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Comparing Retraction Methods with Volumetric Exit Flow Measurement in Molten Material Extrusion

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Abstract

The volumetric flow rate, during the molten material extrusion process, is a critical parameter in this type of additive manufacturing process. One reason for this is that the extrusion nozzle diameter is an order of magnitude larger than the 3D printer positioning resolution, for example a 0,5 mm nozzle diameter compared to a positioning micro-step size of less than 0,01 mm. Furthermore, closed loop control of positioning systems is in general well understood. Estimation of the exit flow rate however is relatively more complex. Currently various test objects are used to determine printer parameters. It is not always clear which sub-process is responsible for the final measured errors in the test object. Printer parameter optimisation, through sequential test object printing, can also be a time consuming process. A method to determine the individual sub-process effectiveness is therefore required. The method used to measure the exit flow rate must also not be too expensive as compared to the cost of current open source 3D printers. Here a cost effective method is presented, which can be used to measure the exit flow rate during test extrusions. The filament feed speed and the slippage on the feeding gear is also concurrently measured. This method is used to study different retraction techniques and presents an objective way to compare different printer settings without printing a large set of test objects.

Molten Material Extrusion, In-Process Monitoring

1. Introduction

Improving open-source, molten material extrusion printers, in a cost effective manner, is an exciting challenge. The sheer number and diversity of such printers at homes, offices and labs are astounding [1]. That said many of these printers require continuous detail adjustment procedures to ensure reliable print results. Many times this is done by printing various 'test objects'. Scientists are also printing various test objects to study this fabrication technique. Comparing these test objects objectively is not straightforward. The object is a result of many sub-processes and it can be questioned if the effects of these sub-processes are uniquely identifiable, by examining the final object.

For example, so called extruder "*oozing*" (material flow after extrusion stop) can result in material build up on the nozzle or print area, which in turn can destroy the object surface texture. Incorrect bed-levelling though, can have the same result [2].

A clear requirement therefore becomes apparent: the definition of standardised tests, with which printer performance can be compared objectively. These tests should only validate a single sub-process, for example the bed adhesion, XYZ positioning accuracy or the extrusion process.

Many of these printers use stepper motors to position the nozzle relative to the object origin, as well as to feed the material. The theoretical positioning resolution with micro-stepping is in the order of micrometers (0,01 mm). On the other hand, the nozzle diameter is an order of magnitude larger (0,2 mm - 0,5 mm). The volumetric flow rate is therefore a major limiting factor and the control of it critical.

Methods for measuring the volumetric flow rate are presented in patents [3,4]. This includes filament width estimation and filament presence detection. The concept of using capacitance sensing to determine filament water content is also discussed in [5].

Another measurement method develops a dynamic model to detect nozzle clogging, using an accelerometer [6]. This is however mainly used to determine whether the printer is in an error state or not. The filament feed mechanism slippage was measured in [7] and was used to actively reduce the slippage during printing.

The concept of using strain sensors to estimate the liquefier pressure drop is discussed [8]. The measurements are used to derive an extensive model for the rate limits for molten material extrusion printers. The patent [9] also presents a concept for measuring the liquefier pressure by measuring the liquefier tube expansion with strain gauges.

This paper however aims to present an open-source, cost effective method for measuring extruder parameters. The input flow rate, feed slippage and exit flow rate are measured, along with the pressure drop over the liquefier. This is used to study the effect of retraction by performing different retraction tests.

The experimental setup is described first. This includes the speed estimation with optical flow tracking and liquefier pressure drop measurement with strain gauges. The retraction tests and results are discussed next and finally a conclusion based on these results is drawn.

2. Experimental Setup

A Renkforce 1000 (RF1000) single extruder printer was used for this study [10]. The extruder moves along the X-axis and the heated build plate in the YZ-plane. The extruder allows for open access to the filament feed mechanism. The liquefier, into which the filament is fed, is mounted on a cantilever with strain gauges (see Figure 1). This is used by the RF1000 as a bed levelling sensor.

