

A PRACTICAL APPROACH TO THE DESIGN AND IMPLEMENTATION OF A LOW COST 3D PRINTER USING OPEN SOURCE TECHNOLOGIES

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Abstract

The process of manufacturing parts with additive technologies has seen tremendous growth in recent years, and the emergence of more 3D open source printers has led to complex and personalized shapes at a lower price. For these reasons, 3D printers that form parts by extruding a filament of molten plastic are becoming standard equipment in many laboratories and workshops. In this context, the paper aims to present some theoretical aspects about the implementation and testing of a low cost 3D printer using open source technologies, the description of its main components and the stages to be taken from the 3D modelling of an object to the proper printing.

Key words: 3D printing, additive manufacturing, rapid prototyping, open source technologies

1. Introduction

In order to meet the technical demands of customers who need products of complex shapes, but made in a smaller number of items with a lower production costs, mini CNC (Computer Numerical Control) machines have been developed. These are actually the low cost miniatures of CNC serial production machines and the basic design principles are mostly preserved [1-7]. These equipments have several types of processing tools (drilling, milling, cutting, turning, etc.) or other expansion unit, so their utility increases.

In contrast with the conventional subtractive process, where the material is removed from the raw pieces, additive technologies such as SLS (selective laser sintering), FDM (fused deposition modelling), SLA (stereolithography) appeared [8,9,10]. These 3D (three-dimensional) printing methods are some of the most innovative in creating products with complex shapes. In these technologies the 3D object is built by adding a number of successive layers from different materials.

Initially, the applications of commercialized 3D printers were limited to certain companies due to expensive finished products. Over the last years, low cost market 3D printing systems and services are targeted towards the end consumer. The construction costs for such equipments have fallen below \$500. Some of the most popular budget 3D printers are Prusa i3, Wanhao Duplicator i3, M3D Micro. At the same time, the cost of an industrial 3D printer may

range from \$1,000 to \$500,000, or even more correlated with printing output and quality. Among the most successful industrial printers are Objet Eden260VS, ProJet 3500 HDMax, Objet260 Connex3, EOSINT P 760 [11,12].

The largest class of open source 3D printers is known as RepRap [13-20], and one of the latest versions is Prusa i3. These RepRap printers are designed to be capable of replicating itself by printing many of its own plastic parts, thus increasing the number of such equipments. Its goal is to produce free and open source hardware (FOSH) 3D printer, which is shared online and the community has to use and improve. The equipment is capable of extruding PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), and HDPE (high-density polyethylene) among other materials. Some authors have combined in [16] a low cost commercial gas-metal arc welder and a derivative of the Rostock, a deltabot RepRap to obtain a metal 3D printer controlled with an open source microcontroller.

Although the price of the open source printers is low, the mechanical properties of the printed parts are close to the performances achieved with commercial equipments. The study of basic tensile strengths and elastic modulus for ABS and PLA parts in [18] certifies this. The report [10] investigates, from the perspective of an intellectual property scholar, how 3D printing technology has developed over the last few decades and how 3D printing technologies could challenge the intellectual property rights system.

Applications of 3D printers include rapid prototyping, architectural scale models & maquettes, printed implants and prosthetics, reconstruction of fossils in paleontology, ancient artifacts in archaeology, bones and body parts in forensic pathology, bio-printing of organs and body parts, metal additive manufacturing in aerospace & aviation industries, functional parts in automotive, transmission or flexure mechanisms, simple custom components and entertainment [8,9,21].

This paper presents some theoretical aspects of building a low cost 3D printer, which is actually a mini CNC used to produce prototype parts by fusing plastic. The 3D printer design is based on an open source RepRap with Arduino development board that contains the ATmega 2560 microcontroller. The electronic control unit has been configured and adapted to a metal frame prototype, resulting in a total production cost below \$250.

