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Development of a Low Cost 3-D Printer

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Abstract - The current study outlines the design, development, and experiment-based evaluation of a low-cost fused deposition modeling (FDM) 3D printer intended for education and rapid prototyping applications. The printer comprises a Cartesian motion system, a mechanical frame, a filament extrusion mechanism, a heated build platform, and an Arduino Mega 2560-based control system equipped with RAMPS 1.4 electronics, A4988 stepper drivers, and Marlin firmware. Modeling and G-code generation were conducted with Bambu Studio. The developed prototype is 520 × 505 × 440 mm in size and allows to get a nominal build volume of 200 × 200 × 200 mm. Performance was estimated on the basis of five nominal 20 mm calibration cubes, filament feeding calibration, temperature measurements, visual evaluation of print quality, and printing time and material consumption measurement. The average measured dimensions of the calibration cubes are 19.96 mm, 19.98 mm, and 20.30 mm in the X, Y, and Z directions, correspondingly. Filament feeding at the commanded 50 mm resulted in 50.6 mm measured feed, which corresponds to the deviation of 1.2%. The measured temperature ranges were 55.30–55.59 °C for the heated bed and 200.19–219.21 °C for the hot end. Printing of the calibration cube took 78 minutes and required 3.43 g of PLA filament. Visual evaluation showed good bed adhesion and warping resistance of the print but also revealed some defects that require further calibration.

Key Words **:** Low-Cost 3D Printer, Fused Deposition Modeling, Dimensional Accuracy, Filament Calibration, Print Quality, Rapid Prototyping.

1. INTRODUCTION

The additive manufacturing (AM) is a fabrication approach based on producing parts layer-by-layer according to the information taken from their digital models. In particular, fused deposition modeling (FDM) is one of the widely used approaches of additive manufacturing that involves building components by layer-by-layer depositing the thermoplastic material [1], [2]. The affordable price of FDM printers and availability of a digital work flow make it suitable for prototyping and educational applications.

In spite of such features as affordability, a 3D printer cannot be evaluated only by its cost but should be assessed for its capability to produce the objects with sufficient dimensional accuracy and surface quality. The factors affecting this performance may include a calibration of the motion system, feeding consistency, thermal management, and platform adhesion which could affect the results of printing [1]. For this reason, the evaluation of a low cost printer should be done through measurements and identification of printing defects.

In this project, the design, construction, and experimental evaluation of a low-cost FDM Cartesian 3D printer will be presented. The prototype of this printer includes a mechanical structure, a motion system controlled by stepper motors, a thermoplastic extruder, and a control system with an Arduino Mega 2560 microcontroller, RAMPS 1.4 electronics, A4988 stepper drivers, and Marlin firmware [3]-[6]. Slicing and G-code were made using the Bambu Studio software [8].

Evaluation of this 3D printer was performed based on five 20-mm calibration cubes, filament feed rate test, measured hot end and heated bed temperatures, qualitative printing test results, printing time, and material consumption values. The aim of evaluation of this printer was to define the performance baseline of this machine and find out the parameters to be further calibrated.

2. LITERATURE REVIEW

Fused deposition modeling (FDM) has been widely researched because of the dependence of dimensional accuracy and surface quality of printed parts on the machine setup and process parameters. Previous studies have considered the performance of open-source printers, dimensional deviations, and ways of increasing the accuracy of printed parts.

Minetola et al. analyzed the dimensional performance of an open-source FDM printer by comparing printed benchmark parts to those made by an industrial system. The findings of this study show that experimental analysis and parameter optimization are effective in improving the dimensional performance of open-source printers [11] ; thus, there is a need to test a low-cost printer using measurable dimensional benchmarks and not just based on successful printing.

Cappellini et al. analyzed the effect of layer thickness, printing speed, and the number of contours on geometric deviations and printing time. The findings of the experiments conducted by Cappellini et al. show that these parameters affect dimensional deviations and printing time, showing the importance of choosing the right printing parameters for a particular application [12] . Also, Abas et al. analyzed the

effect of parameters like layer height, infill density, printing speed, nozzle temperature, and build orientation on dimensional deviation and found that different parameters affect different dimensional properties [13] .

