XYZ calibration cube - A misleading tool for achieving print accuracy

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Abstract. Various factors influence the dimensional accuracy in Fused Filament Fabrication (FFF). The kinematic system is a major influential factor, as the motion precision depends on the implemented solution. Kinematics have a direct influence on equipment costs. The FFF 3D printing market has abundant equipment options, from low-cost to high-end solutions. The filament extrusion precision and the shrinkage induced by the thermal contractions are other influential factors for the resulting parts' quality. Nowadays, the XYZ cube is the calibration benchmark. This cube is used to adjust the dimensional accuracy of the resulting parts. The deficiency with the calibration cubes is that they allow only the measurement of external dimensions, which makes the calibration useless when tolerancing the internal features or scaling. This paper discusses the limitations of the accuracy calibration method using the XYZ cube and possible solutions to overcome them.

Introduction

Fused Filament Fabrication (FFF) is a Material Extrusion (MEX) Additive Manufacturing (AM) technology that uses molten thermoplastic polymer-based materials to directly build parts based on a 3D model [1-3].

The FFF technology basics were set by Adrian Boyer and his research team in 2004 through the RepRap (i.e., self-replicating machine) project. After the Stratasys patent termination for the core technology, Fused Deposition Modeling (FDM), the consumer 3D printing market rose significantly [4, 5]. As the RepRap project was open source, the FFF 3D printer idea was taken by various companies (e.g., MakerBot) and sold with a price tag under 1,000 USD [6, 7]. Wohlers reports stated that a budget printer is under 5,000 USD [8].

Nowadays, the consumer 3D Printing market has various options, with equipment starting at a few hundred (i.e., Bambu Lab A1 Mini at 199 US [9]) and going up to thousands of USD (i.e., Ultimaker S7 at 8,400 USD [10]). To those, we can sum up the 3D printers developed by the DIY community (e.g., Voron 2.4). Those are further customized by the users [11]. Knowing that the overall print quality of the resulting parts depends on the printer's kinematics precision, the 3D printer cost reflects the build quality. This way, to address the printing quality of a given 3D printer, the users' community developed benchmark parts (e.g., 3D Benchy [12, 13]) and methodologies to improve the resulting parts' dimensional quality [14-16].

The XYZ cube is a widely used quality benchmark [17-20]. This tool helps adjust the steps/mm or how many rotations the step motor requires to extrude one mm of filament [18-20]. However, the XYZ cube is misleading as it allows only the evaluation of the external dimensions. This makes the cube futile for skew correction, internal features tolerancing, or scaling for thermal contraction compensations [21]. Thus, this paper discusses the limitations of current accuracy adjustment methods and examines potential alternatives.

Methods

Calibration cubes are probably one of the most 3D printed parts as they are used as a tool to see if equipment prints dimensional accurately. Usually, the calibration cube has an edge size of 20 to 30 mm [22-36] and is easy to recognize based on the X, Y, and Z embedded letters, which indicate the printer's axes. However, cubes can have a smaller edge size (i.e., 15 mm [18]) or significantly bigger (i.e., 100 mm [36]).

Over the years, there have been many variations of the calibration cube, each iteration aiming to provide more information about the printing process parametrization (e.g., overhangs, filament cooling, seam alignments). On the other hand, other calibration cube designs introduced aesthetics (e.g., Calicat) or interlocking (e.g., Lego calibration cube) as a feature, to increase the resulting parts' utility. Fig. 1 shows the print result of a fraction of the existing calibration cubes available on sharing platforms [37, 38] such as Thingiverse [39], Printables [40], My Mini Factory [41], Cults 3D [42], Grab CAD [43] and others.

Fig. 1. 3D printed calibration cubes made in the past years within their research.