2. Theoretical aspects of low cost 3D printer

An interesting feature of a 3D printer, unlike other applications, is the possibility of being a self-replicating machine because it can produce its own plastic spare parts, contained in the mechanical and guiding components.

A 3D fusion based printer has three large parts: the mechanical part, the electronic control unit with drivers and sensors and the software part.

From a mechanical point of view, a CNC type system with a minimum of three axes is required, and in order to be able to make accurate models, a linear ball bearing mechanism provides smooth movement.

The extruder is the main mechanical component that ensures that the plastic from which the parts are produced is laid flat. It consists of a stepper motor that drives the plastic filament feed mechanism and a plastic heating and melting system that allows the deposition of plastic layers to form the desired object.

In order to get the desired quality of the finished products a great task is the melting and drying procedure of the raw material. In the melting process, it is necessary that the plastic filament be heated sufficiently to lead to the bonding of the layers. A too high temperature can burn the plastic or lead to the formation of bubbles between the layers. At the same time, the extruded plastic should cool down as quickly as possible to maintain its shape.

The 3D printers are not limited to the same material. Printers may have several extruders of different types with different physical properties. If greater print precision is desired, the nozzle diameter is reduced and the feed speed is changed.

The electronic control interface of the 3D printer is responsible for controlling the temperature of the extruder and printbed, respectively the motors that move the table and feed with the plastic material.

Most low cost 3D printers use stepper motors, and the control unit is based on development boards using Arduino microprocessors. This is a fast and very

cheap processor with enough memory space for such applications. The development board allows the addition of sensors and actuators.

The 3D printer only works if the microcontroller is programmed. So, another important part is the software from the control interface (firmware of the printer) which is responsible for understanding the G-Code sent by an application (usually on a PC) and translates it to the drivers which control the motors. In the same time the firmware controls the temperature, feed rate, acceleration, speed, and other parameters depending on the type of the printer.

Today there are a lot of firmware options to choose from, but two of the most common are Repetier and Marlin [10,17,22,23]. Other firmware include: Sprinter, Teacup, MK4duo, Sailfish, Aprinter, ImpPro3D, Redeem, etc. The big advantage of open source firmware is that it allows anyone to access and modify their application, which helps to further development in the field.

A plus in the design of such a printer is also the self-didactic nature regarding knowledge of several technologies such as temperature control (extruder and printbed); control of the stepper motors; melting and cooling plastic material; programming of microcontrollers, control and programming CNC machines.

3. 3D printer implementation

Some details about how to implement a low cost 3D printer using open source technologies are given in this chapter. For future development, the system is designed in modular form. Thus, the architecture of the system is flexible, allowing it to be modified.

Mechanical components

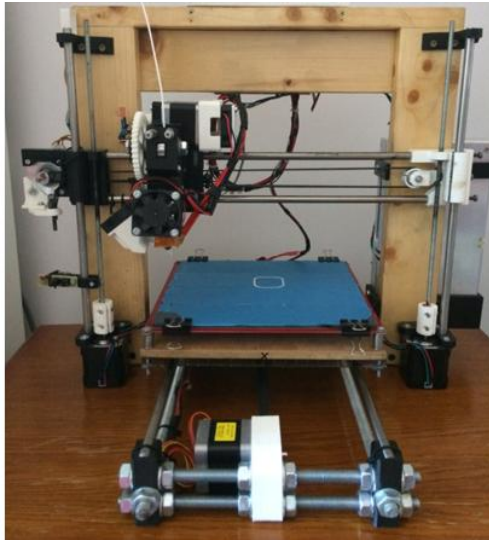
The first step in developing the project was to design a frame and slide mechanism to ensure a perfect 3D movement of the tool. Considering that the working table (with printbed) from fig. 1a has a surface area of 200 x 200 mm, a mechanical frame has been designed to provide a sufficiently large space. The printbed is moved on X and Y axes by two stepper motors with 2 LM8UU linear ball bearings. Due to the weight of the extruder, the movement of the tool on the Z axis is made by a pair of stepper motors with linear ball bearings and mechanical rods.

