine the local transition crossing velocity according to the local geometry and acceleration capabilities given by the machine. Figure 2 shows the case of the connection between any two segments, forming an angle β . For each transition, β is determined by the trigonometric equation:

(5)

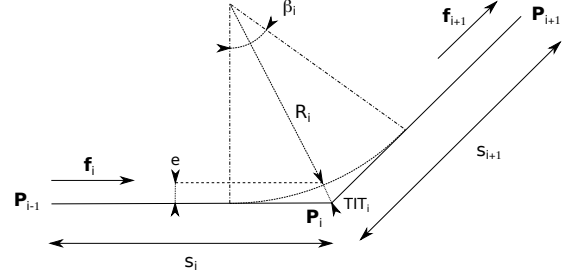


Figure 2. Local connection between two consecutive segments

The local radius R_i connecting the linear segments is:

$$R_i = \min\left(TIT_i \cdot \frac{\cos(\frac{\beta_i}{2})}{1 - \cos(\frac{\beta_i}{2})}, \frac{s}{\tan(\frac{\beta_i}{2})}\right) \text{ with } s = \min(s_i, s_{i+1}) \quad (6)$$

where the local rounding difference at the TIT_i transition is given by:

$$TIT_i = e \cdot \min\left(\frac{1}{\cos(\frac{\beta_i}{2})}, \frac{1}{\sin(\frac{\beta_i}{2})}\right) \quad (7)$$

with e the deviation from the trajectory seen as a tolerance specified by the user for each axis.

Since the rounding is considered here as very local to the trajectory, it is assumed that acceleration capacity cannot vary as the transition is crossed. The maximum transverse acceleration available before and after the transition is therefore given by the smallest. However, it is still necessary to have a transverse acceleration to the trajectory to perform the trajectory variation on a circle given the curvature. The actual velocity at which it is possible to follow this curvature therefore depends on the level of transverse acceleration A_{trans}^{\max} along \mathbf{t} available:

$$V_{trans,i,i+1}^{\max} = \sqrt{k \cdot A_{trans,i}^{\max} \cdot R_i} \quad (8)$$

where the coefficient k depends on specific settings in the NC. Finally, this local maximum velocity on the transition V_{trans}^{\max} must be limited again by the tangential velocities to the upstream and downstream trajectory:

$$V_{trans,i,i+1}^{\max} = \min(V_{f,i}^{\max}, V_{trans,i,i+1}^{\max}, V_{f,i+1}^{\max}) \quad (9)$$

2.3. Synthesis

At this stage, the machine kinematic constraints can therefore be projected onto the trajectory with a maximum velocity V_f^{\max} , acceleration A_f^{\max} and jerk J_f^{\max} for each segment and a local maximum velocity V_{trans}^{\max} to be respected at each transition (figure 3).

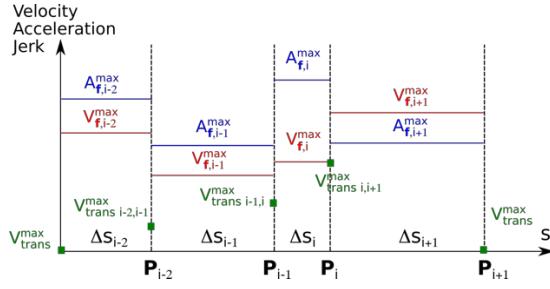


Figure 3. Resulting constraints along the trajectory

3. Trajectory Interpolation

The purpose of the further processing is to determine the position setpoints of the machine axes, sampled at fixed time steps, for the entire path. The pre-processing of the path must respect this interpolation cycle time. The approach consists in performing this temporal interpolation in 1D along the curvilinear abscissa, then projecting this discretization onto the machine space, namely on each of the axes according to the orientation of the trajectory. To do this, we start from the synthesis of the constraints seen in the previous section and interpolate, segment by segment. The assumptions of the interpolation model, which is divided into seven phases (figure 4), are as follows:

- Jerk's profile is rectangular;
- Accelerations are zero at the beginning and end of the segment;
- Jerk levels of phases 1, 3, 5 and 7 are taken equal to the maximum jerk available J_f^{max} ;
- Similarly, acceleration levels of phases 2 and 6 if they exist are taken equal to A_f^{max} ;
- Maximum speed F on the segment when it is reached is equal to the maximum feedrate V_f^{max} previously determined.

By considering the seven phases, we can therefore reconstruct the acceleration, velocity and position profiles by integrating the jerk profile with the previous constraints:

$$j(\tau) = \begin{cases} J_1 & 0 \leq t < t_1 \\ 0 & t_1 \leq t < t_2 \\ -J_3 & t_2 \leq t < t_3 \\ 0 & t_3 \leq t < t_4 \\ -J_5 & t_4 \leq t < t_5 \\ 0 & t_5 \leq t < t_6 \\ J_7 & t_6 \leq t \leq t_7 \end{cases} \quad (10)$$

The profiles thus calculated phase by phase are sampled at the interpolation cycle time.