Research has also been done on dimensional errors in low-cost FDM systems used for practical applications. Rendón-Medina et al. tested a low-cost printer for making anatomical models and got a mean absolute dimensional deviation of 0.65 mm and relative deviation of 1.96% [14] . These results show the reasons why printer performance must be tested for the specific application and dimensions of the printed part.

Overall, from the reviewed literature, it can be seen that dimensional accuracy is affected by machine characteristics and printing conditions. However, it is difficult to make assumptions about the performance of one printer on another because of the differences in the mechanical structure, calibration settings, and conditions of operation. Thus, in this study, the performance of the fabricated low-cost Cartesian FDM printer will be analyzed using calibration cube measurements, filament feed calibration, temperature observations, and print quality evaluation.

3. DESIGN AND METHODOLOGY

A. System Design and Configuration

A cost-effective Cartesian fused deposition modeling (FDM) 3D printer concept and design was developed with educational and prototyping applications in mind. The system features a mechanical base, a Cartesian motion stage, a filament extruder module, a heated build platform, and an electronic control module. Dimensions are 520 × 505 × 440 mm, with a nominal build volume of 200 × 200 × 200 mm.

The control module uses an Arduino Mega 2560 development board with the RAMPS 1.4 electronics including A4988 stepper motor drivers and Marlin firmware. The axes' mechanical endstops are used for homing, the firmware supports thermal protection and EEPROM memory. A 1.75 mm extruder setup was selected. Preparation of the 3D model and generation of the G-code was conducted using Bambu Studio (version 2.8.2.61).

Table I presents the main specifications and control elements of the designed 3D printer.

Table - 1 : Principal Specifications of the Developed Low-Cost FDM 3D Printer

PARAMETER	SPECIFICATION
Printing technology	FDM
Motion architecture	Cartesian
Overall dimensions	520 × 505 × 440 mm
Nominal build volume	200 × 200 × 200 mm
Controller	Arduino Mega 2560
Control electronics	RAMPS 1.4
Stepper drivers	A4988
Firmware	Marlin
Filament diameter	1.75 mm
Slicing software	Bambu Studio 2.8.2.61

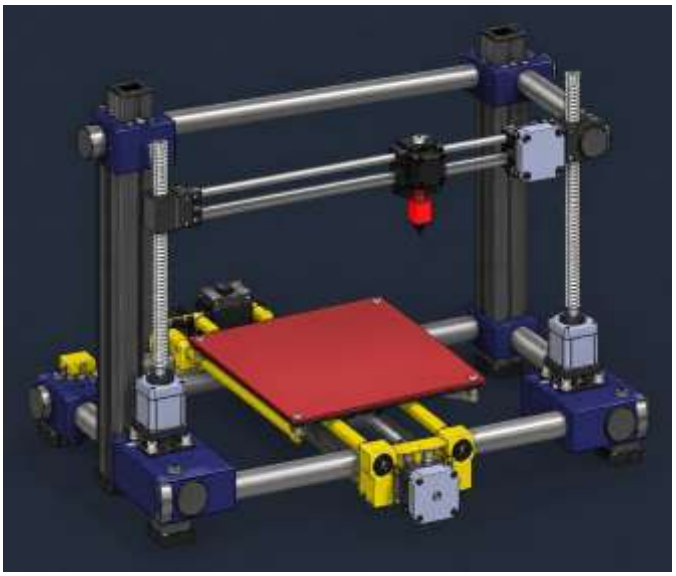


Fig - 1 : CAD model and structural arrangement of the developed Cartesian FDM 3D printer

B. Fabrication and Assembly

The printer frame and mechanical components were assembled to support the motion system, extrusion system, and build platform. The stepper motors, mechanical endstops, and heaters are connected to the controller module. The firmware is set up according to the nominal build volume and hardware. Prior to experimental tests, the printer was operated to check its basic functionality (motion, extrusion, build platform heating and temperature monitoring).

