Additive Manufacturing 22 (2018) 256–264

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Full Length Article

A challenge for enhancing the dimensional accuracy of a low-cost 3D printer by means of self-replicated parts

Minetola P.*, Galati M.

Politecnico di Torino, Dept. Management and Production Engineering (DIGEP), Corso Duca degli Abruzzi 24, 10129, Torino, Italy

ARTICLE INFO

Keywords:
3D printing
FDM
Benchmarking
Dimensional accuracy
IT grades
GD&T

ABSTRACT

Owing to the lack of optimization, the dimensional accuracy of low-cost 3D printers is quite limited. In order to enhance the performances of a Prusa i3 3D printer, an optimization challenge was assigned to the students of the Specializing Master in Industrial Automation of the Politecnico di Torino. The enhancements were applied to four printers by manufacturing new self-replicated parts by means of the same 3D printers. Finally, a benchmarking activity was used to check and validate the results of the optimization activities. The benchmarking involved the fabrication of replicas of an innovative reference artifact by means of the modified printers. A coordinate measuring machine (CMM) was then used to inspect the dimensions of the replicas. Measures were used to compare the performances of the four optimized printers in terms of dimensional accuracy using ISO IT grades. The form errors of the geometrical features of the replicas were also evaluated according to the GD&T system. The benchmarking results show that the most effective modifications to the original printer were those related to the improvement of the structure stiffness and chatter reduction.

1. Introduction

Recent diffusion of new low-cost 3D printing machines was boosted by the expiration of Stratasys company's patents for Fused Deposition Modeling (FDM) technology. The current rapid expansion of this technology in the unprofessional fields is mainly a consequence of the widespread adoption by the so-called "maker movement". In fact, the success of FDM machines, that are also renown as 3D printers, benefits from open-source systems as well as sharing of information to support the process development and optimization. These characteristics yield reduced costs and readily available 3D printers and 3D models.

The first system based on the FDM technique was invented by Scott Crump that cofounded Stratasys in the late 1980 s [1,2]. In FDM the object is built up layer by layer using the extrusion of a melted polymeric filament [3]. This extrusion process is a thermal process because the thermoplastic wire is melted through a heated nozzle, which also deposits the material according to the 2D geometry of each building layer. The material is heated to its melting point, extruded and then solidifies right after deposition. The new building layer is thus welded onto the previous layer. Stratasys provides industrial FDM systems which include advanced mechanical and electronic solutions for ensuring reliability and productivity. The machine architecture comprises a hot working chamber wherein an extrusion head deposits the extruded material on the building platform. The extrusion head usually includes at least two nozzles, one for the part material and one for the support material. The filament is stored and supplied in chipped cartridges and the cost of Stratasys machines starts from about 20,000 euros for a small desktop system.

Owing to the simplicity of the FDM process and the relatively cheap equipment and raw polymeric materials, after patent expiry, this additive manufacturing (AM) technology has gained the interest of the amateur domain to explore and develop low-cost entry-level do-it-yourself (DIY) 3D printers.

The first project with this aim was started in 2005 with the name of RepRap [4]. Since then, other commercial printers based on the RepRap project were brought to market, e.g. Makerbot, Ultimaker and most recently Prusa. Most of these FDM machines are based on a Cartesian structure and the extrusion head, which usually consists of only one nozzle that can be heated up to about 280 °C. The filament is stored in spools and has a standard diameter of 1.75 mm or 3 mm, while the nozzle orifice ranges from 0.10 mm to 0.70 mm. Most common 3D printing materials are the acrylonitrile butadiene styrene (ABS) and the biodegradable polylactic acid (PLA). However, a wider range of thermoplastic filaments can be extruded with open-source printers, provided that the material melting temperature can be reached in the extrusion nozzle.

As far as the machine set-up is concerned, operations of calibration, material changing and cleaning of the nozzle and the building platform

* Corresponding author.
E-mail address: paolo.minetola@polito.it (P. Minetola).

https://doi.org/10.1016/j.addma.2018.05.028
Received 27 March 2017; Received in revised form 25 April 2018; Accepted 13 May 2018

are often manual on low-cost 3D printers. These devices are usually sold through the Internet as a kit that the users should self-assembly. The cost of this new generation of systems starts from some hundreds of euros, so it is highly affordable if compared to one of industrial FDM machines.

Nonetheless, the performance of entry-level low-cost 3D printers in terms of dimensional tolerances and accuracy of built parts suffers from several limitations deriving from the lack of optimization both in mechanical terms as in software. However, since 3D printers are based on open-source hardware, it is possible to enhance their performances by means of suitable improvements. To this aim, a challenge was assigned to four groups of students of the Specializing Master in Industrial Automation of the Politecnico di Torino for improving the performances of a Prusa i3 3D printer. The challenge included the possibility of manufacturing new self-replicated parts by means of the same 3D printer. The competition was carried out with the support of Comau S.p.a. company and resulted in four projects and in the birth of four new 3D printers named Fluo, Ghost, Metallica, and Print-Doh. The aim of this paper is to present the results achieved by each student team after applying the enhancements to the original Prusa i3 printer.