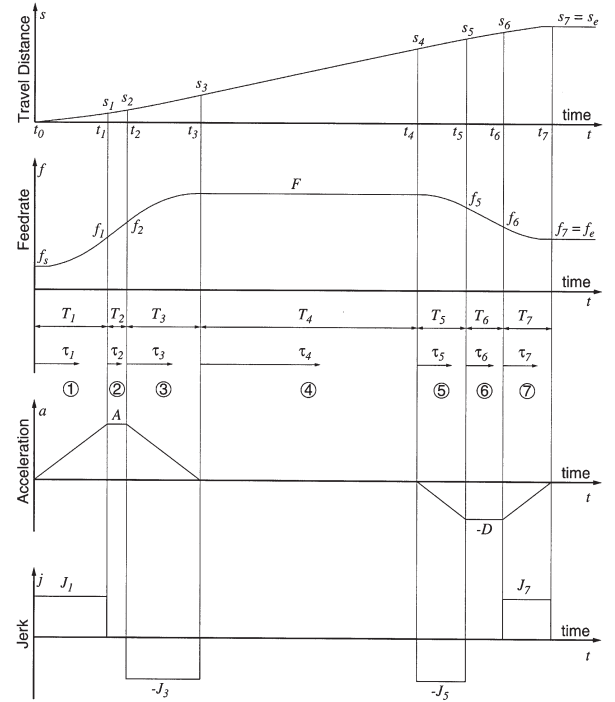


Figure 4. Decomposition of the interpolation of a linear segment with limited jerk in 7 phases [4]

4. Experimental validation

The objective of this section is to validate the simulation model developed on the basis of the BeAM Modulo 400 machine (table 1), to predict the evolution of the movement velocity of the nozzle in relation to the part and the travel time of the manufacturing path. The validation of simulated velocity and time profiles is done by comparison with experimental tests. Given the similar behaviour of the X, Y and Z axes, the following test trajectory is validated for the execution of the trajectory in a single plane (XY). The results are similar in the other planes.

Table 1. Kinematical characteristics of the considered machines

	BeAM Modulo 400			Trumpf DMD 505		
	X	Y	Z	X	Y	Z
V^{max} [m/min]	30	30	30	30	30	30
A^{max} [m/s ²]	3	3	3	4	4	4
J^{max} [m/s ³]	22	22	50	100	100	100

Figure 5 shows the test trajectory made of nominal linear segments in black connected at the black squares, as well as the measured position setpoints in the blue dash line. The deviation e from the trajectory is set to 0.2 mm in the NC parameters. One can see local corner roundings inserted for sharp segment transitions by the NC interpolator.

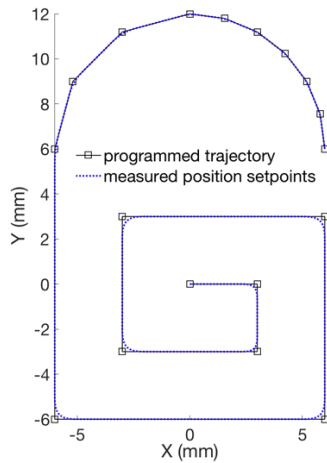


Figure 5. "Lock" trajectory

Kinematic results are depicted in figure 6. The red curve is the simulated curve while the black curve is the one reconstructed from the axes measurements made on the machine through the NC. The blue diamonds represent the start and end positions of the blocks for the simulated curve to locate the connections between segments.

The two curves have the same general speed profiles. The maximum values reached per segment are very well predicted as well as the local speed drop values. The local shapes of the velocities at the connections between segments observed on the measurements are due to the specific treatments carried out by the NC that are not modelled, in particular the geometric modification of the trajectory by the insertion of a connecting radius. We notice that the simulation is a little faster than the measurement, the profiles are gradually shifting. Although the acceleration and deceleration phases are very accurately represented, the model's sensitivity lies on the low speed levels during falls at transitions between segments. Small speed errors generate a time shift that accumulates with each transition. The simulated manufacturing time is 1.9 s. for a measurement of 2 s. or a deviation of 5%.

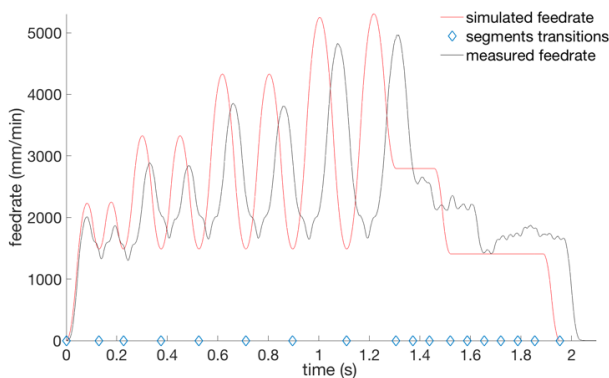


Figure 6. Measured and simulated velocities

In this example, although the local estimate of speeds is less accurate in absolute terms, it remains a good relative indicator. The simulated travel time on the trajectory is then satisfactory.

5. Experimental investigations

Experimental investigations are carried out on the "E-shape" test part which manufacturing trajectories are simulated in figure 7. The part is built according to a strategy based on two contour tracks and zig-zag filling tracks shifted by 90 degrees between each layer. 10 layers are simulated.

