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Investigating the Repeatability of 3D Printers Using a Multi-Sensor Measurement System

Borislav Georgiev
Technical University of Gabrovo
Gabrovo, Bulgaria
gborislav@gbg.bg

Tsanko Karadzhov
Technical University of Gabrovo
Gabrovo, Bulgaria
karadjov_st@abv.bg

***Abstract.* The repeatability of three-dimensional printers is very important because it determines how accurately a model can be reproduced. Repeatability depends on many factors such as printer quality, software settings, material quality, etc This paper evaluates the repeatability of an Openware desktop three dimensional printers in terms of the resulting standard deviation from a set of samples using a multi-sensor measuring machine. Details with optimal parameters were printed. Statistical analysis was performed on this set of samples. From the statistical analysis of the dimensional deviation data, the repeatability of the printer was analyzed.**

Keywords: Repeatability, Openware 3D printer, Statistical analysis.

I. INTRODUCTION

3D printing technology, also known as additive manufacturing (AM) has undergone significant development in recent decades, becoming a key element in many areas of manufacturing, design and engineering. The material layering method that underlies 3D printing allows the creation of complex and customized objects that are difficult or impossible with traditional manufacturing methods [1]. However, issues regarding the reproducibility, accuracy, quality, mechanical strength, resistance to external factors, production speed, and economic efficiency of printed parts remain the subject of intensive research and development [1].

Among the various 3D printing techniques, Fused Deposition Modeling (FDM) is one of the most widespread methods due to its cost-effectiveness and easy application [2]. FDM works by extruding molten plastic material through a nozzle to create an object layer by layer. However, the process faces challenges related to the control of accuracy and quality of the final products, which are critical for the widespread adoption of the technology in industry [3]. In this regard, one of the important aspects for the quality of the final product is the geometric accuracy of the details, including the accuracy of the linear dimensions, deviations from the form and mutual location of the surfaces and axes of the details, since these parameters are essential for their functionality and reliability.

The accuracy and reproducibility of FDM processes can be affected by numerous factors, including the type of materials used, printer settings, as well as environmental conditions [4]. A detailed study of these factors and their optimization is essential to improve the quality of 3D printed products and expand the application areas of the technology.

Against the background of these challenges, the current report focuses on investigating the reproducibility and accuracy of FDM 3D printers through a multi-sensor measurement system. The aim is to identify the key factors affecting the quality of the manufactured parts and to propose methods for their optimization. The results of the research can contribute through new knowledge and reliable criteria in the field of additive manufacturing, providing valuable guidance for professionals or specialists who are involved in the design and creation of new products, software, technologies or systems in the field of 3D printing.

II. MATERIALS AND METHODS

3D printers typically use a material in the form of a filament, most made from plastic, which is fed into the printer, melted, and overlaid onto the platform to form the object. This process is known for its extreme precision and ability to create objects with complex geometries, which is a significant advantage over traditional manufacturing methods. Figure 1 shows the most basic materials that are used for 3D printing.

3D printing technology finds application in a multitude of fields due to its versatility and efficiency. It features the ability to produce complex shapes with less material waste, making it a preferred method in a variety of industries, including medicine.

The quality of 3D printing depends on several factors, including the resolution of the printer, the quality of the

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slicing software used, the speed of printing, and the materials themselves. The importance of high-quality consumables, effective temperature control and regular equipment calibration are critical to achieving optimal results.

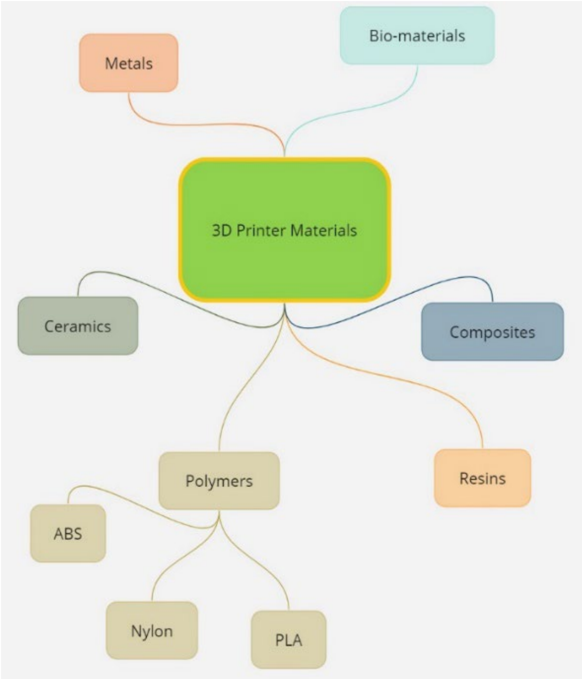

Fig. 1. 3D Printer Materials

A. Resolution

Nozzle resolution refers to the printer's ability to control the thickness of each deposited layer. Higher resolution usually results in better accuracy. Most FDM 3D printers have a nozzle resolution between 50 and 300 micrometers.

