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In-Situ Monitoring for Fused Filament Fabrication by means of Multi-Electrode Resistance Measurements

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Summary:
This work demonstrates in-situ monitoring of additive manufacturing through Fused Filament Fabrication with multi-electrode resistance measurements as an alternative to thermal and optical monitoring methods. Measurements are performed through the means of a resistive filament in combination with multiplexed nozzle to bed electrodes. When printing a beam, measurements show the addition of layers as well as nozzle x-position. Furthermore effects of the electrode placement, size and loss of nozzle contact can be measured. Future work will focus on measurements with a higher number of electrodes and more complex sample geometries.

Keywords: Process Monitoring, In-Situ, 3D-Printing, Fused Filament Fabrication, Electrical Resistance

Introduction

One of the main challenges in Fused Filament Fabrication (FFF) is dealing with uncertainties in the equipment and process. Therefore in-situ monitoring of the process is an important step towards understanding the process and improving its quality and efficiency [1, 2]. Research in this field is quickly developing and is considered fundamental for the industry [2, 3]. Thermal and optical imaging are the most common monitoring methods and have been used successfully for defect detection and closed-loop control purposes [2, 3]. Despite these advances, there is still a lack of effective and cheap in-situ monitoring techniques for non-destructive structural fault detection. Especially of those that can easily be incorporated into 3D-printers [1, 3], since the surface-based optical methods give very limited information on adhesion and bonding quality. In-situ electrical resistance measurements with conductive filament are able to measure bonding quality, part geometry, print temperature and presence of defects. Previous work applied measurements between two bed electrodes [4] and between a bed electrode and the nozzle [5], generating limited information in complex geometries. This work aims to extend the methodology by multiplexing the measurement path between multiple bed electrodes and the nozzle. The following sections demonstrate the methodology and implementation of in-situ multi-electrode measurements.

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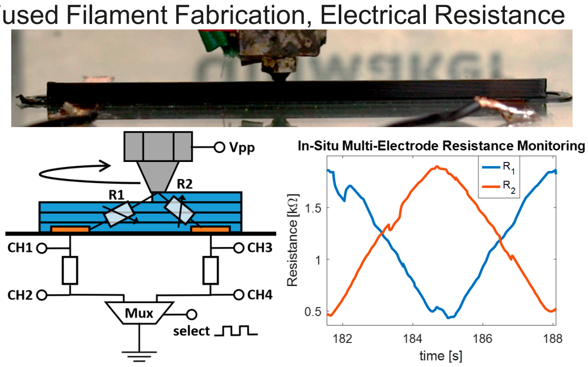

Fig. 1: Setup with the electrodes on the left and right side of the beam (top), schematic of the multiplexed setup (left) and typical data for printing from right to left and back (right).

Methods

Our novel in-situ measurement principle is based on electrical resistance measurements during printing with a resistive filament. By studying the changes in electrical resistance with added layers, the bonding between layers and the effect of printing parameters can be derived. The usage of additional electrodes with multiplexing allows for measurement of multiple resistive paths (R_1 forming the left and R_2 the right resistive path), Fig. 1. In this experiment a beam is printed across two bed electrodes, where the resistance to the nozzle typically increases and decreases as a result of the sideways movement of the printhead, fig. 1 (lower right). A long, thin sample is used to achieve a low thermal time constant, reducing the effect of the temperature-dependent electrical resistivity [4]. The setup consists of a customised Ultimaker 2 printer with a BondTech Bowden extruder and an E3D 0.8 mm stainless steel nozzle. The resistive filament of choice is carbon black filled Polylactic Acid (PLA) by Protopasta [6], which is printed at $30\,\mathrm{mm\,s^{-1}}$ with a $210\,°$C nozzle temperature and a $50\,°$C bed temperature. The beam has a length of 100 mm, a width of 3.2 mm and a height of 4 mm, and is printed with 0.25 mm layer height and a two track skirt. Copper tape with a width of 6.35 mm and a thickness of 66 µm is used to form the bed electrodes. Measurements are performed through voltage dividers, with $3422\,\Omega$ and $3243\,\Omega$ resistors and $V_{\mathrm{pp}} = 24$ V DC. The 2-to-1 mux circuit (2x BS170 NMOS) is triggered by a square wave at 10 kHz (Siglent SDG1032X) and sampled by an oscilloscope (Rigol DS1054Z). Signals are post-processed in MATLAB with an envelope function and a moving average filter to remove switching effects and provide noise reduction respectively. A 2D FEM simulation for a single printline is performed in COMSOL using the Electric Currents module with same sample geometry and a resistivity of $\rho = 0.2\,\Omega\,\mathrm{m}$. The nozzle position is swept over the sample length to simulate the printing.