Fifteen of the available calibration cubes are shown in Table 1. The resulting captions are screenshots of the print preview made using the Cura slicing tool. As can be observed, besides the flat, parallel surfaces (cubes 1, 4, 5, 11, and 15), these calibration cubes integrate features that give information about clearance between assembled parts (cube 6), filament retraction length and speed (cube 7), circular interpolation (cube 4, 5 8 and 10), small features size quality (cube 3, 5, 7 and 9), horizontal holes (cube 3 and 13), overhangs due to X and Y letter marks, appearance of ringing (also known as ghosting or rippling [44]) defects next to the X, Y letters or other details, or axels skewness (cube 15).

The calibration cubes help adjust the filament-feeding stepper motor's number of steps/mm. In other words, the number of rotational steps needed to feed the filament during the 1 mm travel of the printhead [45, 46]. The common practice is to print a cube, with a given edge of 20 mm, take a measurement using a caliper, and adjust the steps/mm accordingly. Then, after the motor's steps/mm adjustment, the cube is printed again, aiming for its edge nominal dimension. This process is repeated until the printer has produced a cube with the aimed level of dimensional accuracy.

In FFF parts are made layer-wise, by multiple passes of the extrusion head. This way, each layer integrates walls (also known as permitters or shells), one or more solid layers, and an internal structure (i.e., infill). A preview of FFF printed parts is illustrated in Fig. 2. Each construction element is characterized by a rectangle cross-section (*i.e., layer height by extrusion width*) with rounded corners and deposited along some extrusion paths. One misconception is that calibration cubes are needed to adjust the printhead positioning [47], the $P_{x_1y_2}$, $P_{x_2y_2}$, $\cdots$, $P_{x_iy_i}$ points highlighted in Fig. 2. In reality, they are used to adjust the number of steps/mm of extruded filament, to prevent under or over-extrusion [48]. The updated values are introduced in the printer firmware and depend on the used g-code flavor.

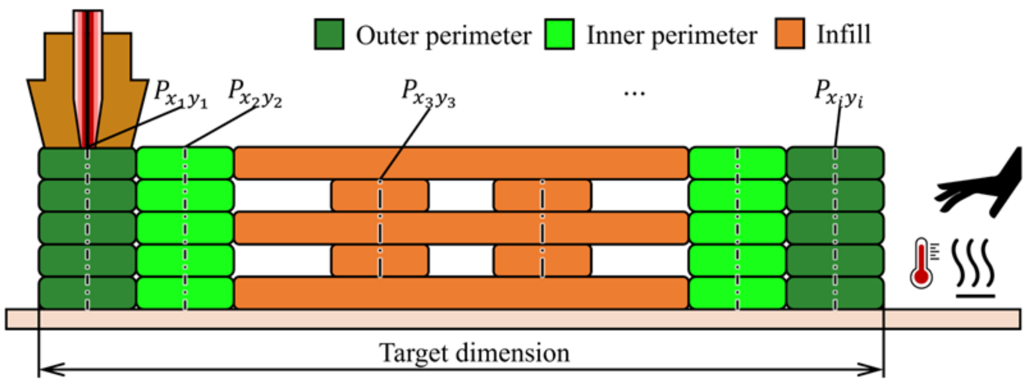
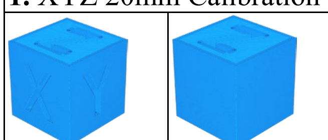
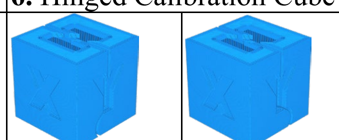
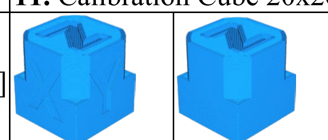
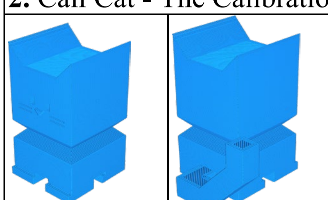
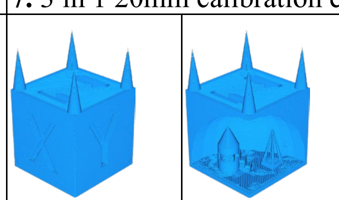
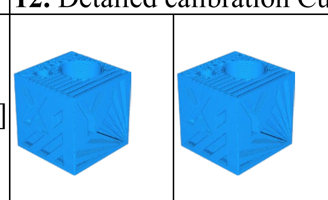
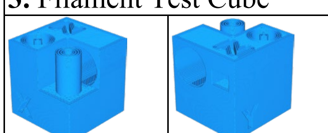
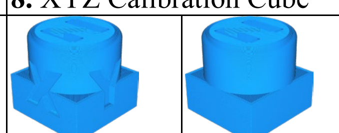
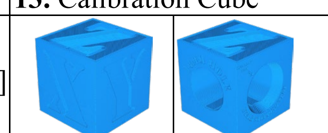
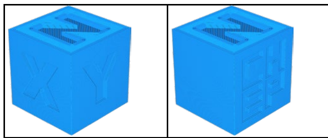
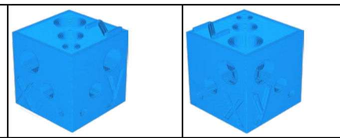
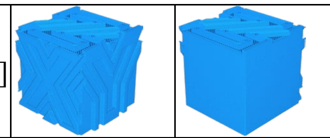
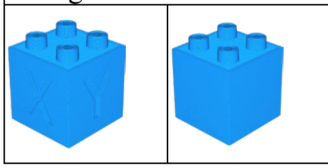
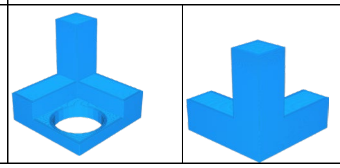
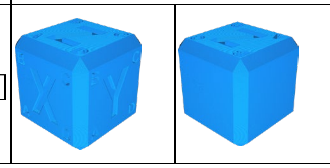