In this study white PLA was used for all tests, with a nominal diameter of 2,85 mm and a recommended extrusion temperature of 215 °C [11].

The gear, filament and exit speed are measured optically with USB microscopes and image processing. The filament width is also estimated with image processing. All of the measured data, including the strain data, are captured in real-time, integrated into a single file and saved for data analyses, by the main control application running on the host PC.

The extrusion process is controlled by this application, which also coordinates the experiment execution. All custom software, user interfaces, image processing and data processing were developed in the Python programming language.

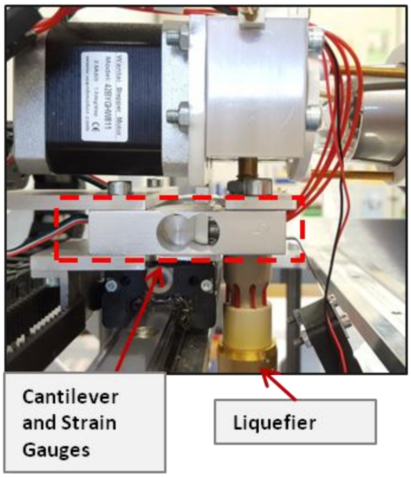

Figure 1. RF1000 3D printer, with liquefier mounted on a cantilever beam.

2.1. Pressure Drop Measurement

The cantilever deflection is measured with strain gauges and converted by the printer electronics with an ADC (Analogue to Digital Converter).

The firmware was modified to simply report the strain value, in ADC counts, at a regular interval of 10 Hz. This is the maximum rate achieved so far with this setup. A software program, Repetier Server [12], interfaces with the printer via a USB connection. A client script interfaces with this local server and obtains from it the strain values and temperature values. Each reading is also accompanied with a time stamp, which is used for data alignment.

The strain gauge reading was verified by loading calibrated weights on a rod, mounted in the place of the liquefier. The weights were used to generate a mass from a 0,1 kg to 4 kg in steps of 0,1 kg. This data was used to determine linear conversion coefficients which is used to convert the strain ADC counts into mass (Equation 1), with $\boldsymbol{x_{counts}}$ the ADC counts, $\boldsymbol{m_{fit}}$ = 0,584 g/count, $\boldsymbol{c_{fit}}$ = 0,0 g and $\boldsymbol{y}$ the mass in kilogram. Each mass was applied for 5 seconds and the maximum range over all the measurements was 5 counts (2,9 g) and average range was 2,4 counts (1,4 g).

$$y = m_{fit}x_{counts} + c_{fit} \qquad (1)$$

The mass is converted to force, assuming a constant gravitational acceleration (9,81 mm/s^2). The pressure, or the pressure drop over the liquefier, is calculated with Equation 2, by dividing the force with the filament area, where filament diameter ($\boldsymbol{D_{filament}}$) is assumed to be constant and round.

$$\Delta P = \frac{F}{A_{filament}} = \frac{9.81*(m_{fit}x_{counts}+c_{fit})}{\pi\left(\frac{D_{filament}}{2}\right)^2} \qquad (2)$$

The filament width, as measured by the extruder camera image processing, can also be used for the pressure area calculation. The challenge is to determine the exact location of the melt front, which is the distance from the width measurement location to the plane where the filament area is currently pressurising the melted material. The filament diameter ($\boldsymbol{D_{filament}}$) is therefore considered as constant in this work and equal to 2,85 mm.

2.2. Optical Flow Tracking

Optical flow tracking algorithms are used to estimate the different speeds of the gear, the filament feed and the exit speed. Cost effective USB microscopes are used to capture frames and dedicated software processes estimate the measurands in real time [7].

The maximum speed which can be measured is limited by the frame rate. Two different USB microscope cameras are used. The extruder camera achieves 30 fps and the nozzle camera 26 fps. This frame rate was found to be fast enough for realistic printing speeds.

A frame, as captured by the extruder USB microscope, is shown in Figure 2. Here aggressive filament feeding seems evident, due to the saw tooth pattern on the filament.