The extruder from fig. 1b is a very important component because it heats and melts the plastic filament to produce the parts. It must ensure uniform deposition of constant thickness plastic.

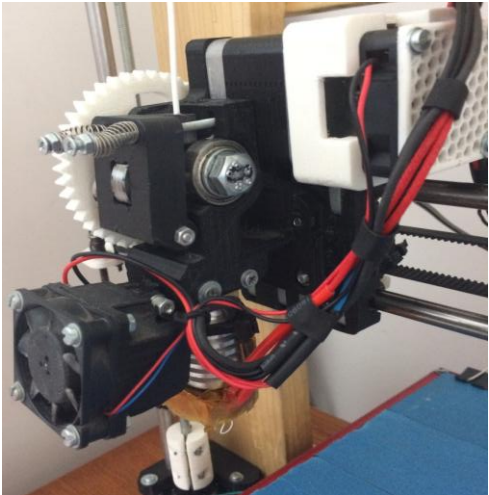
Extruder construction is based on the Greg's Wade open source version [24]. It is known that this design has a transmission mechanism that does not force the driving motor. The extruder has two components: the filament feed mechanism and the print head. To feed the filament, an M8 screw is used which has a slot in the middle so that it catches the filament and presses it toward the print head, the drive being carried out by a stepper motor. The transmission ratio between the stepper motor shaft and the screw shaft is 1:4.3. The

filament is pressed into the extruder, heated to the melting temperature, and leaves the print head through the exit nozzle.

The extruder has a hole of 1.8 mm diameter at the entrance, where the plastic filament with diameter 1.75mm will enter. The exit nozzle can be changed depending on the type of use (0.2mm, 0.4mm, 0.6mm, 0.8mm). It is obvious that for a higher accuracy a smaller diameter nozzle is mounted, while a longer diameter is used to reduce the production time.



a



b

Fig. 1: (a) Mechanical guiding system; (b) Extruder

Electronic control unit

The block diagram of the 3D printer control unit including the drivers, stepper motors (denoted by M) and sensors is presented in fig. 2.

The control unit is built around the Arduino development board that contains the ATmega 2560 microcontroller and allows the addition of peripheral components to the expansion board. The expansion board increases the number of elements connectable to the microcontroller [25].

In this case, five stepper motors, two power heaters, two thermistors for temperature

measurement, four end stop sensors, one optical sensor for recording Z-axis position and a 2x 16 LCD display have been connected to the expansion board.

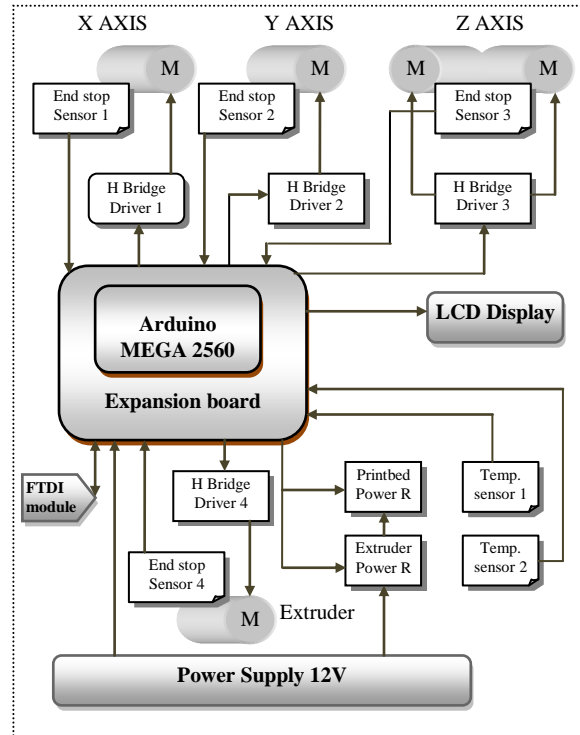


Fig. 2: Block diagram of the 3D printer

The stepper motors that provide the necessary movements for the 3D printer are NEMA 17 and are controlled by the microcontroller via the DRV8825 integrated circuits. This circuit contains a microstepping stepper motor driver (H bridge type). Although the electronic circuit use a TTL command signal, it operates from 8.2 V to 45 V and delivers up to approximately 1.5 A per phase without a heat sink.