Fig. 2. Printhead positioning during the filament deposition.

Table 1. Different types of calibration cubes available on the internet. Print preview made using Ultimaker Cura 5.7.2.

1. XYZ 20mm Calibration Cube	**6.** Hinged Calibration Cube	**11.** Calibration Cube 20x20
 [22]	 [27]	 [32]
2. Cali Cat - The Calibration Cat	**7.** 3 in 1 20mm calibration cube	**12.** Detailed calibration Cube
 [23]	 [28]	 [33]
3. Filament Test Cube	**8.** XYZ Calibration Cube	**13.** Calibration Cube
 [24]	 [29]	 [34]
4. CHEP Calibration Cube	**9.** Test Cube for calibration	**14.** Calibration cube

	[25]		[30]		[35]
5. Lego Calibration Cube		**10.** Calibration Cube & Circle		**15.** XYZ 100mm calibration cube	
	[26]		[31]		[36]

Faulty measurements

On the one hand, the XYZ cubes within the above-described methodology are misleading as the resulting measured surfaces can have one or multiple defects, such as elephant foot or inconsistent extrusion (as shown in Fig. 3). This makes outer dimension measurement flawed.

On the other hand, the XYZ cubes are misleading because of their small scale. A 20 mm edge cube adjusts the printer's "dimensional accuracy". This 20 mm cube gauge is used as a reference to calibrate all printable dimensions in the build volume. A 0.2 mm measurement flaw on the 20 mm edge block is a 1% error. The same measurement error on a 100 mm edge block is 0.2%. In other words, the smaller the size of the measured gauge, the higher the error in case of a faulty measurement. For this reason, a high-resolution caliper or micrometer should be used for a small-size gauge.

