(DRAFT) Accurate Material Shrinkage and Extrusion Multiplier

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2024-01-05

Abstract

The dimensional accuracy of FDM 3D printed parts depends on many factors. Among those are material shrinkage and extrusion multiplier, the accurate computation of which we will discuss in this paper. We propose a method that computes material shrinkage correctly even in the presence of a bias error in extrusion rate. *If you're looking for the step-by-step tutorial, please navigate to: github.com/cmdremily/BoronTrident/, this document aims to prove the correctness and accuracy of the method rather than being a calibration guide.*

1 Introduction

Commonly calibration procedures for material shrinkage consist of measuring a reference dimension on a calibration print and dividing the measured value over the reference value and using that as a scale factor. This has issues, most notably that the printed reference dimension has other sources of error, mainly extrusion width and errors from the XY motion system.

We will introduce a differential measurement method that cancels out the error introduced from extrusion width and only measures the compound of the XY motion system and the material shrinkage. Given that the XY motion system has previously been calibrated by the procedure here: github.com/cmdremily/BoronTrident/, then the material shrinkage is obtained directly.

2 Prerequisites

- A printer that has an accurately calibrated XY motion system.
- Filament to calibrate
  - The filament must already have a good value calibrated for pressure advance.
- A pair of 150 mm digital calipers with a precision of 0.01 mm or better.
- A micrometer with a precision of 1 μm or better.

3 Method Overview

For brevity this paper builds heavily upon the foundations laid out in in the previous paper: Differential Calibration for A/B-steps on Core XY Printers, please review that paper before reading this.

To recap, given two reference dimensions on the same axis, L_1 and L_2, their respective measured lengths l_1 and l_2 and associated errors ϵ_1 and ϵ_2, we can compute the scale error factor introduced from material shrinkage δ and XY motion scale error factor λ as:

$$\frac{\Delta l_{1,2}}{\Delta L_{1,2}} = \lambda\delta + \frac{\epsilon_1 - \epsilon_2}{\Delta L_{1,2}}. \tag{1}$$

3.1 Material Shrinkage

Assuming an accurately calibrated XY motion system as per the above paper, we have $\lambda \approx 1$. This means that the material shrinkage, δ can be directly computed from equation 1, provided a suitable calibration model which we will outline in section 4.1.

3.2 Extrusion Multiplier

While it's possible to compute, to directly obtain the extrusion scale factor equations in Differential

Calibration for A/B-steps on Core XY Printers, the results would be poor as the measurement error dominates the result.

Instead, we will calibrate the extrusion multiplier by printing a test cube in single wall vase mode and directly measure the wall thickness and compensate for the known material shrinkage.

Attempting to do this with consumer or prosumer calipers that typically have a precision 0.01 mm will produce unreliable results as the even if the calipers have an accuracy of 0.02 mm (which is good), when measuring an extrusion of width 0.5 mm, the worst case error is $\frac{0.02}{0.5} = 4\%$, this is larger than the typical adjustments of 1-2% that need to be made to the extrusion multiplier. Therefore we must use a micrometer for measuring the wall. A good micrometer available to consumers might have an accuracy of 0.5 µm and a precision of 1 µm, resulting in a worst case error of $\frac{0.5}{500} = 0.1\%$ which is good enough for what we're doing.

If we let E be the extrusion multiplier that would have produced an extrusion with the desired width W, then

$$W = E \cdot F$$

where F is a constant determined by the current E-steps and extruder geometry. The measured width of the extrusion will be:

$$w = \delta(E_c \cdot F) + \epsilon$$

where E_c is the current extrusion multiplier. Using these two expressions, we solve for E:

$$\frac{w-\epsilon}{\delta} = \frac{E_c W}{E}$$
$$E = \frac{\delta E_c W}{w-\epsilon}$$

3.3 A note on other methods of calibrating extrusion multiplier

4 Designing Calibration Models

4.1 Material Shrinkage

The calibration model must have two reference dimensions in each direction. We minimize the error to the computed shrinkage factor by maximizing the difference between L_1 and L_2. We pick

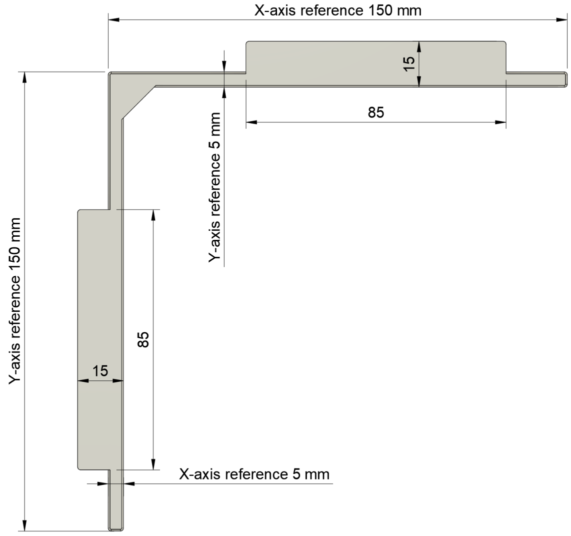

Figure 1: Calibration 'square' for material shrinkage.

