Experimental measuring of printing speed in FDM

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Abstract: Fused Deposition Modeling (FDM) technology, based on material extrusion, helps additively manufacture, using cheap printers, stable mechanical parts in different materials. The dimensional deviations and staircase effect are the main drawbacks of this approach and limit its use to prototypes. The linear interpolation used to define the hot-end movements is responsible for continuous speed changes along the tool-path, contributing to dimensional and surface errors. In that sense, the study of the speed profile can help to improve the process. This work explains two printing speed estimation approaches an out-process measurement method, which estimates the average speed as a function of the interpolation segment length and direction, and an in-process method based on encoder measurements. We applied these solutions and an analytical approximation based on a trapezoidal speed profile to a printed 3D Archimedean spiral. All approaches detect abrupt speed changes, potential candidates to produce extrusion-movement synchronization problems, and, therefore, part errors.

Keywords: 3D Printing, FDM, Step motor speed, 3D printing speed, Uncertainty.

1. Introduction

Fused Deposition Modeling (FDM) is the commercial name of a well-known 3D printing technology. According to the standard ISO/ASTM 52900-15 [1], FDM is a material extrusion process where a filament, usually a polymer material, is pushed inside an extruder, fused in a hot-end, and deposited following 2D tool-paths in layers at different heights.

The number of practical applications of additive manufacturing processes continuously increases and covers topics from bio-printing to education. Regarding FDM, it finds applications in rapid-tooling [2] and industrial prototypes [3].

On the other hand, final parts require good dimensional accuracy and surface roughness, current weaknesses of the FDM technology. The hot-end movement and its synchronization with the extrusion contribute to the above problems and should be optimized [4, 5]. The common discrete representation of the CAD model to obtain the 2D layers lead from linear interpolations in the programming of the hot-end tool-paths, which are related to frequent speed changes, and dimensional and appearance defects. Moreover, polygonal tool-paths are the main reason why the printer cannot maintain constant reference theoretical speed. The real printing speed is as far as the reference speed, define in the G-code, as shorter is the interpolation segment length, and larger is the angle change among segment directions. An accurate knowledge of the hot-end speed will allow further studies to overcome dimensional and appearance defects. Additionally, speed measurement is needed to obtain accurate process time and energy consumption estimations.
Authors such as Ertay, Yuen, and Altintas [4] define an analytical model to predict and optimize the printing speeds. These models require a deep knowledge of the machine parameters and its operating system and time-consuming computations.

On the other hand, the experimental speed measurements can be achieved directly (in-process approach), if there are speed sensors attached to the actuators, or in an indirect way (out-process approach) that predicts in advance the speed, for example, using a model built with an experimental setup. The interesting work of Kralji, Stefani, and Kamnik [6] explains an out-process measurement system to predict the print speed for a 6D material extrusion printer. Their approach uses a Neural Network trained with a random set of tool paths where the actual average time in each interpolation segment is provided by the used robot (in-process approach).

This paper explains an out-process method and compares it to an in-process estimation. The study is limited to Cartesian FDM printers, where the hot-end motion is along perpendicular x, y, and z axes, and stepper motors run it.

The out-process measurement system (encoder system) is based on stepper motor angle measurements registered by an encoder fixed to the x-y printer stepper motors. On the other hand, the out-process solution (speed-surface method) is based on estimating a speed-surface, described by the authors in reference [7], whose parameters are the interpolation segment lengths and angles. We explain the procedure to calibrate the encoder system, determine its uncertainty and the way to use it. The speed-surface approach and is uncertainty estimation are also briefly recalled.

To compare both methods, we printed a 3D Archimedean spiral due to curvature changes induce speed variations. The experimental measures are represented beside a speed analytical approximation, computed as the author described in [8], to note the measurement estimation performance.

The description of the measurement methods and the experimental conditions are detailed in Section 2. Section 3 shows the measurement results for a case study. Finally, Section 4 draws the main conclusions.

2. Materials and Methods

2.1. Printing Speed Measurement Systems

The proposed measurement methods can estimate the printing speed of Cartesian machines run by stepper motors. The examples are conducted with an Ender pro-3 desktop FDM printer (figure 1), and the models and calibration of the following methods are based on this machine. Table 1 lists the main characteristics of this printer.