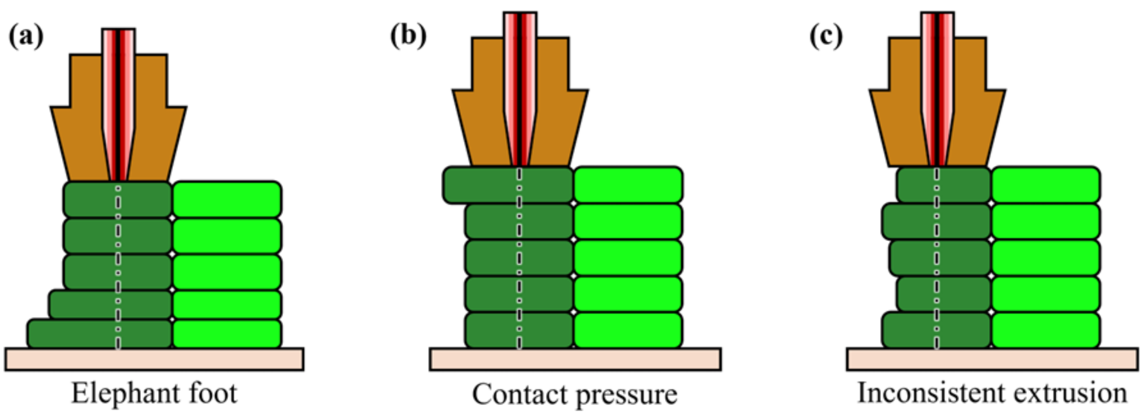


*Fig. 3. Possible causes of variation for resulting dimensions: (a) Elephant foot; (b) Nozzle contact overpressure; **(c)** Inconsistent material extrusion volume.*

When printing the XYZ cube, one or multiple defects can appear on the block's external surface, which impacts the resulting measurements of the parts. These printing defects include:

- ***Elephant foot***: the defect occurs when the gap between the nozzle and the build plate is too small [49] (i.e., smaller than the layer height). As a result, the molten material squeezes out and increases the part cross-section for the first few layers (i.e., 2-3 layers). Another cause for the elephant foot appearance is build plate over-heating, above the glass transition temperature of the printing polymer. Elephant footstep appearance can be reduced via slicing tool through the initial layer horizontal expansion setting or by creating a minimum 1x45° chamfer at the part's base;

- ***Nozzle contact overpressure:*** appears when the distance between the nozzle and the previously added layers is too small, and the material squishes out [50]. This effect is problematic when printing the outer shell because it affects the part's dimensional accuracy. The gap size between the nozzle and printed layers can influenced by material thermal expansion or over-extrusion of the previous layers or construction elements (i.e., inner perimeters, infill);

- Inconsistent extrusion: referees to the variation of the molten material flow. Inconsistent material filament diameter, and issues with the filament feeding mechanism, as the extruder melting rate is too small relative to the maximum volumetric speed are possible reasons for melt flow variation. Those issues must be solved by elimination;

- Ringing (Ghosting): this issue appears when the nozzle is unable to lay down material in a controlled manner leaving after images of a printed feature in the neighboring area [44, 52] (X and Y cube faces of Fig. 4). This effect appears only on a part's sides and caused by vibration due to over increasing the print speed (by not considering the extruder inertia), uneven belts tension or a bad frame design (i.e., not rigid enough). This issue is solvable by reducing print speed and acceleration;