B. Positioning accuracy

This refers to the printer's ability to maintain a constant nozzle position during printing. Better positioning precision ensures layers are laid evenly and accurately, resulting in improved overall accuracy.

C. Material quality

The type of material used can also affect the accuracy of an FDM 3D printer. Some materials may be more susceptible to warping or warping during the cooling process, resulting in reduced accuracy. Using high-quality materials with low coefficients of thermal expansion can help improve accuracy.

D. Temperature and speed

The optimal printing temperature and speed can significantly affect the accuracy of the FDM 3D printer. Printing at too high a temperature can cause material to bleed or warp, while printing at too low a temperature can result in poor adhesion between layers. Likewise, printing at too high a speed can result in insufficient bonding between layers, resulting in reduced accuracy.

E. Print Settings

Printer settings such as layer height, fill density, and fill pattern can also affect accuracy. Optimizing these settings for the specific model and material can help achieve better accuracy.

F. Temperature Control

Effective temperature control is critical to maintaining consistent material properties during printing. Insufficient temperature control can lead to problems such as material leakage, poor layer bonding and reduced accuracy.

G. Calibration and Maintenance

Regular calibration and maintenance of the FDM 3D printer can help ensure its accuracy over time [5]. This includes checking and replacing worn parts, cleaning the nozzles, and performing regular calibration tests to verify the printer's performance.

In general, the accuracy of FDM 3D printers can be affected by various factors, including print setup, material quality, and machine performance. By optimizing these factors, it is possible to achieve a high degree of accuracy with FDM 3D printers.

PLA (polylactic acid) is a biodegradable thermoplastic material that is often used in 3D printing due to its relatively low cost, ease of processing, and environmental compatibility. The coefficient of thermal expansion of PLA is approximately 40-60 x 10^{-6} mm/mK. This value may vary slightly depending on the specific formulation and environmental conditions.

The coefficient of thermal expansion (CTE) is a measure of how much a material expands or contracts when the temperature changes. In the case of PLA, it shows that the material tends to expand or contract uniformly in all directions when the temperature changes. This property is important for 3D printing as it helps ensure that printed objects retain their shape when exposed to changing temperatures. However, it is important to note that the coefficient of thermal expansion of PLA is relatively high compared to other materials used in 3D printing, such as ABS (acrylonitrile butadiene styrene) or PETG (polyethylene terephthalate glycol). This means that objects printed using PLA may be more prone to warping or warping at high temperatures or significant temperature fluctuations. To minimize this risk, it is ESSENTIAL TO FOLLOW THE RECOMMENDED OPERATING temperatures for PLA and avoid exposing the printed objects to extreme temperature changes.

III. Results and Discussion

After checking and calibrating the printer, 35 pieces of solid cubes (fig.2) with dimensions of 20 mm on each side were printed. The slicing application used is CURA (Cura is an open source slicing application for 3D printers), with 25% material fill. The time for printing the details is 1 hour and 08 minutes. The material required for the process is PLA with a working temperature of 190-230 ℃ with a diameter of 1.75mm ±0.05mm and the cost for each part at 25% filling is 6 grams. The ambient temperature during printing is 20-21℃, and after several experiments, the most optimal temperature setting for the printer plate was calculated to be 70℃ and for the nozzle 220℃. Print speed is 20 mm/s, layer height is 0.2 mm and wall thickness is 1.5 mm.

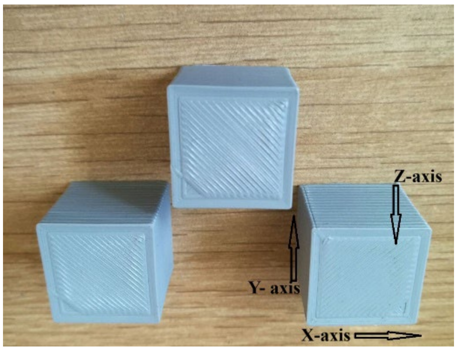

Fig. 2. Magnetization as a function of applied field.

The accuracy of the printer along the x and y axes is ± 0.5% with a lower limit of ± 0.5 mm. On the z-axis it is ± 0.5% with a lower limit of ± 0.15 mm.

The measurement of the printed parts was done with OPTIV M 4.4.3 multisensor and optical coordinate measuring machines (CMM), which provides a measurement accuracy of ±0.025 mm (0.001 inch) or better, depending on the specific configuration and application [6], [7].