The dimensional performances of the four modified machines are tested and compared by means of a benchmarking activity. To this purpose, an innovative reference artifact was first fabricated by means of the improved printers and then inspected by means of a coordinate measuring machine (CMM). Measures were used to evaluate and compare the dimensional accuracy of the four printers in order to validate the results of optimization activities. ISO IT grades are used to summarize the machine accuracy, whereas the form errors of the geometrical features of the artifact replicas are considered according to the GD&T system.

The replica manufactured by means of the original Prusa i3 has been excluded from this study due to the difficulties to complete the fabrication of the benchmarking artifact. The performance of the original machine was tested by the students before and after the improvements by using a simple cube with an edge of 10 mm as a test piece. Fig. 1a and Fig. 1b show the result of the test cube fabrication prior to the improvements of the Prusa i3 printer, that is by using the original machine without and with an optimization of the printing parameters respectively. After the modification of the machine, the cube could be fabricated with a higher quality by using the set of optimized parameters (Fig. 1c). The definition of the optimal process parameters was left to the students. From the point of view of the methodology, the application of the design of experiments (DOE) was requested, but no specific indication was provided about the set and levels of the parameters.

This paper is organised as follows: firstly, the original Prusa i3 3D printer is described together with the enhancements made to it by each of the four student groups. Then, the procedure of the benchmarking analysis is detailed and finally the dimensional performances are compared, highlighting the main differences between the four machines, in terms of dimensional accuracy and form errors of the geometrical features of the reference artifact.

Table 1
Technical specifications of Prusa i3.

Technical specifications	
Build volume (mm^3)	200 × 200 × 180
Supported materials	ABS, PLA
Number of extruders	1
Heated platform	Yes
Minimum layer thickness (mm)	0.05
Filament diameter (mm)	1.75
Nozzle diameter (mm)	0.4 (easily changeable)
Open Source	Hardware and software

2. Description of Prusa i3 and improvements

Prusa i3 is named after the third iteration of the design by Josef Prusa. All parts of this 3D printer are open-source and are part of the RepRap project. Table 1 resumes the main characteristics and Fig. 2 depicts the original Prusa i3 assembly kit and an assembled printer.

The machine architecture is very simple: the building platform translates along the Y-axis, whereas the extrusion head moves in the XZ plane. The horizontal translation of the head is controlled by the X-axis and the vertical translation allows the increment along the Z-axis. The mechanical structure is minimal and consists essentially of two rails along those the building platform is moved, other two rails for the motion of the extrusion head and the structure to support the rails.

As far as the challenge to improve the performance of the original machine is concerned, the four activated projects have led to the development of machines that differ greatly one from the other as well as from the original printer. Several aspects were analysed which included mechanical, electrical, esthetical and safety aspects. Esthetical and safety aspects were mainly aimed to improve the appearance and the ergonomics of the machine. These aspects were introduced to consider the impact with the user and marketing mode for the modified machines. However, for the scope of this paper only the modifications in terms of mechanical and electrical aspects are presented because they are those affecting the dimensional performances the most. The analysis of the original machine showed the need to work on four main weak points (WPs):

- reducing the jamming of the filament during the process by the introduction of elements to drive the filament and ensure its correct flow, such as a holder of the wire spool and a guide for the filament;
- improving the stiffness of the machine by using rigid components to

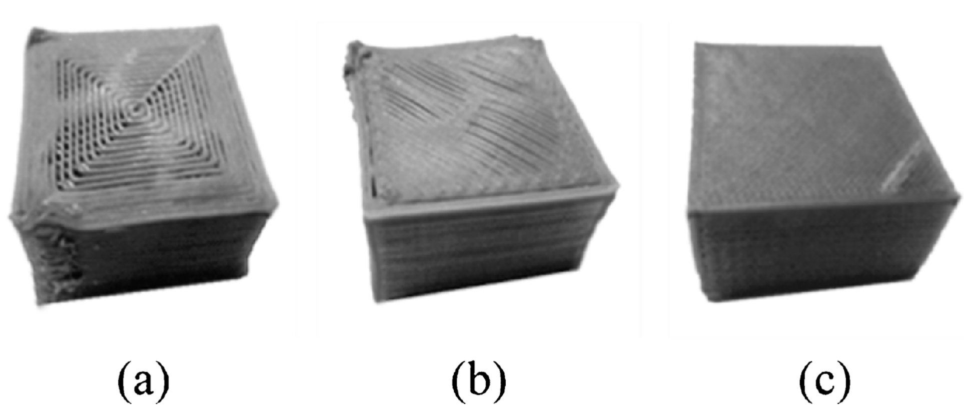

Fig. 1. Test cube geometry: original Prusa i3 without parameter optimization (a); original Prusa i3 with parameter optimization (b); modified Prusa i3 with parameter optimization (c).