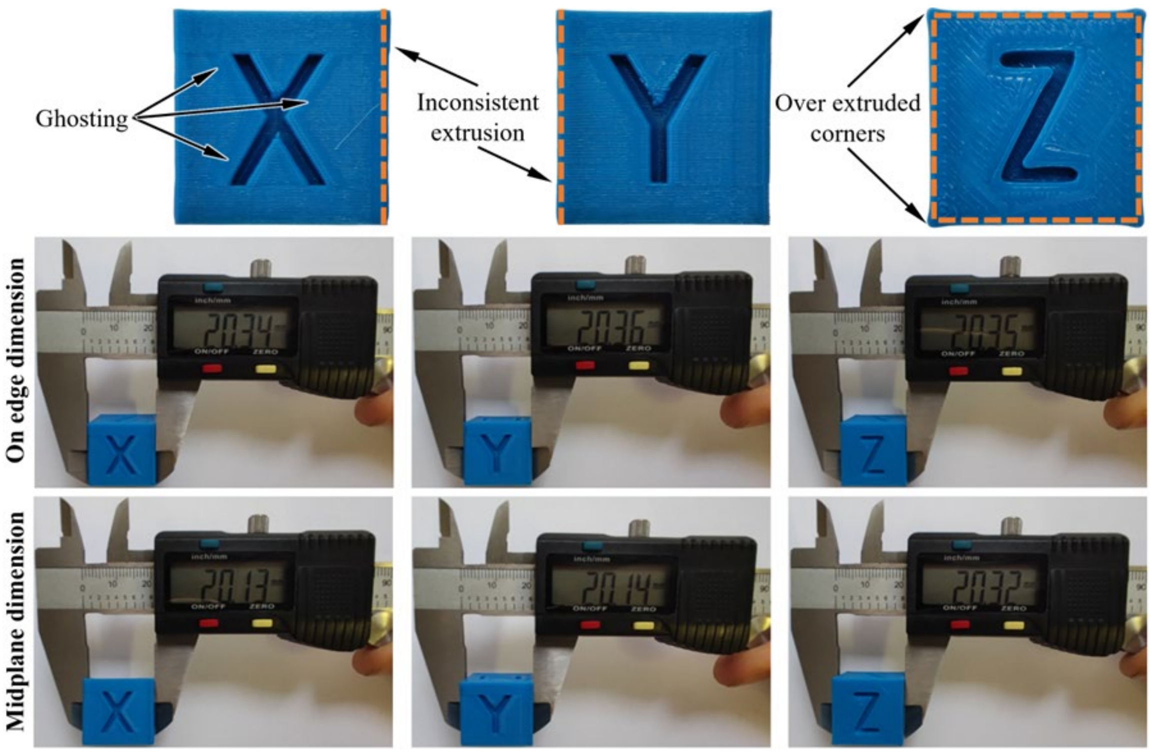


Fig. 4. Measured dimensions of an XYZ cube relative to analyzed sides and locations.

- Exposed seam: in FFF a seam refers to the start and endpoint of a perimeter [53, 54]. Depending on the material, nozzle size, and parametrization, the closing point of the outer shell can be more or less visible. In the case of a calibration cube, an over-exposed seam can increase the part size. The seam exposure is adjustable through the contour closing method, nozzle wipe distance, filament retraction, and material volume coasting;

- Over-extruded corners: Every Computer Numerically Controlled machine has a tool head whose movement is controlled through velocity and acceleration based on blank specifics and Material Removal Rate [55, 56]. Jerk Speed is specific for FFF equipment that controls the speed at which the printhead can travel through corners [54, 58]. Firstly, the Jerk Speed is set at a value greater than zero to avoid excessive material ooze when turning corners [54, 57, 58] (i.e., the over-extruded corners presented in the cube Z face of Fig. 4). Secondly, the jerk speed is always lower than the global printing speed to reduce vibrations (which lead to ghosting X and Y cube faces of Fig. 4). Over-extrusion corner formation can [54, 58] be avoided by decreasing the print speed or by creating filets (i.e., rounded corners) to replace the linear interpolation printhead movement with the circular interpolation one. For the printers introduced in the past four years, the over-extrusion corner issue was solved via input shaping, a control technique that creates a commanding signal that cancels vibrations.

Thermal contractions

During the deposition of the molten thermoplastic, the polymeric chains are rearranged along the extrusion paths. Subsequently, the melt is wetting adjacent extruded filament creating intimate contact. Simultaneously, the polymeric chains diffuse, creating interpenetrating networks (i.e., coils, entanglements, or crosslinks) promoting molecular adhesion [59, 60-62].

Thermodynamically speaking, when melted, the polymeric chains have a high degree of freedom, and a high entropy, which allows material reshaping. As the melt cools down, the polymer begins to crystallize. During this step, the polymeric chains start to lose their mobility (entropy decreases), and the chains try to occupy all available volume [62]. As a result, a volumetric decrease can occur due to thermal contractions (i.e., shrinkage), as illustrated in Fig. 5.