The printed solid cubes were measured on a CMM three times to minimize random measurement error. Deviations observed along the three sides in printed parts were recorded. Descriptive statistics were calculated from these readings (Table 1, Table 2). In these descriptive statistics, indicates a measure of central tendency and a measure of dispersion.

Cp and Cpk are statistics that are used to evaluate the ability of a process to meet specifications. Cp (Process Capability Index) is calculated when the process is under statistical control. This usually refers to a mature process that has been around for some time. This metric is based on the process sigma value, which is determined by movement, range, or sigma control charts. The purpose of Cp is to determine the ability of the process to approach the upper and lower specification limits. Cpk (Process Capability Index with Process Centered) is also calculated when the process is under statistical control. This metric takes into account both the capability of the process and its location. The purpose of Cpk is to determine the ability of the process to meet specifications while also considering the process average.

When Cp and Cpk are close in value, the process average is near the middle of the specification limits. When Cp is greater than Cpk, the average value is closer to one of the specification limits (Table 1).

Once we understand our process, we can make a good decision about how to prioritize our process improvement efforts.

On the X axis, the process is not capable, not centered, on the Y axis, the process is capable, centered and on the Z axis, the process is not capable, centered (fig.3,4 and 5).

"Sk" measures the asymmetry of a data distribution. It determines whether the probability function is skewed to the right (positive skewness) or to the left (negative skewness). If the skewness is zero, the distribution is symmetric. Positive skewness indicates a right tail (tail of values to the high side), while negative skewness indicates a left tail (tail of values to the low side see Sk on the Z axis). Skewness values typically range from -2 to 2.

TABLE 1 SIZE DEVIATION ALONG THE X, Y, AND Z AXES

	X-axis	Y-axis	Z-axis
Arithmetic mean	20.22231	20.00703	19.97286
St.deviation	0.16254	0.17668	0.11523
Range	0.639	0.698	0.428
Min.value	20.004	19.706	19.741
Max.value	20.643	20.404	20.169
USL	0.5	0.5	0.15
LSL	-0.5	-0.5	-0.15
Sk	0.49032	-0.04935	-0.23290
Ku	-0.41692	-0.83096	-1.01929
Cp	1.02541	0.94334	0.43391
Cpk	0.56949	0.93008	0.35539
Total rejected parts	1	0	6
Reject USL	1	0	1
Reject LSL	0	0	5
Reject %	2.85714	0	17.14286
Reject % USL	2.85714	0	2.85714
Reject % LSL	0	0	14.28571

"Ku" measures the curvature or flatness of the data distribution. High kurtosis (positive kurtosis) indicates a sharper peak (peak) in the center of the distribution, suggesting that most data points are concentrated around the mean. Conversely, low kurtosis (negative kurtosis) shows a flatter peak, meaning there are more values away from the mean. Curtrose values usually range from 0 to 10.

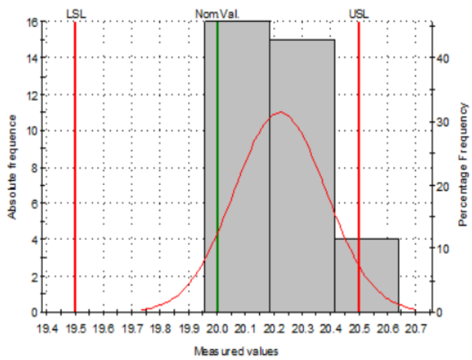

Fig. 3. X-axis histo chart.

The standard deviation shows how much variation there is in the values of the random variable. When the standard deviation is low, the values are close to the population mean (expected value). When the standard deviation is high, the values are spread over a wider range. The standard deviation is calculated as the square root of the variance of the random variable.

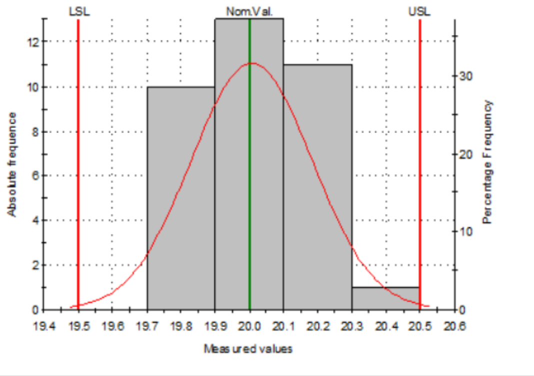

Fig. 4. Y-axis histo chart.

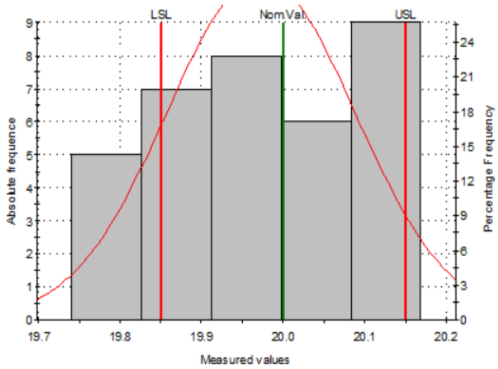

Fig. 5. Z-axis histo chart.