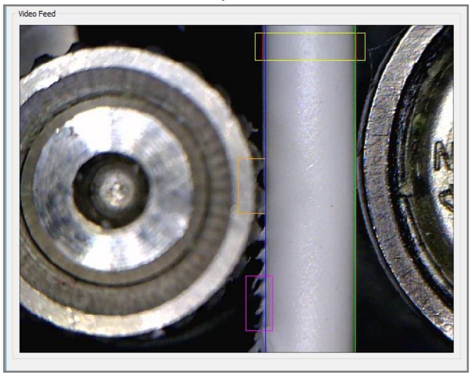

Figure 2. Screenshot of the extruder feed mechanism image processing application.

The optical flow algorithm estimates the distance certain points moved between frames. Ideally, the points should be in the same plane, have the same intensity in all the frames and the step distance should be small. Furthermore, it is beneficial if the points have a strong gradient in both spatial directions.

The speed ($\boldsymbol{v}$) is calculated with Equation 3, where $\boldsymbol{S_{pxl}}$ is the mean step distance per frame, $\boldsymbol{\Delta t_{average}}$ the average time step between each frame and $\boldsymbol{k_{cal}}$ the calibration factor. The speed is filtered with a low-pass filter, by convolving it with a Gaussian window ($\boldsymbol{f}$) [13], with a window length of 15 points and a standard deviation of 2.

$$v = f * \left(\left(k_{cal}/\Delta t_{average}\right)S_{pxl}\right) \qquad (3)$$

The calibration factor ($\boldsymbol{k_{cal}}$) is determined once for a specific test as per Equation 4. The width of the filament is measured with a micrometer ($\boldsymbol{w_\mu}$) and divided with the average width, as detected by the image processing ($\boldsymbol{w_{detected}}$).

$$k_{cal} = w_\mu / w_{detected} \quad (4)$$

The detected filament width and the filament feed speed can be combined to estimate the input volumetric flow rate. The difference between the gear speed and filament speed gives G-Code independent feed slippage estimation. The controller therefore does not need know the current feed speed command, to control feed slippage, which can be useful if the printer is controlled by a computer. More details regarding filament feed slippage and the optical flow measurement can be found in [7].

2.3. Exit Flow Measurement

The material exiting the nozzle is moving approximately 32 times faster than the input speed (filament diameter 2,85 mm; nozzle diameter 0,5 mm). This requires that the field of view should be large enough to detect the exit speed. The extruder camera can track the gear tooth in-print on the filament or texture of the filament (see Figure 2), but this is not possible with the exit flow camera. The extruded material is not only thin and fast, but also smooth (see Figure 3). A solution is to generate marks on the extruded material, which can be tracked. These marks can be generated with ink jetting. This is achieved using a 96 DPI inkjet cartridge and hardware from an open source project called '*InkShield*' [14].

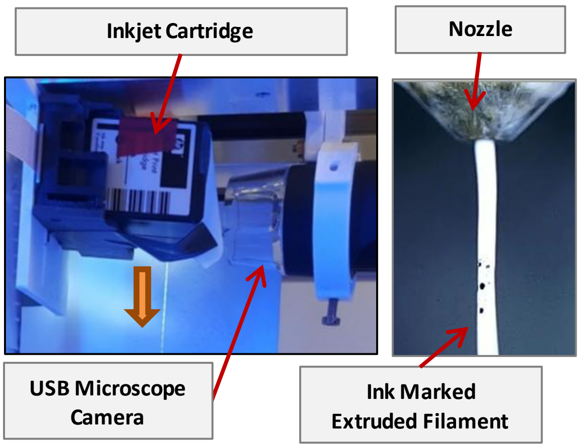

Figure 3. Left is a photo of the inkjet cartridge. The downward arrow indicates extrusion flow direction. The figure on the right shows an image frame captured by the nozzle camera. The black dots on the white filament are the jetted ink drops.

The inkjet rate is controlled by the main controller application. This is also varied relative to the measured gear speed. This ensures that there are always spaced dots on the extruded filament, which can be tracked. The exit width is also estimated and combined with the exit speed to determine the exit flow rate.

