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

Robert H. Schmitt[1], Kilian Geiger[1], Dominik Wolfschläger[1], Martin Peterek[1]

[1]*Laboratory for Machine Tools and Production Engineering of RWTH Aachen University, Germany*

K.Geiger@wzl.rwth-aachen.de

Abstract
Although often seen as a hobbyist niche, polymer additive manufacturing has its advantages for small sized batch production and is therefore more and more frequently considered as a potential investment for small- to medium-sized enterprises. One of the main concerns regarding the process is often the reliability of the structural strength of the printed parts and the necessary experience to circumvent corresponding production issues. In order to resolve these reservations, the influence of the large variety of adjustable print process parameters on the quality of the final product needs to be investigated to its full extend. In this work, a method is proposed to investigate the dependency of the part density on the shape of the individual filament lines. By integrating laser line triangulation sensors into a common fused filament fabrication printer, the influence of the print process parameters on the filament shape as well as the interaction between neighbouring and stacked lines of filament can be measured during the print process.

Geometric modelling, In-process measurement, Metrology, Quality assurance

1. Introduction

Within the last decade, Additive Manufacturing (AM) evolved from mere prototyping to full production of work pieces with researchers and machine manufactures eagerly working on further advances towards large-scale production. Two main concerns hindering the adoption of AM technologies in industry, especially for small- to medium-sized enterprises, are the high complexity of the processes and uncertainty about the quality of the produced parts [1]. To address these problems and thereby further lower the entry barrier for AM technologies, such as fused filament fabrication, the intricacy of the printing process needs to be reduced from an end user's perspective. One approach increase user friendliness is the introduction of assisting systems based on an extensive understanding of the underlying processes. Therefore, the effects of different print process parameters on the resulting part quality during fused filament fabrication is of great interest for the AM community [2].

While some approaches for modelling the extrusion process based on computational fluid dynamics simulations or simplified mathematical models exist, only few have been validated by methodical experimental investigations [3]. Hebda et. al describe a model for the prediction of filament shape based on the assumption of conservation of mass [4]. Their models achieve high R^2 values of 94.1% and 84.7% for the width and height of the filament, respectively but conduct most of the experimental investigation under high extrusion rates, which are uncommon for practical applications. Fuhrmann et. al investigate empirical or black box models for the whole process of fused filament fabrication but not for single filament lines [5]. One of the fastest growing topics for metal-based AM is the inclusion of in-situ metrology [6]. For fused filament fabrication, no previous research on the application of on machine metrology could be found.

The hereby-presented research project aims to analyse the influence of a range of print process parameters on printed filaments and the resulting three-dimensional (3D) structure, in particular the geometrical density of the final part. Through integration of two laser line triangulation sensors into a fused filament fabrication printer, the geometry of printed filaments is measured during the print process. Thus, the impact of selected print process parameters on single filaments and the interaction between neighbouring and stacked filaments can be analysed, filament by filament as well as layer by layer. The collected data can be used to detect unwanted cavities between the filaments and thereby determine the geometrical density or porosity, which in turn is a major influencing factor on the mechanical properties of the printed part [7].

The initial work focusses on the measurement setup used to collect 3D surface data of the printed filaments during the print process. First, the physical setup and used sensors are introduced. Following, the different calibration routines needed to get reliable and repeatable data are described. In the end, an outlook on the studies of single, neighbouring and stacked filament geometries is given.

2. Methodology

In order to investigate the influence of single filament lines and the interactions between neighbouring and stacked lines, it is necessary to implement a metrology system, which is able to measure the filament during the print. Two laser line triangulation sensors are used for the detection of 3D surface information in the magnitude of single filament lines during the print process.

2.1 Experimental setup

Two Keyence LJ-G080 laser line triangulation sensors as well as a ASM POSIMAG PMI3 magnetic tape encoder (MTE) are integrated into a MakerBot Replicator Z18 fused filament fabrication printer (cf. figure 1).

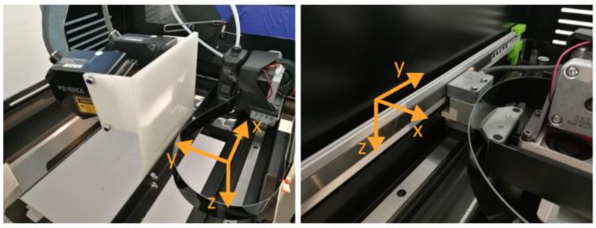

Figure 1. *Left:* Keyence laser line triangulation sensors mounted to the x-axis of the 3D-printer, moves along y-axis.
Right: ASM magnetic tape encoder tracking y-axis movement.