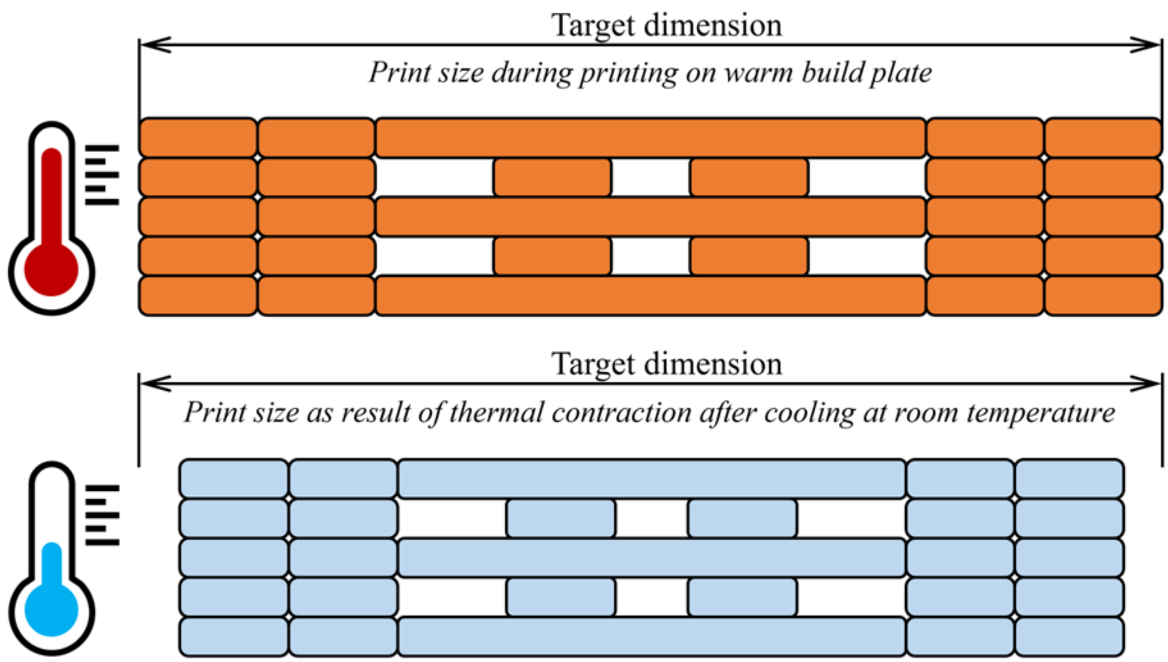


Fig. 5. Part shrinkage as a result of thermal contractions during cooling.

All polymeric materials are affected by thermal contractions. Engineering-grade polymers such as ABS, ASA, or PC require a heat chamber to reduce thermal stress and shrinkage caused by the thermal gradient resulting from the difference between printing temperature (e.g., 240-260°C for ABS) and environment (e.g., 25°C).

Skewed axes

A precisely designed and assembled cartesian 3D printer requires X, Y, and Z axes perpendicular to each other. Otherwise, the axles are skewed, and the resulting parts are deformed compared to the original design. When printing the calibration cube, instead of a part with a square cross-section (Fig. 6.a), the printer will make a part with a parallelogram-like cross-section (Fig. 6.b). In other words, the resulting parts will have diagonals of different sizes.