This method however only works for test extrusions as there is no space for the exit flow measurement setup during normal printing. This is acceptable for extruder parameterisation tests, but not for real time control. The removal or the conveying away of extruded material is the greatest issue with this method. The weight of the extruded filament can also pull the bead down, affecting speed and width measurements. In this work the weight effect is not considered.

2.4. Extrusion Experiments

There are three extrusion process changes: (1) extrusion start, (2) feed speed change and (3) retraction. Here retraction is studied with the experimental setup.

The purpose of retraction is to reduce the pressure in the liquefier as fast as possible, in order to stop the unwanted flow of molten material (or '*oozing*').

Retraction was investigated with extrusion tests. A '*nozzle prep routine*' is executed first, after which different retraction techniques are executed. The extruder stepper motor is switched off a set time after retraction completion (i.e. holding torque removed). After another short delay, filament is extruded. This is done by first extruding a 1 mm '*refill*' filament at 16 mm/s and then continuing extrusion for another 13 mm at 0,75 mm/s. The different retraction parameters tested are summarised in Table 1. The values for the '*Normal Retraction*' are derived from standard RF1000 printer settings.

Table 1 Retraction test parameters

Retraction Name	**Speed** *(mm/s)*	**Length of Filament** *(mm)*	**Legend Key**
No Retraction	-	-	None
Normal Retraction	-16,0	1,0	V16
Speed Variaion	-20,0		V20
	-12,0		V12
	-8,0		V08
Length Variation	-16,0	0,5	L05
	-16,0	1,5	L15
Multi-Step	-16,0 0,5	1,0 0,1	Multi-Step
	Repeated 3 times		

Before each extrusion experiment the '*nozzle prep routine*' was executed. This routine is the same set of commands that the RF1000 normally performs, before starting an actual print. This start sequence involves three extrusions: (a) fast nozzle infill (13 mm at 13,33 mm/s), (b) longer preparation extrusion (25 mm at 0,52 mm/s) and (c) retraction (1 mm at -16 mm/s).

3. Retraction Tests Results

Figure 4 shows a single multi-step data set. The input flow rate, measured by the extruder camera, is compared with exit flow rate (top graph). The lower graph visually compares the exit flow rate with the pressure drop.

At certain points it can be seen that the exit flow rate deviates from the expected range and these are locations where the extruded material removal causes speed detection errors, as discussed in the experimental setup. Several measurements however where taken, aligned and averaged to process the data.

Sharp peaks in the input flow indicate retractions (negative speed is inverted). The first period on the graph (0-55 seconds) shows the nozzle prep routine. From this data we can already motivate the use of the prep routine, as it takes a relatively long time before the flow rate and pressure reaches a semi-steady state situation.

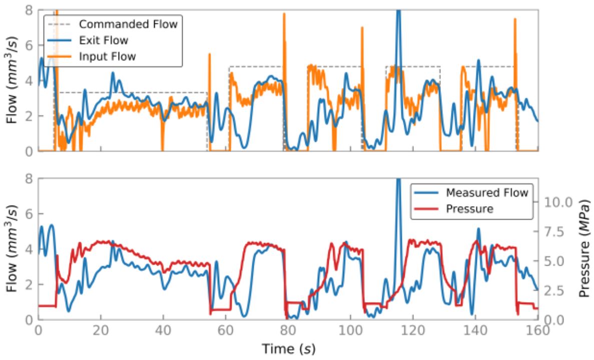

Figure 4. Example data for a multi-step retraction test at 215 °C.

Secondly, unwanted material is till flowing after stopping the filament feed mechanism. This is further investigated in more detail next. The average pressure against time curves for different retraction tests are shown in Figure 5. The first sharp drop in pressure indicates the retraction event. After a time delay, the stepper motor is disabled. Extrusion is then restarted and all curves show a fast rise, after which different step responses can be distinguished.