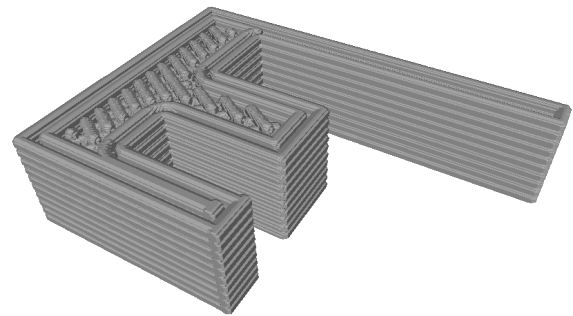


Figure 7. "E-shape" test part

Figure 8 shows the trajectory in one layer, where the red trajectory portions correspond to a fast speed movement (laser off), while the blue trajectory portions correspond to a programmed movement at the manufacturing speed (laser on). The arc-shaped trajectories are discretised here by segments of short length.

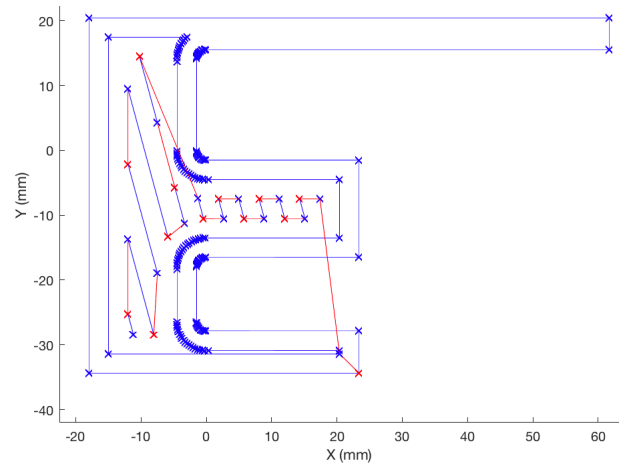


Figure 8. Trajectory in a given layer

The programmed velocity is 1.6 m/min. Figure 9 shows the kinematic behaviour for a path-following tolerance of 0.2 mm for the BeAM machine. According to the same colour legend on the velocity profile, the fast portions are identified in relation to the portions with material deposition. The programmed velocity is generally respected except very locally where it decreases a little bit when crossing the transition. The theoretical manufacturing time for one layer based on the lengths of

the trajectories performed at the programmed velocity or at the maximum axis velocities is equal to 25.5 s in this example. The time simulated with the proposed method is 34.5 s and allows a nominal time overrun of about 40% to be predicted.

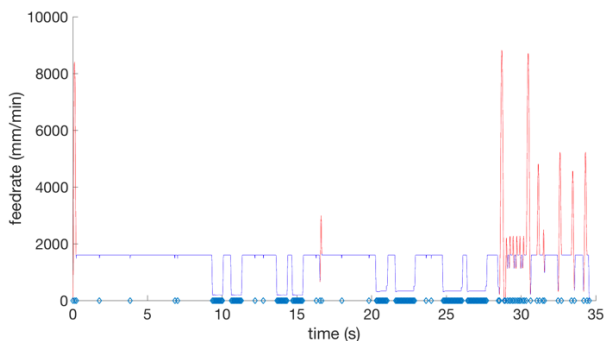


Figure 9. Velocity profile with the BeAM Modulo 400

Figure 10 shows the kinematic behaviour for the Trumpf DMD 505 machine. It should be noted that transitions between short linear segments are not subject to slowing down for the programmed velocity. The travel time is 27.1 s. The simulation shows the difference between the two machines, Beam and Trumpf, with a time variation of 27% for one layer of the same part.

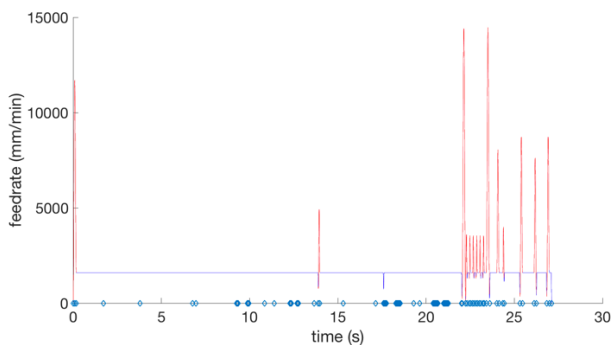


Figure 10. Velocity profile with the Trumpf DMD 505

6. Conclusion and future works

A method for simulating the kinematic behaviour of articulated mechanical structures for the DMD process has been proposed. This allows to simulate a production configuration composed of a machine, a trajectory and a deposition velocity. The model developed was validated based on experimental manipulations on industrial machines. It was then implemented on two machines using Z-level trajectories. The results show that the manufacturing times estimated from a nominal velocity are very underestimated and many slowdowns penalize the consistency of the process and therefore the quality of the part. It provides useful information to the programmer in order to improve the manufacturing strategy. The model will have to be extended to trajectories combining linear and rotary axes while maintaining simulation times of a few minutes.

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