The standard deviation is expressed in the same unit as the data, making it useful for comparison and analysis. So, the standard deviation helps us understand how much variation there is in the values of the random variable and how far they are from the mean. In conclusion, the standard deviation is an important tool for data analysis and helps to understand the distribution and mixing of values in our measurements. Knowledge of the distribution of data around the mean is essential in statistics and data analysis.

Parallelism tolerance in 3D printing refers to the maximum distance that layers can deviate from each other in terms of parallelism. This is an important factor in ensuring the quality and accuracy of the printed object.

In a typical 3D printer, tolerances from parallelism typically range from 0.05mm to 0.1mm. This value can be affected by various factors such as material quality, printing temperature, printing speed and machine design. Some high-quality 3D printers can even achieve deviations below 0.05mm.

It is important to note that the tolerance for parallelism does not necessarily mean that all layers will be perfectly equal. In reality, this is unlikely due to the nature of the 3D printing process. In this case (see table 2) the deviations from parallelism of the entire detail are above the permissible values. However, keeping the parallelism tolerance within the specified range ensures that the differences between the layers are minimal and will not significantly affect the overall quality and appearance of the final product.

TABLE 2 PARALLELISM DEVIATION ALONG THE X, Y, AND Z AXES

	X-axis	Y-axis	Z-axis
Arithmetic mean	0.811154	1.15246	0.44471
St.deviation	0.19926	0.25941	0.14485
Range	0.696	0.988	0.512
Min.value	0.52000	0.893	0.209
Max.value	1.21600	1.88100	0.721
USL	0.1	0.1	0.1
LSL	0	0	0
Sk	0.26886	1.23894	0.20572
Ku	-0.79976	0.80536	-1.00817
Cp	0.08364	0.06425	0.11506
Cpk	-1.19029	-1.35237	-0.79326
Total rejected parts	35	35	35
Reject USL	35	35	35
Reject LSL	0	0	0
Reject %	100	100	100
Reject % USL	100	100	100
Reject % LSL	0	0	0

From the measurements made, we can conclude that the printer used in this experiment has significant deviations from the parameters provided by the FDM 3D printing technology. However, several factors can affect repeatability:

The use of high-quality materials with consistent characteristics is essential to maintain repeatability. Changes in material properties such as viscosity, melting point and color can result in variations in the final product. Regular printer maintenance, including nozzle cleaning, replacement of worn parts and system calibration, can help maintain accuracy and repeatability. It is necessary to use the recommended media and printer settings provided by the manufacturer. This includes optimum nozzle temperature, bed temperature, print speed and layer height. Implementing quality control processes, such as inspecting the model before printing, monitoring the printing process, and measuring the finished product, can help identify and fix problems that affect repeatability. Ensuring that operators are well trained and understand the 3D printing process as well as potential sources of error can improve overall repeatability. Although FDM 3D printers generally have good repeatability, it is important to continuously monitor and optimize the process to maintain consistent print quality. With the right practices and maintenance, it is possible to achieve a high degree of repeatability with FDM 3D printers.

IV. CONCLUSION

This report presents a study that focuses on the repeatability and accuracy of 3D printers using Fused Deposition Modelling (FDM) technology. By analysing the influence of various factors such as printer resolution, material quality, print settings, temperature control and regular calibration, the study highlights the complexity of the 3D printing process and the importance of optimization applied in practical applications to achieve a high degree of accuracy and quality of printed objects.

The results of measurements carried out using the multi-sensor three-coordinate measuring machine OPTIV M 4.4.3 provide valuable data about the accuracy of the printer and the printed parts. Statistical analysis, including the use of Cp and Cpk metrics, as well as skewness and kurtosis estimates, further demonstrates the ability of the process to produce quality parts within set specifications and to provide reproducibility of results under various manufacturing conditions.

It is important to note that although 3D printing technology allows for significant flexibility and innovation in design and manufacturing, the accuracy and repeatability of printed objects are critical to their practical applicability. This research highlights the fact that achieving high quality and accuracy requires careful control of multiple factors, including, but not limited to, the quality of materials used, printer specifications, and printing conditions.

Finally, the presented conclusions and results serve as a basis for future research, with a view to the continuous improvement of 3D printing technologies and the expansion of their applications in various fields. Effectively addressing the challenges of accuracy and repeatability will help establish 3D printing as a key technology for the future of manufacturing.

In the next study, we plan to examine in more details the influence of some of parameters on the accuracy of 3D printers.

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