The 4-wire bipolar stepper motor NEMA 17 has 1.8° per step for smooth motion (meaning 200 steps per revolution) and a nice holding torque.

Important information about the main parameters of the printer is read using the position and temperature sensors. Because stepper motors are used to drive the axes then only some end stop sensors for the linear axes are required.

The heating process is very important in manufacturing the plastic parts. For high accuracy it is necessary to measure and adjust the temperature. Plastic is very sensitive to temperature during melting and solidification. For this reason, a difference of 5°C can introduce defects between deposited layers. So, to measure temperature NTC (Negative Resistance Coefficient) thermistors with 100K resistance operating up to 350°C is used.

3D printer has two areas where it is necessary to keep the temperature at the desired values. Although value ranges for these temperatures are general accepted and specified by the filament manufacturer in the technical data, the optimum values are

determined by experiments. In the first area which is the extruder, the optimal temperature during printing was maintained around 190°C for PLA (240°C for ABS). Here 40W maximum power resistor 6R with 12V supply voltage is used. For the printbed, which contains a special wiring with a heating resistance, that can produce a maximum temperature of about 130°C, it was determined that a temperature of 70°C is sufficient for PLA.

To program the electronic control unit, monitor and troubleshoot the 3D printer, a FTDI (Future Technology Devices International) module containing the FT232RL integrated circuit is also connected. The module assures data transfer from the computer USB port to the serial interface of the microcontroller.

The power is given by a 12V stabilized switching source that supplies a maximum current of 30A required for power circuits of the control unit (containing the H bridges, the stepper motors and the heating elements). For the electronic components that operate with TTL signals, the expansion board also has a 12V-5V voltage converter.

Firmware of the 3D printer

The firmware is running all the time on the controller and manages the real-time activities of the 3D printer by sending out the commands to the peripherals and reading the sensors. Typically, an open source firmware is designed for a standard configuration that refers to both hardware and mechanical components (related also to the kinematic model). Thus, depending on the desired facilities, the mechanical model is initially selected and then the hardware is added. The closer the replicas of the prototype model, the less firmware changes are needed. Thus, in this case, it was sufficient to customize the firmware and calibrate the servomotors and sensors.

The program used to control this printer is an open source firmware named Marlin, version 1.0.2, which has multiple features:

- over 150 G-code commands;
- movement suite, including lines, arcs, and curves;
- support for different kinematics
- closed-loop PID heater control with auto-tuning, thermal protection, safety cutoff;
- support for extruders plus heated printbed;
- support for printing data from SD Card or ethernet;
- communication with computer via USB;
- LCD controller user interface;
- bed leveling compensation;
- support for filament runout;
- print job timer and print counter.

Programming the microcontroller is done using the Arduino IDE (Integrated Development Environment) environment, which is available in various versions. Due to the open source nature, the firmware allows free reproduction, modification or custom development.

Besides programming the open source firmware to the microcontroller memory, a series of operating tests and calibrations are required for: the three-axis movements driven by the stepper motors, the extruder plastic filament feed, the use of the end stop sensors and the temperature control. Also, the firmware allows the choice of an on/off temperature controller for the printbed and a PID control for the extruder because higher accuracy is required. The PID control signal is a sum of three terms. The P-term and I-term are proportional to the control error (difference between the set point and the measured temperature of the extruder) and its integral, while the D-term is proportional to the derivative of the measured temperature of the extruder. Also, some limitations of the I-term are used to overcome the windup effect.