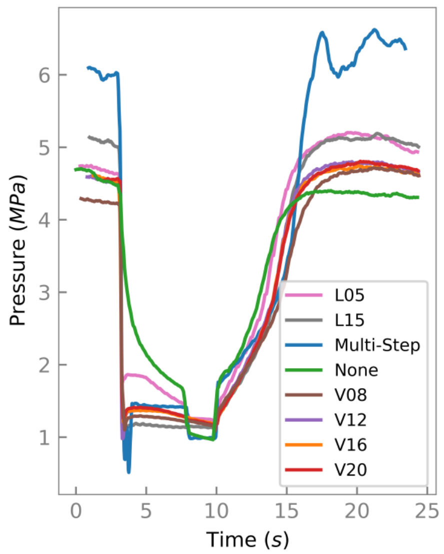

Figure 5. Pressure change during different types of retractions.

The motor is turned off at about 8 seconds which results in a force decrease in the 'None', 'L05' and 'Multi-Step' retraction tests. The motor was therefore still applying a compressive force on the melt due to the holding torque of the motor. This force decrease is therefore an indication of how successfully the filament was detached from the melt.

The multi-step method applies a sequence of three retractions and extrusions. The last extrusion is therefore most likely the cause for the filament still applying the compressive force on the melt, whilst the effective retraction length of the L05 retraction is too short to free the filament from the melt.

The detail of the minimum pressure achieved by each technique is shown in Figure 6. Here the minimum point is indicated by a filled circle marker.

After retraction completion there is a small, but fast pressure increase. One explanation for this is that the returning force acts on the system due to the cantilever stiffness and the weight of the extruder, similar to the response of a compressed mass-spring system.

The three retraction steps of the multi-step method can also be seen in Figure 6. Each consecutive retraction reduces the minimum pressure. The question is if this really reduces the pressure on the melt and therefore the amount of unwanted flow of material or only detaches the filament from the melt. Another question is whether the method pulls the semi-melted material into the cold (cooler) zone of the liquefier. This can block the liquefier as result of material build up in the non-melting zone of the tube, which will increase the pressure drop, or force required to extruder filament, at a certain speed and temperature. Another possibility is the creation of air bubbles, which will also adversely affect the extrusion process.

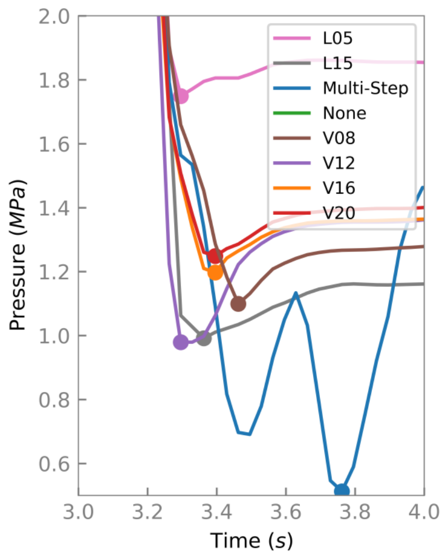

Figure 6. Pressure change detail during different types of retractions.

The exit flow rate was also measured during the different retractions. The averaged and time aligned volumetric exit flow, during and after retraction, is shown in Figure 7. The minimum point is indicated with a filled circle. Note that the increase after the minimum point can be the result of measurement noise, due to filament movement or removal.

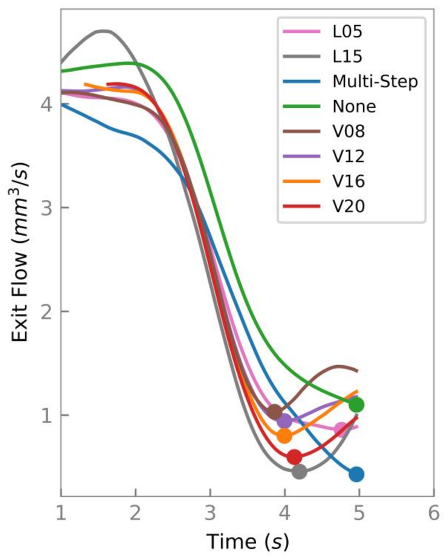

Figure 7. Averaged exit flow after different retraction methods.