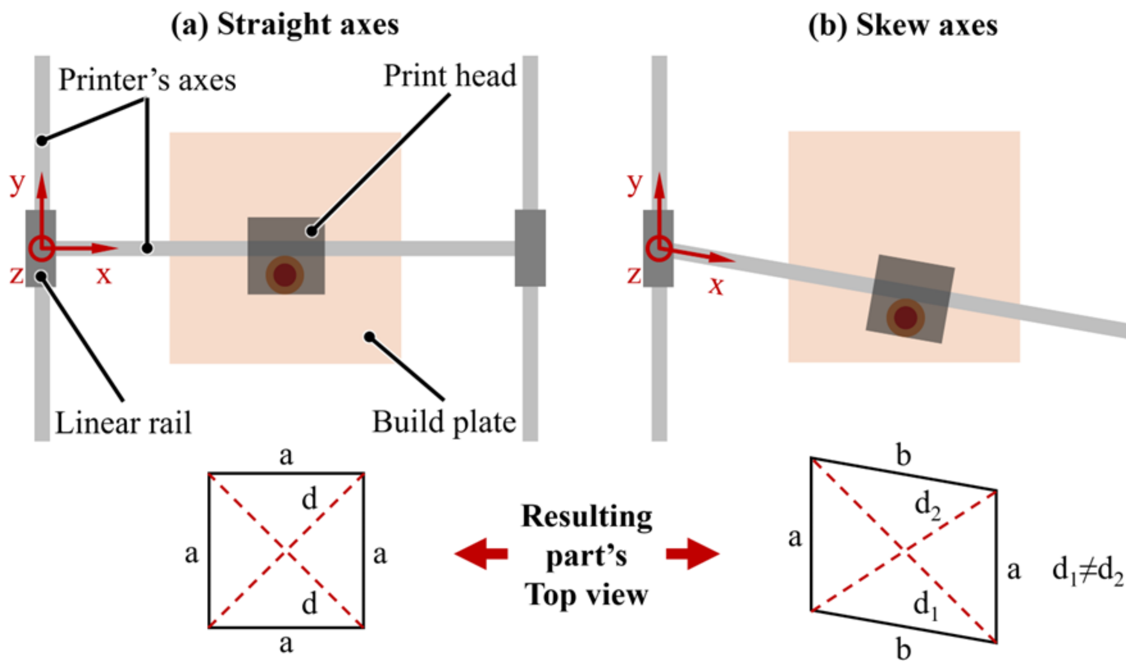


Fig. 6. Schematic of a 3D printer with (a) right-angled axles; and (b) skew axles.

On the one hand, the main limitation of the conventional calibration cube is its size. At 0.5-1° axles inline, it becomes hard to tell if the difference between the measured diagonals results from skewness or thermal contractions. On the other hand, the current cubic design with sharp edges leads to flawed measurements when using calipers. Chamfering the cube edges as shown in Design 15 from Table 1 reduces the measurement error.

When printing esthetical (i.e., non-functional) parts such as vases, figurines, or toys, the effect of skewness is hard or even impossible to notice. This statement is especially valid if the part has multiple details, textures, or multiple bodies. However, when switching to functional parts (e.g., cases, gears, brackets) mounted in a precise environment, axle skewness significantly influences the dimensional accuracy, particularly for larger parts (e.g., over 50 mm). Fig. 7 demonstrates a scenario illustrated for a 100 x 200 mm rectangle. Even at a relatively small axel incline of 0.5°, the resulting profile has a deviation of 1.745 mm. This way, a square profile will result in a parallelogram, a circular profile as an ellipse, and so on.

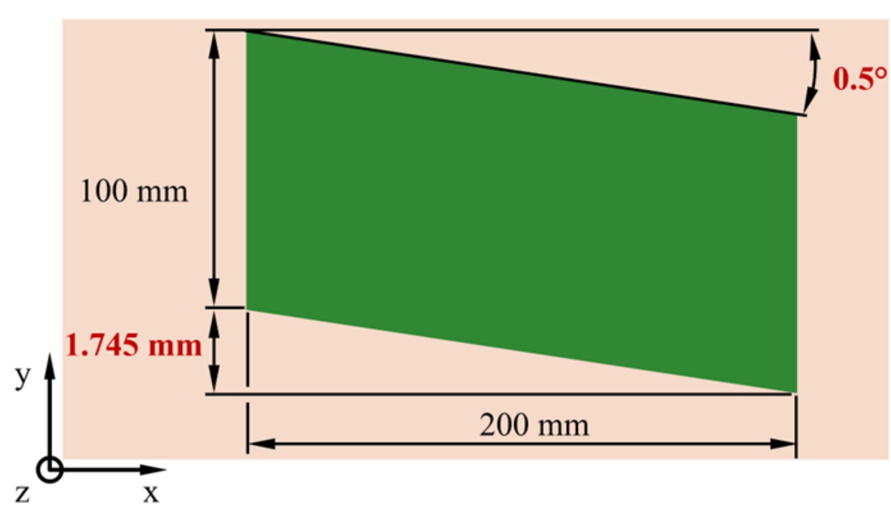


Fig. 7. Illustration of the effect of 0.5° skew axis over the resulting part cross-section profile.