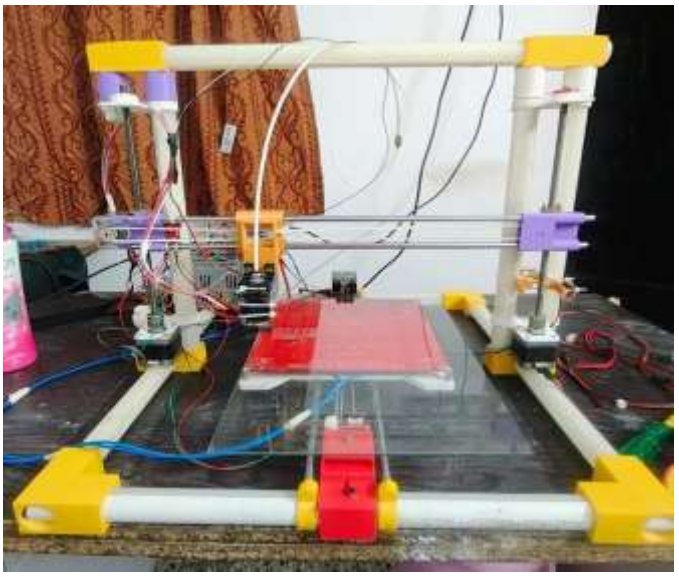


Fig - 2 : Fabricated and assembled prototype of the developed low-cost FDM 3D printer.

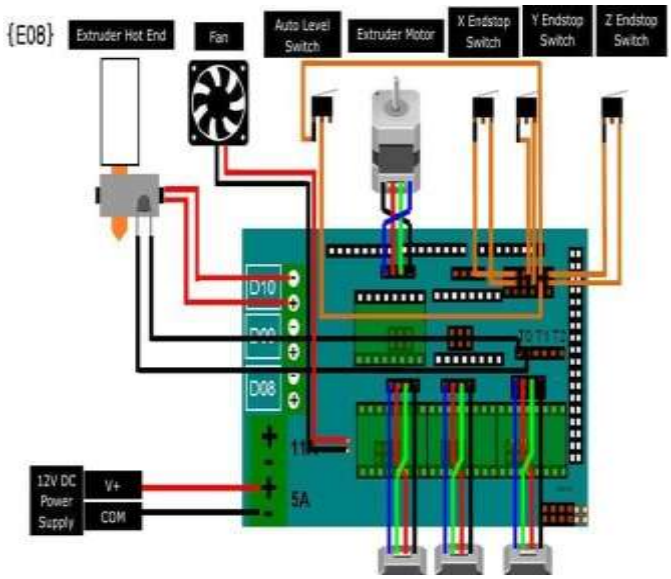


Fig - 3 : Electrical interconnection of the controller, stepper drivers, endstops, and heating components.

C. *Experimental Procedure*

Testing involved conducting of dimensional measurement, filament feed rate measurement, temperature recording, visual inspection and documentation of printing time and material usage.

1) Dimensional accuracy : Five calibration cubes with a nominal dimension of 20 × 20 × 20 mm were printed. For each specimen, the dimensions were measured in X, Y, and Z directions. The average dimension in each direction was computed and compared against the nominal 20 mm dimension.

   The signed deviation in dimension was defined as:

$$D = \bar{} - _{oia}$$

   where $\bar{}$ is the average measured dimension and $_{oia}$ is the nominal dimension. Also, the mean absolute error and mean absolute percentage error in dimension were computed to represent the dimensionality deviation magnitude.

2) Filament feed rate calibration: The commanded filament feed of 50 mm was compared to the measured one. Deviation in absolute and percentage was calculated to see the correspondence between the commanded and real filament movement.

3) Temperature readings: Minimum and maximum recorded temperature values for the hot-end and heated bed were identified. The range (maximum minus minimum) was calculated for each of the components.

   These ranges were considered indicative of observed temperature variation but not a thorough analysis of the thermal stability.

4) Visual quality inspection: Print specimens were inspected for presence of stringing/oozing, warping/corner lifting, adhesion/visible gaps between layers, surface defects such as ringing, adhesion to the bed and any other defects. Each criterion was marked pass or fail depending on the quality of the inspected specimen.