The laser line triangulation sensors and the MTE are synchronously read out via a Keyence LJ-G5001 Controller and an ESP8266 based microcontroller, respectively. The data obtained from the laser line triangulation sensors is two dimensional point cloud with distance values along the measuring axis of the sensor. In combination with the y-axis position from the MTE, the data is transformed to a 3D point cloud. Due to the mounting, the y-axis of the 3D-printer can be used to move the laser line triangulation sensors across the build plate, while the MTE records the current position with a resolution of 5 µm and maximum linearity error of 26 µm (15 µm + 40 µm / m · 0.3 m). To prevent interference issues between the two laser lines, the laser line triangulation sensors are mounted with an offset along the y-axis and are slightly tilted. A slight angle between the laser line triangulation sensors along the y-axis of the printer allows to measure filaments with higher resolution along the z-axis, as planes parallel to the line of sight of the sensor cannot be detected. The laser line triangulation sensors have a repeatability of 1 µm and a linearity error of ± 0.1% of the measuring range, which in this case is limited by the layer size and number of printed layers. Along the x-axis, the laser line triangulation sensors provide a resolution of 50 µm with a repeatability of 10 µm. As a motion along the y-axis of the 3D printer is used to realize a 3D measurement, the resolution along the y-axis is dependent on the measuring frequency of the laser line triangulation sensors (≈263 Hz) and the MTE (50 kHz), the resolution of the MTE and the speed of the scanning motion. With a scan speed of 0.5 mm/s, the resolution of the MTE limits the y-axis resolution to 5 µm. A spray painted glass plate of 230 mm by 255 mm replaces the printer's original build plate, as glass is expected to be more even than the original build plate. Additionally, it can be used as a carrier for computer tomography (CT) reference measurements. The mat colour is necessary to prevent the reflectiveness of the glass obstructing the laser measurements, it additionally increases the adhesion of the filament to the unheated build plate.

2.2 Calibration

In addition to a manual bed levelling using three thumb screws, the internal printer software performs a z-axis levelling by contact of the extruder hot end with a single point on the build plate frame. The x- and y-axis are calibrated in a similar fashion by running into end switches during the start-up procedure ahead of each print job. During this procedure, the MTE passes a specified magnetic end signal, which is used as an absolute reference point between measurements.

Considering the orientation and shift of the laser line triangulation sensors towards the build plate and each other, a transformation from the individual coordinate systems (COS) into one joint coordinate systems is required to analyse the recorded data. Aiming to keep the measurement system autonomous, the printer is used to generate a calibration standard by printing an object with detectable features, which in combination describe a unique COS. Here three isosceles tringles that share one corner are used (cf. figure 2).

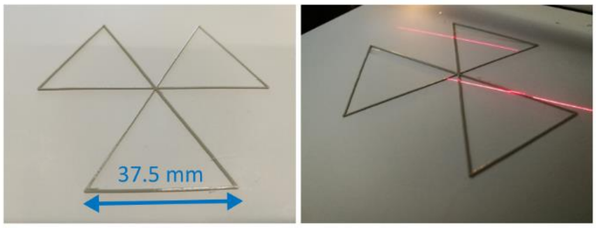

Figure 2. *Left:* Print used to calibrate laser line triangulation sensors
Right: Calibration print during the scan process.

2.3 Filament studies

In a first step, individual lines of filaments are printed with varying print process parameters, for example nozzle traveling speed, filament feeding rate or layer height (cf. figure 3, left). For each set of parameters, the geometry of these lines is evaluated by extracting relevant dimensional quantities, such as the average width, height and shape from the recorded 3D surface data, obtained by the laser line triangulation sensors. Based on this analysis, the influence of neighbouring filaments is investigated by printing two filament lines in close proximity and reducing this gap up to a forced overlap in a series of print tests (cf. figure 3, right). In combination with the information about the expected filament geometry and thereby volume, the amount and spread of excess material can be described. In a last step, additional layers are stack on top of filaments with varying distances to study the influence of previously generated gaps on additional layers and consequently the geometrical density, i.e. the reciprocal value of the porosity, of multiple stacked layers. In order to have control over the print process parameter settings of individual filament tracks, tool path is created directly in machine code without the use of external slicer software.

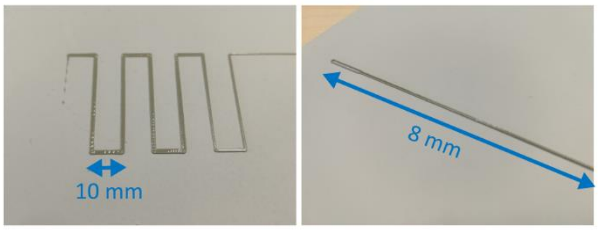

Figure 3. *Left:* Single filament study with increasing feed rate
Right: Multiple filaments with decreasing gap size.

3. Results

The calibration method for the laser line triangulation sensors consists of several steps, calculating the rations and translations along all three axis independently. The steps are run through in the following order:

- Individually for each sensor:

1. Segmentation between build plate and filament point clouds
2. Projection of build plate points along the y-axis
3. Two dimensional morphological operations to reduce noise
4. Linear fit through the projection
5. Rotate points along y-axis and normalize lowest point

6. Repeat 2.-4. for rotation along x-axis
7. Projection of filament points along z-axis
8. Two dimensional morphological operations to reduce noise
9. 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

1. Match intersections
2. Select one intersection as COS-origin
3. Calculate rotation in z-axis and translation in xy-plane
4. Apply transformation to the point clouds

A selection of the previously described steps in presented in figure 4.