![Figure 1. Ender-pro machine used in the measurement tests and encoders.](image-url)
### Table 1. Ender-3 Pro main characteristics

| Technology | FDM |
|------------|-----|
| Filament Diameter | 1.75 mm |
| Axis X-Y | Belt driven system |
| Pitch, $p = 2$ mm | Pulley tooth count, $d = 20$ |
| Printing Size | 220 x 220 x 250 mm |

2.1.1. **Out-process approach.** The out-process approach, hereafter speed surface estimation, is based on the procedure described in [5], which consist of two stages:

- **Calibration.** By moving the hot-end through reference 2D paths, we can estimate the actual average printing speed surface (figure 2) as a function of the interpolation segment length and direction change.
- **Estimation.** It is based on reading the G code used for printing the part and applies the experimental calibration model to estimate the real speed.

2.1.2. **In-process approach.** The in-process method is based on holding electronic encoders on the printer stepper motors. In this work, we only mount two AS5600 encoders with a uStepper S-lite controller board on the stepper motors that run the X and Y axes (additional encoders can be used to measure the speed in the Z-axis and the extrusion speed). These devices record the number of encoder angles and time, and computations with this information allow estimations of the actual position and speed through the printing process. The encoder can send the measurements through a PC serial port, and software, such as Arduino Ide, can be used to read the information.

![Figure 2](image.png)

**Figure 2.** Printing speed surface of the Ender-Pro printer. Surface built according to [7].

Length and speed estimations depend on the conversion between motor steps and mm. This conversion depends on the axes transmission system. For the ender-pro 3 machine, the following equations can be used to determine the appropriate length $L$ and feed rate $F$ from the encoder angle $\theta$ measurements:
\[ L = \pi \cdot D \cdot \frac{\theta}{360^\circ} = p \cdot d \cdot \frac{\theta}{360^\circ}, \quad F = \frac{L}{T} \]  

(1)

where system parameters are \( p \): the belt pitch, \( d \): the pulley tooth count (\( D \) its diameter), and \( T \): the movement time interval. Note that the nominal values of \( p \) and \( d \) can be found in Table 1.

Nevertheless, the nominal parameters \( p \) and \( d \) can be different from their real values. Thus we accomplished a calibration procedure to determine the actual relation between \( L \) and \( \theta \):

\[ L = y_0 + y_1 \cdot \frac{\theta}{360^\circ} \]  

(2)

The calibration curve (Equation 2) is also used to estimate \( V \) and its uncertainty. To reduce the number of experimental runs, we calibrated the \( X \) axis and consider the same calibration curve for the \( Y \) axis, which used the same stepper motor and transmission system.

The following steps summarize the calibration and measurement procedure:

- Measure angle \( \theta \) and time \( t \) for a set of 10 distances \( L[mm] = \{20, 40, 60, \ldots, 160\} \). We wrote a g-code file to perform the tool-path shown in Figure 3. The hot-end goes from \( L = 0 \) mm to \( L_i \) and back to \( L = 0 \) mm. We stop 5 s at each \( L_i \), to register the values of \( \theta \) and \( t \).
- Compute the intercept \( y_0 \) and the slope \( y_1 \) of the calibration curve (Equation 2) using least squares. According to the recorded data: \( y_0 = -1.48 \) mm and \( y_1 = 39.32 \) mm/turns, which is close to the product of the nominal values \( p \cdot d = 40 \).
- Estimate the feed rate in an axis:
  \[ v = \frac{y_0 + y_1 \cdot \frac{\theta}{360^\circ}}{T}. \]  

(3)

Note that this equation provides an estimation of the average speed.

- Use the combined standard uncertainty to estimate the speed uncertainty. Let the uncertainties of \( \theta \) and \( T \) measurements be negligible, using the Guide to the expression of uncertainty in measurement GUM [9]; we obtain the uncertainty of \( v \) estimation (Equation, 3):
  \[ u^2(v) = \left( \frac{\partial v}{\partial y_0} u(y_0) \right)^2 + \left( \frac{\partial v}{\partial y_1} u(y_1) \right)^2 + 2 \cdot \frac{\partial v}{\partial y_0} \frac{\partial v}{\partial y_1} u(y_0) \cdot u(y_1) \cdot r(y_0, y_1), \]  

(4)

GUM Annex H.3 describes how to compute the correlation coefficient \( r(y_0, y_1) \), and the intercept and slope uncertainties \( u(y_0) \) \( u(y_1) \). According to the values registered in the calibration process, we obtained: \( u(y_0) = 0.31 \) mm, \( u(y_1) = 0.11 \) mm/turns and \( r(y_0, y_1) = -0.85 \).

Figure 4 shows the axis speed uncertainty versus the stepper revolutions. The estimation of the instantaneous speed leads to high values of uncertainty. This information can help to get an appropriate time interval to estimate the average speed. For example, let \( t = 78 \) ms (\( \theta/360^\circ = 0.04 \) and \( L = 0.1 \) mm), then \( u(v) = 3 \) mm/s. Hence to obtain \( u(v) = 3 \) mm/s we should get samples every \( t = 78 \) ms.