For the PID control, the initial parameters are configured manually then auto tuning procedure of the firmware finds the optimal values. For the 190°C desired temperature of extruder and 45 seconds heating cycle the following initial values were chosen for the controller parameters: proportional gain $k_p=2.04$, integral constant $k_i=0.08$ and derivative constant $k_d=3.18$. These values were determined by testing and are in accordance with the firmware recommendations [22,24].

4. Steps for creating a 3D object

The manufacturing process begins with a 3D digital model which is created on a computer. The object is converted into CNC machine code (G code) and these instructions are sent to the printer. The printer prints out the object by laying down successive layers of material, providing in this way the additive manufacturing of the plastic part (fig. 3).

Before printing, the printbed must be prepared because it may contain dust that does not allow the extruded plastic to adhere. The first layer is very important because the plastic in the cooling process contracts and the part can deform.

The object model is drawn on a computer in a CAD (Computer Aided Design) environment, then saved in a .stl (statement list file) format, to be opened by the software application that converts the project into G code instruction sequences.

The most powerful 3D modelling software is Autodesk Inventor Professional [26]. This program is well-designed, all commands and functions are designed to be as user-friendly as possible. A great advantage is the existence of free license versions for learning in the academic environment. Other CAD application include: Dassault SolidWorks, OpenSCAD, FreeCAD, HeeksCAD PTC Creo, AutoCAD, SketchUp, FABFabbers, CoffeeSCad, RapCAD, ImplicitCAD, Cubehero, Libre 3D, etc. [8-10, 15]

The complexity of the created pattern is also limited by the printer's capabilities. The diameter of the nozzle is the main reason for determining the precision of the parts.

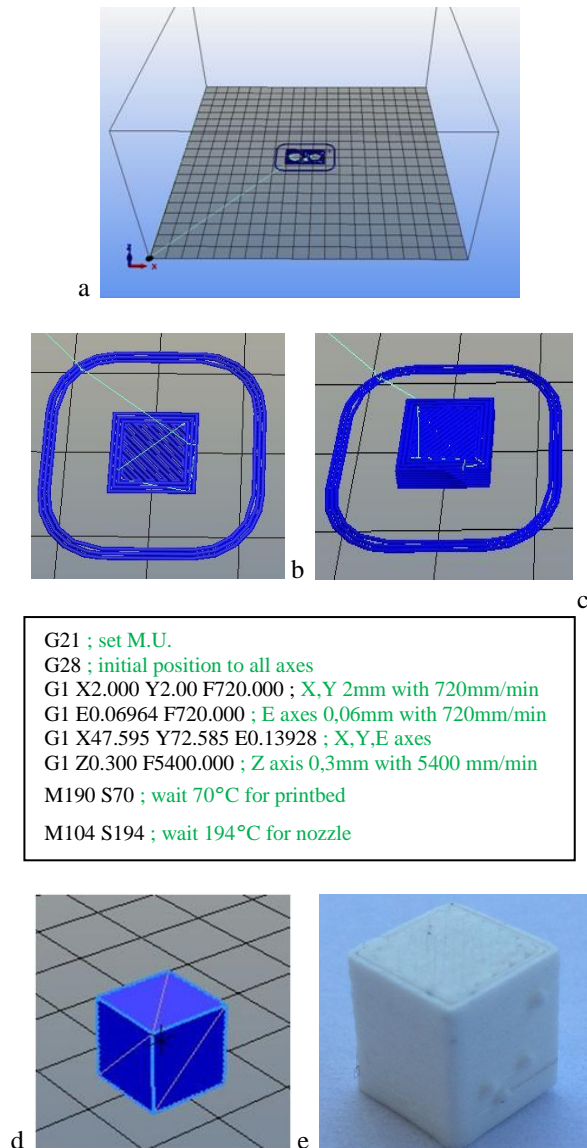


Fig. 3: Steps for creating a 3D part; (a) creating the 3D virtual model; (b) dividing the part in layers; (c) conversion to G code; (d) virtual object; (e) real object 3D printed

In order to create a 3D virtual object, it is first necessary to create a 2D model quoted on the X and Y axes, which is then modified. Extrusion is actually a process by which the 3D object is created by overlaying multiple 2D layers.