The L15 retraction achieves the best results here. The multistep method reaches a lower minimum, which can indicate that there is a better chance that '*oozing*' is completely stopped, but this is at a later time point than the other methods.

Figure 8 summarises the minimum pressure and flow points, as achieved by the different techniques. The L15 retraction performs the best, if the evaluation criterion is set at the minimum ooze volume, that is, minimum flow rate multiplied by time. The speed variation tests also show that a slower speed (e.g. V12) can perform better than the normal retraction (V16). A factor to consider here is that the feed mechanism slippage also increases at higher speeds.

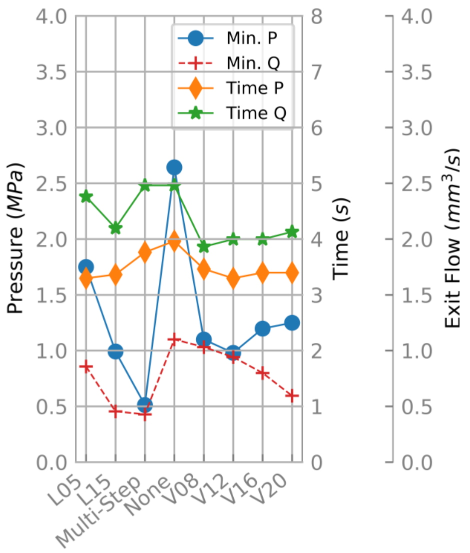

Figure 8. Summary of the minimum pressure (Min. P at Time P) and minimum flow rate (Min. Q) achieved by the different retractions.

Finally, these results were tested, by designing a test object. This object was sliced, and a Python script was used to generate the g-code, so that the different retraction methods could be tested with a single test print (Figure 9).

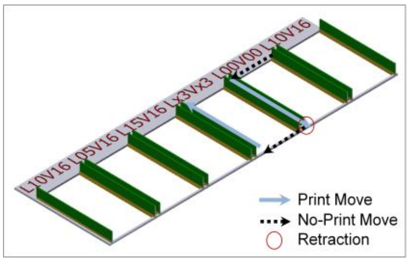

Figure 9. CAD view of the test object. The green features were generated with a python script

Close up photos of the test piece, at the point where the retraction was applied are shown in Figure 10. The multi-step method performs qualitatively the best. Again it is seen that slower speeds give better results. Apart from the feed slippage, the main reason for improved retraction is longer dwell time at the end of an extrusion, so that the bead can freeze.

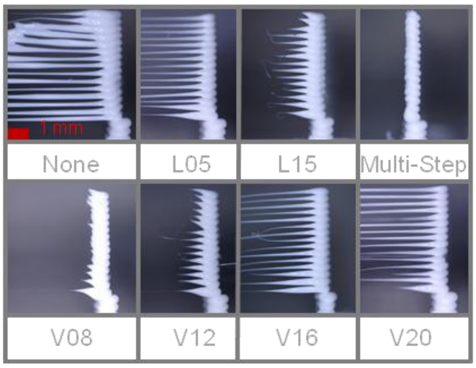

Figure 10. Photos of the stringing or oozing, as result of the different retraction methods.

4. Conclusion

A cost effective method to measure the input flow rate, the feed slippage, the exit flow rate and the pressure drop over the liquefier was presented. Different retraction methods were also investigated. Here measuring of the pressure and the exit flow rates during different types of retractions are achieved.

The measurement technique presented is open source and aimed at open source, molten material extrusion 3D printers. These printers require exact configuration and this is currently done by printing time consuming test pieces. The developed experimental method aims to introduce a way to parameterise an extruder (i.e. feed mechanism and liquefier). This can then be used to verify if an extruder is working properly, compare different extruders or determine optimal configuration parameters for a new feedstock.

Secondly, by understanding the relationship between pressure and exit flow, specifically during extrusion start, stop and speed changes, can lead the way toward implementing a cost effective exit flow rate control system.

Acknowledgements

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