5) Printing duration and material usage: Printing time and the amount of material consumed were documented. The latter was taken as the recorded value; if obtained as an estimation in the slicer, then it must be stated clearly in the final manuscript.

4. RESULTS AND DISCUSSION

A. *Dimensional Accuracy of Printed Components*

Evaluation of dimensional accuracy was done by manufacturing five calibration cubes having nominal dimensions of 20×20×20 mm. Dimensions along X, Y, and Z axes for each specimen were measured and compared with nominal dimension.

Table II provides details of measured values. Average dimensions for X, Y, and Z axes were 19.96 mm, 19.98 mm, and 20.30 mm, respectively. Signed average deviation of the measured values from the nominal value of 20 mm were −0.04 mm (X), −0.02 mm (Y), and +0.30 mm (Z).

Average dimensions for X and Y axes were similar to nominal values, while that for the Z axis exceeded nominal dimensions by 0.30 mm. Mean absolute percentage errors were 1.00% (X), 0.70% (Y), and 1.50% (Z). Amongst all the three axes, minimum mean absolute error occurred on the Y axis, while maximum mean absolute error occurred on the Z axis.

Table - 2 : Dimensional Measurements of the Five Calibration Cubes and Summary of Dimensional Deviations

SPECIMEN / METRIC	X-AXIS (mm)	Y-AXIS (mm)	Z-AXIS (mm)
Print 1	19.9	19.8	20.2
Print 2	20.3	20.1	20.5
Print 3	19.7	20.0	20.4
Print 4	20.1	19.8	20.3
Print 5	19.8	20.2	20.1
Mean measured dimension (mm)	19.96	19.98	20.30
Mean signed deviation (mm)	−0.04	−0.02	+0.30
Mean absolute error (mm)	0.20	0.14	0.30
Mean absolute percentage error (%)	1.00	0.70	1.50

Note : *The nominal dimension was 20 mm in all the three axes. The mean absolute error refers to the average of the absolute difference of each measured dimension from the nominal dimension. The mean absolute percent error is calculated on the basis of the nominal dimension.*

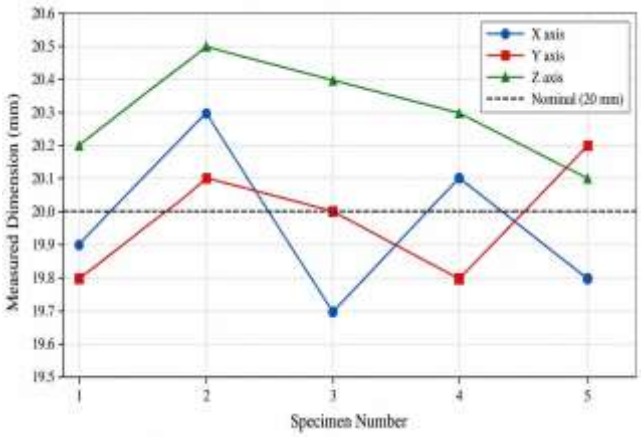


Fig - 4 : Dimensional measurements of five calibration-cube specimens along the X, Y, and Z axes, compared with the nominal dimension of 20 mm.

B. Filament Feed Calibration

Calibration of Filament-feed was done through the process of generating a displacement of 50 mm of the filament and comparing it with the measured feed distance. The measured feed distance obtained was 50.6 mm, resulting in an absolute error of 0.6 mm and a percentage error of 1.2%.

The measured feed distance was larger than the commanded feed distance, showing a small difference between the commanded feed distance and the measured feed distance. This shows that further calibration would be helpful. However, since only one test was taken into account, this does not prove repeatability.

