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Low-cost 3D food printing

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Abstract

In a close future, it will be possible to print any kind of food through a nozzle, with the desired nutritive quantity, originating richer, healthier and more controlled meals. The exponential growth of this new market led to intensive research worldwide; however, dealing with a low cost printer is not an easy task for the general consumer. This paper presents the difficulties that a common user might face using a 3D food printer, and explains the assembly, configuration and modification of a RepRap Prusa I3 3D printer. An extrusion equipment capable of extruding materials in paste form, focused in the cake industry with sugar pastes, was developed. This extruder allowed the deposition of new materials that couldn't previously be used since they have a solid consistency at low temperatures. The new extruder was tested with two different types of pastes: Nutella® chocolate and sugar pastes. The sugar paste prototypes already produced opened different opportunities to improve the surface quality, use of pastes with different colours, more than one extruder and others that in the limit contribute to the possibility of a small business in the cake design area.

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1. Introduction

The evolution and quick growth of the low cost three-dimensional (3D) printers' sales makes this an interesting and updated topic of study. Three-dimensional printing applied to the food industry will be the focus of this work. As this topic takes first steps, this study reveals to be a major opportunity, considering that it will become an important part of the daily routine of the general consumer in a not so far away future, being also an enormous change on people habits. For example, NASA has been studying ways to implement 3D food printing in space [1].

1.1. Structure

The bibliographic review of this study was organized in a way that allows the user to understand the

sequence of processes involved in 3D printing, as well as the equipment and software available that are suitable to each kind of user. The non-subtle growth watched in the last decade and how far this technology has evolved will be discussed in this topic. The types of printers and its specific use, the importance of such machines for industry and the way they can revolutionize mass production lines are also addressed. Throughout this chapter, special attention is given to the food industry, but also to the advances that could be associated with this kind of development [2].

The experimental component deals with the configuration development and settings modifications so that handling during the printing process is suitable.

An explanation of the assembly and programming a low cost 3D printing equipment will be given. In the user point of view, this chapter will be very important because it will allow understanding the biggest faults and difficulties in using an equipment of this kind. This work reviews the state-of-art of food printing and

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a 3D commercial printer will be adapted to be able to print sugar paste. This equipment will also open the opportunity to use other types of food, unlocking a new barrier in 3D printing [2].

2. Low Cost Three-dimensional Printing

Low Cost 3D printing is based on a simplification of the FDM process; the principle is the deposition of a melted material by a dedicated extruder. The concept might seem simple, in comparison to industrial processes [3]. Nowadays, low cost 3D printing can be separated in two branches: Open source and Closed source. Having an Open source printer, there is no mandatory software. In other hand, using Closed Source, the choice is limited to what the manufacturer defines for each brand. Companies that produce their own machines mostly use closed systems, while the open systems are more appropriate to the common user; however, as it will be explained, these equipments demand a set of knowledge that are not available to the common users.

In 2013, 3D printers registered a sales increase of 34.9%, the highest value registered until that date. This value corresponds to 2.42 billion euros worldwide [4]. Over the past decade, the average growth was 27%, and in the last three years was 32.2%, according to the *Wohlers Report* from 2014 [5]. This growth was boosted by the appearance of equipments of less than 4,000 €. The personal 3D printers are the roots of a technologic advance that was not seen in over twenty years. The reason for this sudden change is related to the appearing of new low cost technologies, especially with the easy-use that makes them available for every type of users, creating a new market. This change is happening now due to the breaking of patents of FDM in 2004, liberating this process to all users [6].

2.1. Its importance

In what way can a 3D printer be profitable in industry? The basic principle in this sector is manufacture cheap and in large quantities in order to obtain profit. How can be rentable to print a model while in the same period of time an injection machine is able to produce two or three? Three-dimensional printing offers a different perspective of selling, the concept of personalization to companies. The large-scale producers are able to sell small series of a product without falling in great expenses [7]. For example, a toy company decides to fabricate a new car model. For its production several injection moulds are necessary, and each one will cost approximately 100,000 €. As the main goal is to obtain profit, the