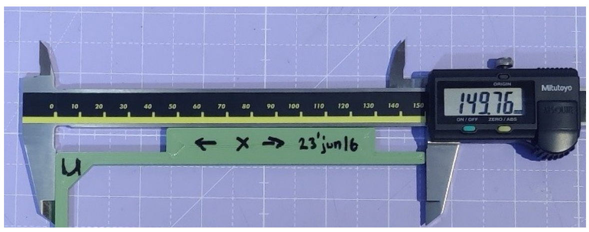

Figure 2: Tabs for caliper alignment.

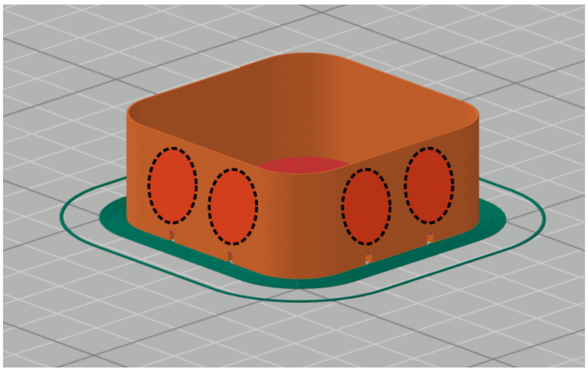

Figure 3: Extrusion multiplier calibration cube with notches to indicate where to measure (dotted circles).

$L_1 = 150$ mm as that's a common maximum measurable size for consumer calipers, we arbitrarily pick $L_2 = 5$ mm as a 'small' value.

We propose a right angle bracket as in figure 1. We make use of structural components for the small reference dimensions for the opposite axis to save on material. There are additional dimensions indicated that can be used for redundancy. The 15 mm wide, 85 mm long tabs on the sides allow the part to be easily aligned in the jaws of a caliper as in figure 2 for repeatable and accurate measurements.

If the pressure advance setting is too low, then the corners can buldge slightly affecting the accuracy of the calibration. Inspect the model for any bulging around corners prior to measuring and adjust pressure advance up temporarily if necessary. Other than the convenient tabs and effective use of material there is nothing remarkable about this calibration model. Use thin layers for printing this model reduce the impact from filament inconsistency by spreading the inconsistency over longer distances and stacking up more layers. The 5 mm beams must be solid material to guarantee homogeneous shrinkage. Let cool slowly to room temperature before measuring.

4.2 Extrusion Multiplier

When designing a calibration print for extrusion multiplier we want to minimize the impact of errors in the pressure advance calibration and in filament diameter variance. With this in mind, a cube with rounded walls as in figure 3 allows the toolhead to make a smooth transition between the sides, minimizing the impact from errors in pressure advance impacting the measurement. By using thin layers (0.01 mm) we attempt to spread out the variance in filament diameter over all four sides of the cube, producing more even wall thickness between the sides. A generous brim is highly recommended as any warping may cause the walls to become thicker than intended. We add notches along the bottom to give a visual aid of where to measure. Let cool slowly to room temperature before measuring.

5 Error Analysis

As this per material calibration is done on top of the XY motion calibration on the same printer, it will by nature cancel out small errors in the XY motion by compensting the material shrinkage factor slightly in either direction. Meaning that the dimensional accuracy of the final part may be higher than initially indicated by the XY calibration. It is still necessary to perform the XY calibration for reasons mentioned in Differential Calibration for A/B-steps on Core XY Printers.

Filament inconsistency, motion precision and measurement error still affect the calibration part. But bed expansion does not, as the part will simply delaminate from the bed as it contracts when cooling instead of the part shrinking.

Because the measurements for the material shrinkage calibration are taken of a calibration part that already has the error in the XY calibration baked in, the material shrinkage factor will end up compensating for the slight error in the XY calibration. This means that the error factors from these two calibrations do not compound, but rather the dimensional inaccuracy of the final part is bounded by the error sources of the calibration in this paper.

With the same values as in Differential Calibration for A/B-steps on Core XY Printers, that error is bounded by 35 µm. If the same instrument is used for calibration and verification, the indicated error will be approximately 6 µm, assuming no random factor affecting the measurement.