Results

The measurement data for the first layers is shown in fig. 2. The resistance decreases with added layers and opposing changes of R_1 and R_2 correlate with the nozzle x-position. After several layers, the relative change in resistance reduces with the number of layers N, given $R \propto 1/N$. The placement and size of the highly conductive electrodes influences the measurement and FEM data. The beam extends over the electrodes, increasing resistance when the nozzle extends past the electrodes to the outer positions. Additionally the electrodes act as equipotential, resulting in a small decrease in resistance when the nozzle passes over the electrodes. At the end of the print the nozzle is oozing after which it is pulled away from the part, with the blob being detected by both electrodes as well as the disconnect.

Discussion and Conclusion

In this work in-situ monitoring through multi-electrode resistance measurements is demonstrated. A clear correlation between nozzle position and resistance is shown, with the total resistance decreasing with the number of layers. Furthermore the effects of the electrode size, their location and loss of nozzle contact are observable in the data. The observed $1/R$ curve is not perfect, which can be explained by the parallel resistance of the skirt across the electrodes as well as the presence of thermal effects,

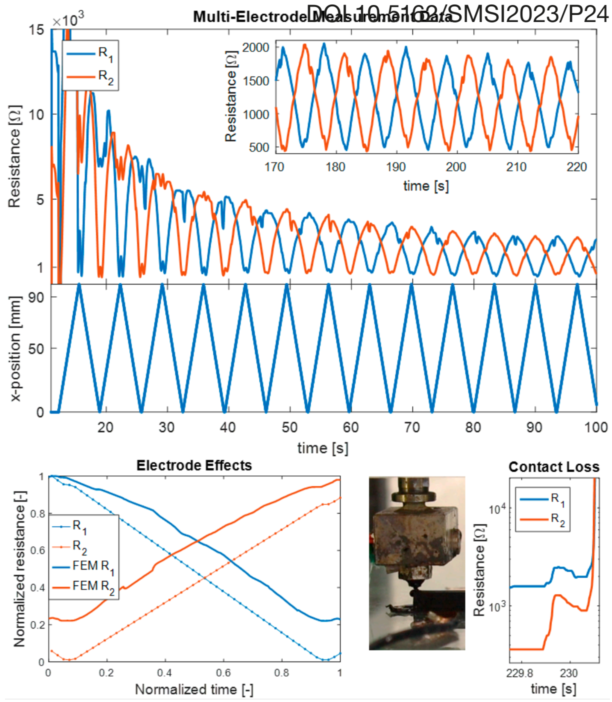

Fig. 2: The resistance data with a close-up at a later time (top), the nozzle x-position (center), the effects of electrode placement and non-zero width (bottom left) and loss of nozzle contact (bottom right).

despite the beam geometry. The geometrical resistance is expected to be linear with nozzle position as simulated, whereas measurements show a curvature for the first layers. Additionally the resolution and noise of the setup could be improved by grounding the nozzle and applying dedicated measurement equipment. Future work will focus towards complex geometries and a scaled number of electrodes, where machine learning could aid in data interpretation [7].

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