company will have to produce millions of units to get positive balance. What if the company gets a production order of 3,000 units for a special edition of that model which is slightly different from the original? There are several ways to solve this problem: the company buys new moulds and faces a significant loss, the company buys a new mould and increases the price of the car, or the company 3D prints the special edition car [7]. Additive manufacturing allows a model x to be different from the model y, exactly with the same production cost. The difference between the two models will only be the CAD file, while with other production techniques the components have to be produced separately. With 3D printing, all parts of the model can be produced at once and with several different materials (obviously depending on the 3D printer employed). Summing up, 3D printing offers the advantage of customization and cheap production for a single part, and capability to produce parts that cannot be created with other methods. However, some disadvantages can be identified: not rentable for large series (at least for the majority of products), worst dimensional tolerances, weaker materials properties, and not the best surface finishing [6].

3. Experimental Procedure

3.1. RepRap Prusa I3 construction

In order to accomplish this project, a Reprap Prusa I3 equipment was acquired, which had to be disassembled and posteriorly reconstructed. This model was chosen due to its metallic structural components. Besides being an Open source equipment that allows all kinds of changes, it is a model that presents a stiffer structure, and presents a higher relation quality-price for this study.

3.1.1. Structure assembly

To properly assemble Prusa I3, it should be set up by axis (Fig. 1). The order of the axis is not important because none requires full operation of the others. The assembly of the axis together, and the vertical structure is the subsequent step. Since each one of the axis has several guides, it is necessary to constantly measure the parallelism and distances. After each assembly, a calibration is demanded. Posteriorly it is added the heated bed, the filament extruder and the end stop sensors.

3.1.2. Hardware assembly

The equipment's hardware consists of the coupling among an Arduino 2506, a RAMPS 1.4 (Reprap

Arduino Mega Pololu Shield) and four Pololus (*stepper motor driver carriers*) that will control the motors. This set will command all the actions of the printer, from the motors rotation to the heating of the heated bed. The programming will tell the motors, for a given displacement, how many rotations are needed; to melt x millimetres of filament, how many rotations are needed; definition of initial positions of the axis, maximum and minimum temperatures, among other essential parameters.

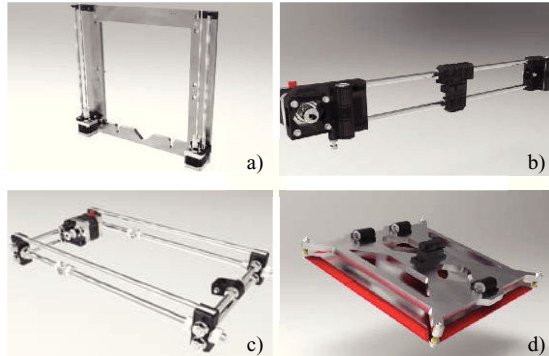


Fig. 1. a) Z axis, b) X axis, c) Y axis and d) heated bed.

3.2. Paste extruder construction

The developed extruder should offer some advantages compared to existing models. Simple structure and easy manufacturing is essential. Some of its components should be produced with a similar Reprap equipment (structural parts) and others CNC machined (heating elements). The extruder should be simple, allowing changes and iterations during the fabrication process (Fig. 2), and enable an easy access to the material container. Keeping in mind that it is a low cost printing equipment, the extruder should be of inexpensive production. More important, it should have the capability to raise the temperature along its reservoir and nozzle, allowing an easy extrusion. After deposition, the material should be refrigerated with a fan, promoting better layer overlap [2].

As the main goal would be operating with sugar paste, the temperature control would be a necessary characteristic since the paste has a solid consistency, needing temperatures in the range of 50 to 65°C in order to flow through the nozzle [8]. To verify these characteristics, it is necessary to use two heating components separately. One of them would ensure the temperature inside the recipient in order to make the paste minimally malleable (heating wire rolled around the reservoir and thermistor). The second element should be placed in the tip of the extruder to have a more accurate control of the temperature. This new nozzle would be created with a machined component

in an aluminium alloy, a cartridge heater and a thermistor. A 40 mm fan would take care of the sugar paste refrigeration.