- Compute the speed magnitude \( V = \sqrt{v_x^2 + v_y^2} \). Regarding \( V \) uncertainty, if we assume that \( u(v_x) = u(v_y) = u(v) \), then the combined standard uncertainty leads to \( u(V) = u(v) \).

![Figure 3. Illustration with the calibration movements.](image-url)
Figure 4. Speed uncertainty evolution with respect to the motor revolutions.

2.2. Experimental conditions

2.2.1. Case Study. To test the measurement methods, we designed an Archimedean 3D spiral with two branches (figure 5(a)). This part has curvature variations that influence the hot-end speed. The model has been sliced, and the printing G-code has been obtained using the software Cura Ultimaker. Table 2 shows the process parameters used to print the part.

In order to interpret the measurement results, we only show the speed estimations at layer 4 (layer height of 1.12 mm, figure 5(b)). It corresponds to a planar two branches Archimedean spiral travelled twice.

Table 2. Printing parameters for the example printed.

| Parameter       | Values            |
|-----------------|-------------------|
| Layer Height    | 0.28 mm           |
| In-fill         | 0%                |
| Wall-thickness  | 0.8 mm (2 walls)  |
| Wall-speed      | 1500 mm/min (25 mm/s) |

Figure 5. Archimedean spiral for testing the measurement methods. (a) 3D spiral. (b) Layer 4, planar spiral curve.

2.2.2. Measurement procedure. Regarding the out-process measurement method, once the machine's printing speed surface is obtained as described in Section 2.1.1, we read the G-code generated in Section 2.2.1 with a function developed in the scientific software Mathematica that also chooses the minimum speed between the reference speed and that predicted by the speed surface. The procedure is simple, but reading the G-code and the speed computation required time.

Regarding the encoder measurement method, we obtained the encoder angle every 30 ms and used
Equation (3) to estimate the average speed for a $\theta/360^\circ = 0.04$, which corresponds with an uncertainty $u(V) < 3 \text{ mm/s}$.

Additionally, to appreciate the difference between actual measurements and the theoretical speed evolution, we followed reference [8] to obtain an analytical model for the printing speed estimation that assumes, such as the printer machine operating system, a trapezoidal speed profile, and a jerk limited cornering algorithm. The model was programmed in Mathematica Software. This approximation requires knowing how the speed is implemented in the printer. It is time-consuming because it requires reading the G-code and computing the speed profile and the cornering algorithm in each interpolation segment. Moreover, it is based on the printer machine's nominal values (maximum acceleration and maximum speed at direction changes: 500 mm/s$^2$ and 5 mm/s respectively for the Ender-pro 3 machine).

3. Results and discussion

Figure 6 shows the axes speed profiles provided by the speed-surface method, the encoders measurements, and the analytical estimation described in Section 2.2.1. All approaches show the same speed behavior along the layer 4 tool-path. The speed-surface solution is closer to the theoretical speed assumed. Besides, the encoder estimation shows oscillations around the analytical approach's evolution, but the maximum variations have the same order as the estimated uncertainty ($u(v) = 3 \text{ mm/s}$).

![Figure 6](image_url)

**Figure 6.** Estimations for the axes speed profiles. (a) X axis. (b) Y axis.

On the other hand, figure 7 portrays the speed magnitude according to the measurement systems and the analytical approximation. Again the speed-surface estimation is close to the theoretical speed profile while the encoder estimation is wavy. Nevertheless, maximum curvature changes related to minimum segment lengths and direction changes are detected by the measurement methods and highlights in figure 7. The approaches help identify where a tool-path can show synchronization problems with the material extrusion.
4. Conclusions

There are different methods to estimate the printing speed. This variable is of interest to improve the dimensional accuracy and the surface finishing in FDM 3D printing. Speed changes are undesirable, and they appear when the path is defined by linear interpolations and tries to approximate curves with significant curvature changes.

Both methods presented in this work help identify abrupt speed changes at specific hot-end path positions related to extrusion-movement synchronization problems, as we have shown through a spiral path case study. In the experimental test, the measurement systems behave as the theoretical printing speed estimated by assuming that the printer control is based on a trapezoidal speed profile and a cornering algorithm with a jerk limit. The encoder estimation is smoother than the speed-surface prediction and the theoretical profile. It stands to reason that the actual speed evolution is continuous such as the encoder prediction behaves.

The above methods required an experimental calibration, but the encoder solution provides in-process measurements because it does not require reading the G-code and performing time-consuming computations such as the speed-surface approach.

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