Table - 3 : Filament-Feed Calibration Result

PARAMETER	VALUE
Commanded feed length (mm)	50.0
Measured feed length (mm)	50.6
Absolute deviation (mm)	0.6
Percentage deviation (%)	1.2

Note : *The percentage deviation is calculated based on the feed length commanded.*

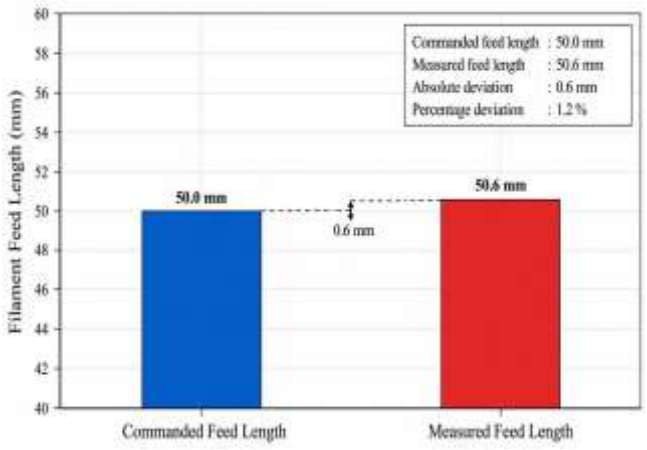


Fig - 5 : Comparison of commanded and measured filament-feed lengths during calibration.

C. Temperature Observations

The data recorded from the temperatures of the hotend and heated build platform was subjected to analysis. The heated bed exhibited a minimum temperature of 55.30 °C and maximum temperature of 55.59 °C, indicating a temperature range of 0.29 °C. The hotend demonstrated a minimum temperature of 200.19 °C and maximum temperature of 219.21 °C, implying that the temperature range is 19.02 °C.

The temperatures on the heated-bed exhibited a smaller temperature range compared to the temperatures of the hotend. However, the available minimum and maximum temperatures cannot be used to find the reasons behind the recorded variation or confirm thermal stability throughout the printing cycle.

Table - 4 : Summary of Recorded Hotend and Heated-Bed Temperatures

Component	Minimum (°C)	Maximum (°C)	Observed range (°C)
Heated bed	55.30	55.59	0.29
Hotend	200.19	219.21	19.02

Note : *The temperature span is calculated as the difference between the highest recorded temperature and the lowest recorded temperature. This is based on observations alone and should not be taken as a full evaluation of thermal stability.*

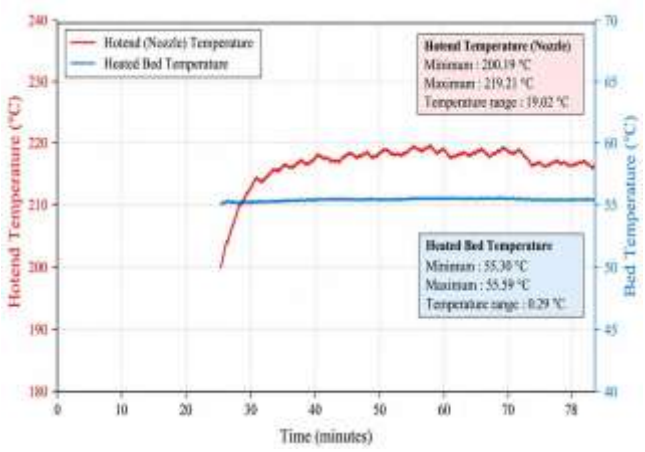


Fig - 6 : Recorded hotend and heated-bed temperatures over the observed printing interval.

D. Visual Assessment of Print Quality

The printed samples were visually examined for the most prevalent FDM printing defects. The evaluation considered the presence of stringing and oozing, warping, layer bonding, surface defects, bed adhesion, and any other visible defects.

The findings revealed good bed adhesion and no major warping or corner lifting. However, the presence of stringing and oozing, visible gaps or poor layer bonding, surface defects or ringing, and other visible defects was observed. This implies that the successful printing of the calibration samples did not solve all the print quality problems.

