Influence of single-filament dimensions on geometrical density as a quality criterion for fused filament fabrication

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Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing Ecole Centrale de Nantes, France
September 18th 2019

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Goal
- Lower the entry barrier into polymer additive manufacturing for small and medium-sized enterprises

Our approach
- Understand influence of print process parameters on single filaments
- Analyze interaction between neighboring and stacked filaments
- Create model to predict part quality (i.e. porosity and dimensional accuracy) based on print process parameters

Implementation
- Integration of two laser line triangulation scanners (LLS) into a fused filament fabrication printer
- Scanning of printed filaments
- First, offline analysis of recorded to generate process knowledge
- Laser, online close loop error detection
Related work

- Computational simulations and mathematical models exist but only few were validated against experimental data [1]
- Hebda et. al achieved $R^2$ values of 94.1% and 84.7% for a model describing the width and height of filaments [2]
  - Most of the experiments were conducted with very high filament feed rates and therefore under over extruding conditions
  - The printed filaments were captured with a computer tomography system, which can only be used for finished prints

Previous work at WZL

- Comparison of scanned filaments with simulated structure based on g-code
- But:
  - Invalidated model for filament shape
  - No information on the cause-effect relation
  - Massive amount of data not applicable for analysis during print process

Experimental Setup

- Adjustments to the experimental setup
  - Stiffer mount for the LLS sensors with new positioning
  - New calibration routine (described in detail in the submitted abstract)
  - Integration of magnetic tape encoders for precise sensor tracking
  - Replacement of print plate by matte spray painted glass plate

- Design of experiments
  - Full factorial
  - Two levels with central point
  - Evaluated print parameters:
    - Filament feed rate in mm / mm (filament / print vector length)
    - Linear print speed in mm / s
    - Distance of nozzle to print plate in mm
    - Nozzle temperature in °C (blocking due to experimental limitations)
Methods – Print strategy

- Supporting print structure to guarantee successful print, non adherent parameter sets would otherwise interfere with the print.
- All print process parameter variations (except temperature) in one print run.
- Due to limitations of the used printer, the nozzle temperature can not be changed during the print process, each full run is printed with different temperatures.
- 70 mm linear vectors with the chosen print parameters.
- Only ~45 mm in the center will be scanned to guarantee stable print conditions.

Printed with chosen parameters
Support for good adherence

100 mm
Methods – Laser scanning

Scanned with laser line triangulation sensors

100 mm
Methods – Data segmentation

- Data points in a slice of 200 µm width in the x-axis are taken and projected to the y-z-plane
- Distance in x between data points is ~50 µm
Methods – Peak finding

- Whole slice is cut into multiple bins
- Moving average finds area with highest z values

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Data points within a margin (±1 mm) around each of the found peaks are extracted separately for the analysis of the filament shape.
**Methods – Repetition**

- Procedure is repeated 10 times for different positions along the x-axis
- Fit parameters are averaged over positions in x
## Major findings – Example profiles

<table>
<thead>
<tr>
<th>Peak</th>
<th>Temp. in °C</th>
<th>Flow Rate in mm/mm</th>
<th>Layer Height in mm</th>
<th>Print Speed in mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>205</td>
<td>3,326</td>
<td>0,1</td>
<td>5</td>
</tr>
<tr>
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<tr>
<td>10</td>
<td>205</td>
<td>1,663</td>
<td>0,5</td>
<td>305</td>
</tr>
</tbody>
</table>

Center point for flow rate based on the ratio between filament cross-section area before and after the nozzle.
Major findings – Gaussian fit

- Single fit for every x-axis position of every found peak
- Combined fit of a linear background function and a signal function
- **Height** of the filament is determined based on the **amplitude** $A$ of the calculated fit
- **Width** of the filament is determined based on the **standard deviation** $\sigma$
- **Chi²** used as indicator for **goodness of fit**

$$A = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y-\mu)^2}{2\sigma^2}}$$

$A$: Amplitude
$\sigma$: Standard deviation
$\mu$: Center of fit
$y$: position along y-axis
Major findings – Rectangle & Sigmoid fit

Chi-Square: 0.104
Reduced Chi-Square: 0.000182
Fit Center: 22.190
Height: 0.267
Width: 0.464

A · {min[1, max(0, α₁)] + min[−1, max(0, α₃)]}

A: Amplitude
σ: Slope
μ: Center of fit
y: position along y-axis

α₁ = \frac{(y−μ₁)}{σ₁} and α₃ = −\frac{(y−μ₂)}{σ₂}
Major findings – Chi square comparison

- Chi square average over all 10 x-axis positions for each peak
- Gaussian model does not provide an adequate fit
- Rectangle fit with linear slopes (trapezoid) and rectangle fit with sigmoid sides provide similar averaged chi square values
- But sigmoid fit fails for some peaks
Conclusion

- Successfully enhanced laser line scanning system integration into a fused filament fabrication printer
- Implemented and validated new calibration routine
- Established a method to measure single printed filament lines
- Found trapezoid model to be best fit for filament shape description
Outlook

- Validate filament shape by measuring with print rotated by 90°
- Multiple lines with reducing distance between filament
- Multi-layer prints
- Integration of additional sensors
  - Optical flow sensor to track filament feed rate
  - Custom laser line triangulation scanner for true in-process measurements
Acknowledgement

The support of the German Research Foundation (Deutsche Forschungsgemeinschaft DFG) through the funding of the research project “SmoPA3D - Sensorgestützte modellbasierte Parametrierung von 3D-Druckprozessen” (Sensor-aided model-based parametrization of 3D-print processes, SCHM1856/78 1) is gratefully acknowledged.

I want to thank my co-authors and our student workers Timm Siegfried and Florian Walter.
Backup – Calibration routine

- Individually for each sensor:
  01. Segmentation between build plate and filament point clouds
  02. Projection of build plate points along the y-axis
  03. Two dimensional morphological operations to reduce noise
  04. Linear fit through the projection
  05. Rotate points along y-axis and normalize lowest point
  06. Repeat 2.-4. for rotation along x-axis
  07. Projection of filament points along z-axis
  08. Two dimensional morphological operations to reduce noise
  09. Hugh transformation to detect lines in projection
  10. Calculate intersection
  11. Cluster intersections in close proximity and remove outliers
To combine the point clouds into a single COS:
- Match intersections
- Select one intersection as COS-origin
- Calculate rotation in z-axis and translation in xy-plane
- Apply transformation to the point clouds
- Additional rigid body fit of the point clouds
Backup – Closing gap

Multiple filaments with decreasing gap

z-axis/mm

y-axis/mm

x-axis/mm

-7.6

-7

-7.2

-7.4

-7.6

-6.8

-6.6

-6