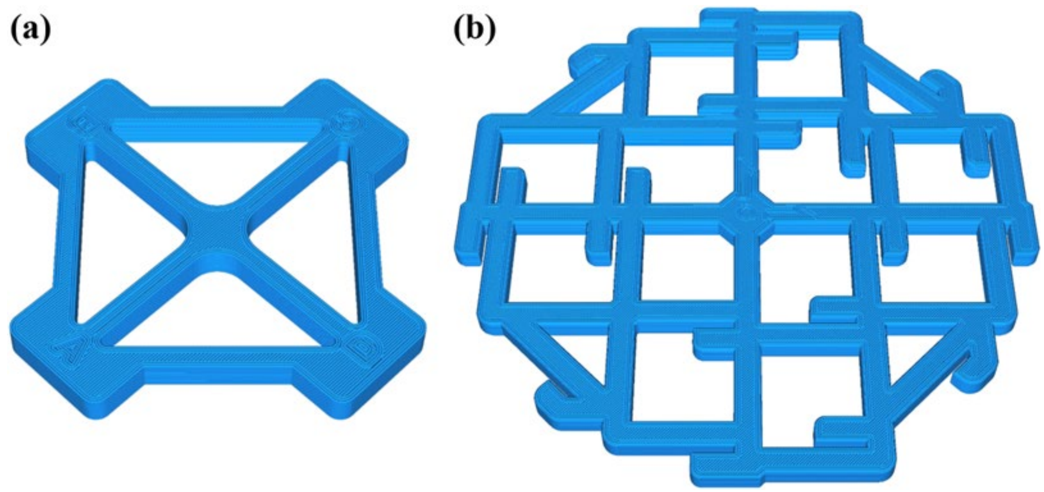


Fig. 8. Skew correction models: (a) cross-like model for diagonals measurement [63]; (b) Califlower Calibration Tool [64]. Print preview made using Ultimaker Cura 5.7.2.

Skew axle correction requires a larger model to reduce the measuring errors. Gauges with a nominal dimension of 50 mm are a good starting point in adjusting the printer's skewness. The 3D shared platforms provide reference models to correct the skew (Fig. 8.a). However, not all of them are equal regarding the provided information. An interesting approach is the Califlower (Fig.8.b) created by Adam Meadows from Vector 3D [64], which besides the skew correction, allows for dimensional error correction by measuring both external and internal features, together with scale factor calculation when printing with different materials (e.g., PLA, PETG, ABS). The results are more consistent as the Califlower has ten reference regions of 50 and 100 mm.

Conclusions

Nowadays, the FFF 3D printing market shows great equipment availability suitable for all categories of consumers, with prices ranging from a few hundred to thousands of USD. This diversity and the open-source character of the FFF printers lead to an increased, and sometimes overwhelming, number of approaches to improve the resulting 3D printed parts quality.

Dimensional accuracy is one of these quality benchmarks. Over the years, the accuracy problem was approached multiple times, but poorly understood due to the vast available information, and poor methodical documentation. Thus, the current paper proposes systematic documentation regarding misconceptions about printing accuracy calibration using the XYZ calibration cube.

The currently available XYZ cubes can be misleading when calibrating the printer's dimensional accuracy due to their small size, printing defects, and possible flawed measurements. Not least, the cubes are not suitable for tolerancing internal dimensions or evaluating axle skewness. The development of better gauge models can solve a part of those issues. The Califlower represents a good example in this direction.

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