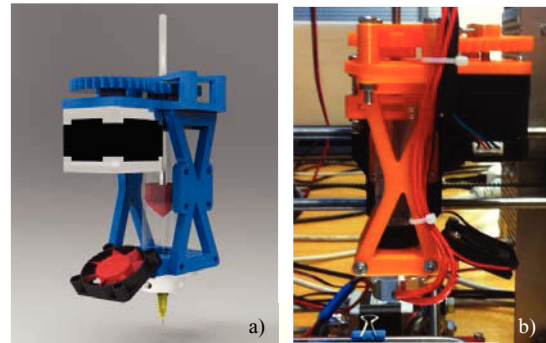


Fig. 2. a) Extruder rendering (CAD), b) real extruder.

The extruder application in the printer should be done in a simple way since this was drawn according with the structure where it would be mounted. However, there will be the possibility of applying the extruder in other Reprap equipment or even in a different machine. After the extruder's application, the Arduino controller should be programmed accordingly to its physics characteristics. The most important parameters of this programming are the displacement speed through the axes and the axes motor rotations. The extruder displacement relation is created in this way. This programming will be required because the new extruder has different working relations from the original one, initially placed on the printer.

3.3. Configuration and testing

To become functional, this equipment needed a new set of configurations. These new configurations had to be created from scratch. The goal was to work around the parameters like part filling, layer height, working temperatures, number of runs per layer and speeds. These parameters define the kind of print that is being done. To make these configurations possible, the software Slic3r was used which allows all kinds of modifications to fit all of those values.

After some of these parameters were created and before using a paste to be extruded, the component's functionality had to be tested. These simple tests granted the proper operation of the equipment (Table 1).

The functionality tests were designed to assure that the extruder mechanical components were working correctly. If any component was faulty, it would be easier to redesign and replace the part before working with some kind of material, and avoiding any damage to the printer structure itself.

Table 1. Extruder functionality tests.

Type of test	Function to test
Movement and displacement	Movement through the axis
Nozzle heating	Simple heating to a defined temperature Thermistors calibration
Reservoir heating	Simple heating to a defined temperature

The tests consisted in moving the equipment through the axis, moving the spindle and plunger in the reservoir which became the most problematic part in this series of tests. Next, the first tests with a material were made. It was chosen *Nutella*® cream because it was easier to print due to its soft consistency and no need of high temperatures. Introducing the first bundle of parameters with this paste led to understanding the equipment's reaction, taking part in a series of iterations in order to find the machine's best performance (Table 2).

Table 2. *Nutella*® tests.

Type of test	Function to test
Essential parameters configuration	Relation between velocity and displacement in deposition Filling ratio Layer height

This equipment's functionality was only possible through the creation of a bundle of slic3r configurations, which were systematically changed to find the best deposition pattern. Each one of these features was not tested apart but merged together in a way that the printed part itself was analysed to see what was wrong, and what could be changed to improve the print quality. In this stage the temperature was disregarded, which could be added in a simple way later on the project. Using *Nutella*® was a good test because its extrusion was easy to do, without great effort to the extruder engine and gears. In addition, the paste consistency allowed the layer overlap, maintaining its geometry until the fourth passage. Iterations were made until the filling percentage was raised to 30% and the layer height increased to 1.6 mm, which is 80% of de extrusion diameter (maximum value). The newly developed configurations were used in the subsequent operation with sugar paste (Table 3).

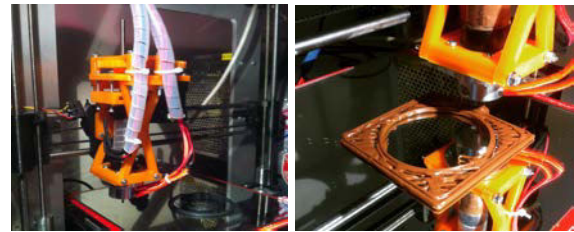
The sugar paste tests allowed a data gathering, leading to a new configuration upgrade started with the *Nutella*® paste, introducing now features, such as raising the temperature in both nozzle and reservoir.

The usage of different kinds of sugar pastes revealed that the temperature values had to be changed.

Table 2. Sugar paste tests.