Table - 5 : Visual Print-Quality Assessment of the Calibration Specimens

INSPECTION CRITERION	OBSERVATION	RESULT
Stringing and oozing	Unwanted strings or oozing observed	Fail
Warping or corner lifting	No significant warping or corner lifting observed	Pass
Layer adhesion and visible gaps	Visible gaps or poor bonding observed	Fail
Surface finish and ringing	Surface irregularities or ringing observed	Fail
Bed adhesion	Satisfactory bed adhesion observed	Pass
Other visible defects	Additional visible defects observed	Fail

Note : *Pass/Fail categorizations come from the actual visual inspection that is done. They are qualitative and not quantitative measures of surface finish.*

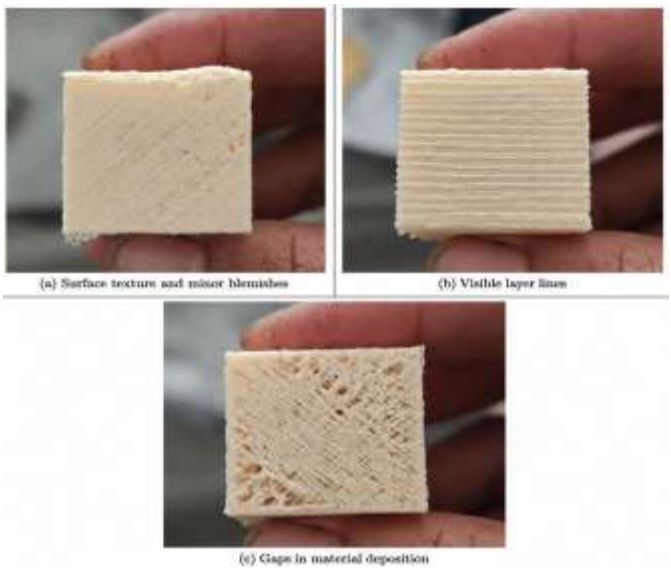


Fig - 7 : Observed surface defects in the printed calibration specimen.

E. *Printing Duration and Material Consumption*

The calibration cube print was recorded as having taken 78 minutes, with material usage being 3.43 g. This data provides additional information on the timing and material usage related to the test print.

This time measurement applies only to this particular test print and not others, and this is a point to be careful about when referring to the results. The same is true for the material usage measurement, which may be referred to as a slicer estimate or experimental mass in the paper's final version.

Table - 6 : Recorded Printing Duration and Material Consumption

PARAMETER	RECORDED VALUE
Calibration-cube nominal dimensions	20 × 20 × 20 mm
Printing duration	78 min
Filament consumption	3.43 g

F. *Overall Discussion*

The obtained experimental results show the initial performance parameters of the designed low-cost Cartesian FDM printer. The mean dimension measurements are close to the nominal 20 mm size of the test specimens along the X and Y axes, while there is a greater positive deviation along the Z axis. Filament feeding shows a 1.2% deviation from the desired feed length.

The temperature measurements show different ranges for the heated bed and hotend, but the information provided is not enough to determine the complete thermal stability of the system. From visual inspection, it is clear that there is good bed adhesion and no significant warping. There are also some issues with stringing, layer bonding, and surface finish.

Overall, these results prove that the designed printer can produce the test specimens, but further calibrations and testing are needed to improve its performance.

5. CONCLUSION AND FUTURE WORK

A cheap Cartesian FDM 3D printer has been developed, fabricated and tested experimentally for educational and rapid prototyping purposes. The resulting design provides a nominal build volume of 200 × 200 × 200 mm and features a control unit based on an Arduino Mega 2560, RAMPS 1.4 electronics, A4988 stepper motor drivers and the Marlin firmware.

The dimensional calibration of five cubes nominally sized as 20 × 20 × 20 mm resulted in the following means of 19.96 mm, 19.98 mm and 20.30 mm along the X, Y and Z axes, respectively. The outcomes show lower mean dimensional errors on the X- and Y-axes and greater positive error on the Z-axis. As for the filament-feed calibration test, there was observed a feed value of 50.6 mm for the length command of 50 mm, thus the deviation was 1.2%. The results of temperature monitoring reveal a range of 0.29 °C for the heated bed and 19.02 °C for the hotend among available measurements. The surface examination revealed good bed adherence without major warping, although with stringing, voids and surface imperfections.

This set of results sets an initial experimental baseline for the developed 3D printer performance. Future research needs to focus on axis calibration, consistency of extrusion and improving print quality. More calibration runs and documenting measurement uncertainty, temperature readings with timestamps, surface quality would provide a more thorough system testing.

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