The 3D model from the STL (STereoLithography, also referred as Standard Triangle Language or Standard Tessellation Language) description of an virtual object is converted by a slicer program into the G code instruction sequence tailored to specific 3D printers. The most common open source applications of this kind are Slic3R and Cura [10,17,27,28]. They are often included in 3D printing clients such as Repetier-Host (offered free of charge by Stepcraft) [10,23]. Autodesk also offers various free 3D printing design software tools.

The Slicer application displays the printing progress, allows real-time 3D printer setup and

sending manually the G code sequences through a dedicated user interface.

The Slicer application plays the important role of dividing the object into equal layers depending on the diameter of the extruded plastic filament. Usually, the first layer is thicker to adhere better to the printbed. The application also allows setting the working temperatures at the extruder and printbed, the axes speeds and the filament feed (for the outer perimeter a lower speed is used and for the filling the holes a higher speed), the diameters of the filament and exit nozzle (which determines the total volume of the plastic to be extruded).

After getting the G code instructions file, there are three ways to send it to the printer:

- USB serial connection which involves direct command and displaying the print progress;
- saving instructions in a .gco file on SD memory;
- over ethernet module added to the printer's control unit.

There are also mobile applications designed to view the status of the printing as well as the most important manufacturing parameters.

5. Results and conclusions

3D printing can generate objects with complex shapes at lower price that until now have been impossible to achieve by traditional methods and mass production techniques. The 3D printer also offers the ability to create personalized products.

After implementing and testing the 3D open source printer at a final production cost of less than \$250, several considerations can be made.

In order to physically achieve this machine, proper alignment of the sliding mechanical systems is required; the differences of only 1mm can cause a variety of problems, because the physical precision of these machines is very important. Thus, if the axes are not parallel, they can generate a slower movement or even stop positioning the extruder.

Because the extruder is made up of a cold and a warm part, there is a tube that minimizes the heat transfer. It is difficult to achieve perfect insulation and to heat the plastic filament only in the warm part. Due to the pressure, it is possible for the filament to soften and clog the nozzle, blocking the extruder.

The low cost 3D printer requires continuous maintenance and recalibration due to the moving parts and various parameters need to be configured at startup and during printing.

From the point of view of construction, the metal chassis and its wooden support, respectively the sliding mechanical system represents a prototype. For this reason, although a Marlin open source firmware was used, it required the customization to this 3D printer. Also, temperature sensors, end stop sensors and stepper motors require test and calibration operations before printing objects.

To improve printer performance, the end user can: implement another version of the extruder; separate

the filament feeder from the printhead to reduce the Z axis weight; replace the end stop sensors with proximity or position sensors on mechanical slides; use precision sensors to accurately determine the height of the first layer of the object; use a lower nozzle diameter to increase the accuracy.

In terms of energy consumption, the power resistors have an extremely high average consumption of 72W/h, and so 170W/h can be achieved for a heating cycle of the extruder and the printbed.