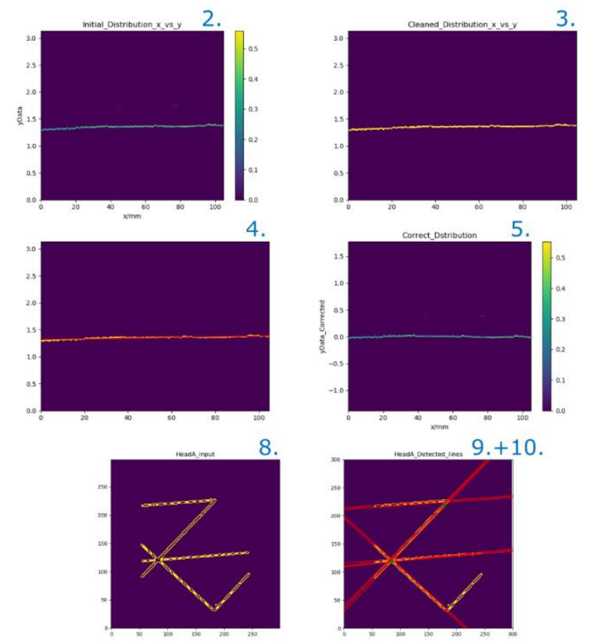

Figure 4. Selection of steps executed during calibration of the laser line triangulation sensors. The numbering corresponds to the procedure description in text.

Examples of a measurement of a single filament with increasing feed rate along the print path from right to left, can be seen in figure 5. Two connected lines, one horizontal and the other vertical, have the same feed rate. After each L-shaped filament, the feed rate is increased. As expected, with an increase of the feed rate, the width of the printed filament grows.

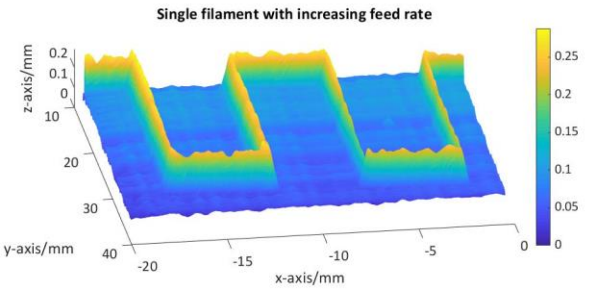

Figure 5. Scan of a single filament with increasing feed rate from right to left.

Figure 6 displays the effects of a closing gap between neighbouring filament lines. A straight single line is approach from both sides by parallel filament lines with the distance decreasing every 10 mm by 50 µm. The additional surrounding lines are used as supports for the filaments of the following layer, which are printed perpendicular to the current filaments.

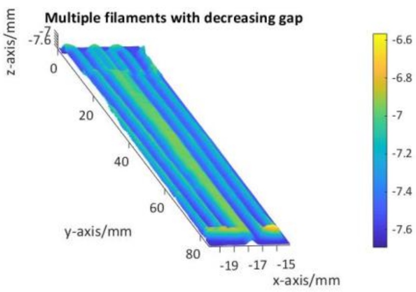

Figure 6. Multiple filaments with decreasing gap.

As can be seen, the presented measurement setup is able to measure the printed filament with an accuracy high enough to detect single filament lines. Although the resolution along the y-axis is higher than along the x-axis due to the scanning motion, there is a visible periodic error in the data along the y-axis. The assumed to be smooth glass build plate shows a sinus-wave like characteristic. This is assumed to be caused by an unintended rotational movement of the laser line triangulation sensors along the x-axis. A stiffer mounting fixture can potentially address this issue.

4. Conclusion and future work

In this work it is shown that by integrating laser line triangulation sensors into a fused filament fabrication printer, it is possible to detect single and multiple filament lines during the print process. A calibration method is presented, which is able to transform the recorded data of both sensors into a single coordinate system. This transformation permits the sensors to be shifted and tilted relative to each other, which in return can be used to detect the filament edges in higher resolution. First measurements of single and neighbouring filaments show promising results for further experiments and detailed analysis.

With this testing framework laid out and set up, the planned investigation of the influence of different print process parameters on the shape of single and the interaction between neighbouring and stacked filaments can be carried out. By Design of Experiments, various combinations of parameters will be chosen, measured and analysed with statistical methods. The results will be used to establish empirical models to describe the influence of the investigated parameters on the shape and interaction of the filaments and in return the quality of the printed parts in terms of geometrical density. These models can furthermore be compared to previously mentioned mathematical approaches to predict the filament's shape.

Another issue is to verify the testing framework and the reliability of the recorded measurements. During bed-levelling, the distance between the extruder hot end to the build plate appeared to be inconsistent over the whole area of the glass plate. Assuming errors in the straightness of the printer's linear axis, a calibration procedure with an external reference system could be used to integrate compensation methods into the tool path generation. While the error in distance between the laser line triangulation sensors and the build plate can be compensated during the data analysis, a constant gap size would improve the consistency of the printed filaments.

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