Type of test	Function to test
Essential parameters configuration	Relation between velocity and displacement in deposition Filling ratio Layer height Relation between velocity and displacement in deposition
Temperature insertion	Sugar paste extrusion
Previous parameter adaptation	Filling, layer heights, velocities
Nozzle temperature iteration	Sugar paste heating in this area
Reservoir temperature iteration	Sugar paste heating in this area
Geometry tests	Ability to draw simple shapes
Overlapping tests	Paste reaction to layer overlapping Overlapping with several layers
Angle tests	Ability to draw closed angles

Fig. 3 shows some of the prints done in this test phase, with the parameters chosen from the previous iterations.

Fig. 3. Sugar and *Nutella*® prints.

4. Results

Fig. 4 represents what the final configurations could do in some simple prints. These models were purely illustrative of the capabilities of the paste extruder with several kinds of sugar pastes. For these last couple of prints, the plate lined with a paper sheet were used allowing a simple removal from the machine. If the paper was moistened, the sugar paste would be easily separated without damaging the print.

4.1. Operation problems

Being a prototype, even with the majority of the working problems solved, the extruder is still missing some key elements on the way of steady and flawless performing. For the time amount available to conceive and conceptualize, study and create this project, this

was the most that could be done. Even though the extruder can perform prints, there are some elements to improve. A couple of persistent problems were diagnosed and solutions to these failures were presented. The print quality was significantly improved with iterations introduced. Initially there were gaps between each line made. Raising the filling percentage, combined with the speed reduction, helped to solve this problem.



Fig. 4. 3D printed shapes with sugar paste.

The first analysed problem was the lack of tightness in the nozzle. During movements with no intended material deposition, the extruder tip could not keep the material inside and leaked, creating what is called “oozing”, damaging the print quality. A sealant rubber was applied between the nozzle and its support, improving the tightness in the nozzle and elevating the negative pressure when the plunger was receding. Other problem consisted in the plunger deterioration during successive prints. Through upward and downward moves, combined with the sugar granular consistency, the plunger would become loose and weak. After several tests, it was verified that the reservoir-heating element penetrated inside due to high temperature values. This problem was caused by faulty positioned thermistors that led to reservoir degradation.

The sugar paste that reveals being a material of complicated extrusion was successfully extruded controlling the heating and cooling temperature. Unblocking this barrier allows materials that previously could not be used with 3D printing to be now tested.

5. Conclusions

This work focus on the biggest barriers that newly 3D printing users will face, since the purchase of a kit to the stage to use it appropriately. The open source models allow the users to modify them to implement personal projects; however, this demands specific knowledge, not common to general users. The selected equipment, RepRap Prusa I3 3D printer, is an

Open source model, normally used in activities that imply modifications and improvements. These changes are only accessible for consumers predisposed to learn by themselves how these equipments work.

The configurations developed were the toughest part, which evolved a lot of iterative testing. The development of an extruder equipment to be used with pastes demanded an in-depth study of the equipment programming. The conception of the new extruder was done in different steps, presenting several challenges. Print with sugar paste revealed itself a much more complex process than print with *Nutella*® paste. The sugar has a more solid consistency, even with high temperatures, and it is more grumpy. These properties made the piston displacement harder, causing mechanical troubles. However, the deposition of this material presented a more solid structure after cooling than the previously test material, which led to a better overlapping layers and better geometries definition.

Despite this work has produced functional equipment, printing with adequate quality and high details level, further research is still demanded to develop a device with commercial interest. With this extruder and with the innovations applied to it, movement control, heating and cooling during and after extrusion, opened up a new area of exploration for printing with new food materials that have consistencies similar to sugar paste.

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References

- [1] J. Kietzmann, L. Pitt, P. Berthon, *Bus. Horiz.* 209 (2015) 15.
- [2] I.A. Ferreira, MSc thesis, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, 2015.
- [3] I. Gibson, D.W. Rosen, B. Stucker (Ed.), *Additive Manufacturing Technologies*, Springer, 2010.
- [4] Biggest ever growth for 3D printing, *Met. Powder Rep.* 69 (2014) 38.
- [5] T.T. Wohlers, T. Caffrey, *Wohlers Report*, 2013.
- [6] H. Lipson, M. Kurman, *Fabricated, The New World of 3D Printing*, John Wiley Sons, Inc., 2013.
- [7] B. Berman, *Bus. Horiz.* 55 (2012) 155.
- [8] M.J. Barros, MSc thesis, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, 2014.