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References

- [1] Floyd Kelly, J., Hood-Daniel, P. (2009), *Build Your Own CNC Machine*, Apress.
- [2] Groover, M.P. (2008), *Automation, Production Systems, and Computer-Integrated Manufacturing*, 3rd ed., Upper Saddle River: Prentice Hall, Inc.
- [3] Jayachandriah, B., Vamsi Krishna, O., Abdullah Khan, P., Ananda Reddy, R. (2014), Fabrication of Low Cost 3-Axis Cnc Router, *International Journal of Engineering Science Invention*, vol. 3 issue 6, pp.1-10.
- [4] Kikaj, A., Maloku, S., Avdyli, M. (2015), Functioning and design of the three dimensional operating machine controlled by computer in workshop environment, *International Journal of Scientific & Engineering Research*, vol. 6, issue 4, pp. 2022-2031.
- [5] Venkata Krishna Pabolu, Sri K.N.H. Srinivas (2010), Design and Implementation of a Three Dimensional CNC Machine, *International Journal on Computer Science and Engineering*, vol. 2, no. 8, pp. 2567-2570.
- [6] Lacoste, R. (2003), The XY-Plotter. Drive High-Resolution LCDs For Less, *Circuit Cellar*, vol. 158, pp. 42-51.
- [7] da Rocha Junior, P.A.S., de Silva e Souza, R.D., de Lima Tostes, M.E. (2010), Prototype CNC Machine Design, *Proc. INDUSCON '10*, pp. 1-5.
- [8] Al-Maliki, J.Q., Al-Maliki, A.J.Q, The Processes and Technologies of 3D Printing (2015), *International Journal of Advances in Computer Science and Technology*, vol. 4, no.10, pp. 161-165.
- [9] Bhandari, S., Regina, B. (2014), 3D Printing and Its Applications, *International Journal of Computer Science and Information Technology Research*, vol. 2, issue 2, pp.378-380.
- [10] Bechtold, S. (2015), *3D printing and the intellectual property system*, ser. Economics & Statistics Series, WIPO, vol. 28.
- [11] Angeles, Sara, (2017), *Best Industrial 3D Printers*, on Business.com, Technology [Online]. Available: <https://www.business.com/categories/best-industrial-3d-printers/>
- [12] Flynt, Joseph, (2017), *How Much Does 3D Printing Cost?* on 3DInsider [Online]. Available: <http://3dinsider.com/3d-printer-cost/>.
- [13] The RepRap website (2017). [Online]. Available: <http://reprap.org>
- [14] Kelly, J.F. (2014), *3D Printing: Build Your Own 3D Printer and Print Your Own 3D Objects*, Pearson Education, Inc.
- [15] Devijver, S. (2011), *Building Your Own 3D Printer. An introduction*, RepRap.
- [16] Anzalone, G.C., Zhang, C., Wijnen, B., Sanders, P.G., Pearce, J.M. (2013), A Low-Cost Open-Source Metal 3-D Printer, *IEEE Access*, vol.1, pp. 803-810.
- [17] Kerbelis, C. (2014), *Setting up the Hardware and Software for a 3D Printer*, Application Note, ECE 480.
- [18] Tymrak, B.M., Kreiger, M., Pearce, J.M. (2014), Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions, *Materials and Design*, vol. 58, pp. 242-246.
- [19] Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C., Bowyer, A. (2011), *Robotica* vol. 29, issue 1, pp. 177-191.
- [20] Pearce, J.M. (2014), *Open-Source Lab. How to Build Your Own Hardware and Reduce Research Costs*, Elsevier.
- [21] Sharkey, J.P., Foo, D.C.W., Kabla, A., Baumberg, J.J., Bowman, R.W. (2016), A one-piece 3D printed flexure translation stage for open-source microscopy, *Review of Scientific Instruments* vol. 87, pp. 1-7.
- [22] The Marlin website (2017). [Online]. Available: <http://marlinfw.org/>
- [23] The Repetier website (2017). [Online]. Available: <https://www.repetier.com/>
- [24] The Ultimate Greg's Wade's Geared Extruder on Thingiverse (2017). [Online]. Available: <https://www.thingiverse.com/thing:961630>
- [25] The Arduino website (2017). [Online]. Available: <http://www.arduino.cc/>
- [26] The Autodesk website (2017). [Online]. Available: <https://www.autodesk.com/>
- [27] The Slic3R website (2017). [Online]. Available: <http://slic3r.org/>
- [28] The Ultimaker website (2017). [Online]. Available: <https://ultimaker.com/en>