Additive manufacturing with RepRap methodology: current situation and future prospects

L. Romero[1], A. Guerrero[1], M. M. Espinosa[1], M. Jiménez [2], I.A. Domínguez[1], M. Domínguez[1]

[1] Design Engineering Area - Universidad Nacional de Educación a Distancia (UNED), Madrid, Spain

[2] Department of Mechanical Engineering, Technical School of Engineering - ICAI, Comillas University, Madrid, Spain

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Abstract

In February 2004, Adrian Bowyer, from the University of Bath, began an open initiative called RepRap, with the purpose of creating an open source rapid prototyping machine which, moreover, could replicate itself. This article analizes the current status of the RepRap initiative, commenting the basic components of RepRap machines, the differences between the different 3D printers developed by the RepRap community so far, and the technical possibilities that opens this technology from the engineering point of view. In addition we propose some improvements that could be perfectly feasible in the short term. For this purpose, the assembly of a RepRap Mendel Prusa was performed, but with some modifications.

1. Introduction to RepRap community.

A 3D printing machine (and any computing device in general) is composed of hardware (electric, electronic, electromechanic and mechanic physical components) and control software (the logical equipment as the operating system or software applications), usually both developed by companies that control them.

However, there are several companies in the world that are dedicated to the development of hardware in a peculiar way: they publish the sources of their inventions and sharing them with the whole world, with the aim that users from all the planet can use them and propose improvements. This is the model of open source hardware: hardware whose design, components, tools and documentation are open and they are publicly available to anyone.

The origin of these companies is varied: some were linked to projects without profit; others employ directly the open source model; in other cases focus on the research and some educational projects (such as the case of Arduino or RaspberryPi). These initiatives, by the fact of being open, have made possible the emergence of other companies that have been able to develop commercially an original product or offer services and products around that initial product.

As in other cases related to free culture, this economy of open hardware is based on the quality of the product and the company innovation capacity and not in the sale of single copies, although it may be under a trademark. This model seems to work: companies like Sparkfun, Adfruit, Ultimaker, Cooking Hacks or RepRap BCN produce open hardware.

RepRap is a rapid prototyping machine, modeled by melting and solidification with a nozzle, self-replicating, and with open source. RepRap is being developed by an open community on RepRap.org, which was founded in 2004 by Adrian Bowyer at the University of Bath. As the term *Fused Deposition Modeling* is registered by Stratasys, the RepRap community has coined the term *Fused Filament Fabrication* (FFF) that can be used by anyone without restriction [1]. RepRap is self-replicating because it is capable of generating a significant fraction of its own components.

RepRap is registered by the University of Bath, and is open source because it is registered under a 2 GPL versión [2]. Under these conditions, any person can distribute and amend a RepRap machine, but must maintain the modifications under this license.

The changes must continue to be publics. As the machine is free and open source, anyone can build, without the payment of any fee, an unlimited number of copies, for him or any other, using RepRap machines to build the plastic parts of the copies.

The founders of RepRap related the prototyping machine with a biological metaphor. They compared it with a mutualism relationship, also known as symbiosis. In this relationship, the machine benefits from the human through its support for playback: the human has to complete the assembly of the new machine with the parts that are not self-replicating and assemble the machine. And the benefit of the human is the use that makes from the machine in order to create the prototypes that he wants. Due to the biological inspiration of their creation, RepRap machines have been baptized with surnames of well-known biologists (Charles Darwin, Gregor Mendel, Thomas Henry Huxley and Alfred Russel Wallace).

2. RepRap models and features.

3D printers developed by RepRap community have the following characteristics:

- They are machines of the type FFF (Fused Filament Fabrication), and they use thermoplastic compounds (usually ABS and PLA).
- Four models have mainly been developed to date (Darwin, Mendel, Huxley and Wallace) with different variants (Prusa Mendel, MendelMax, RepRapPro Huxley, RepRapPro Mendel, etc).
- The accuracy of the model is given by the diameter of the nozzle, which is usually between 0,4 - 0,5 millimeters.

Darwin was the first model developed by RepRap in 2007 (Figure 1). This first version is currently obsolete.

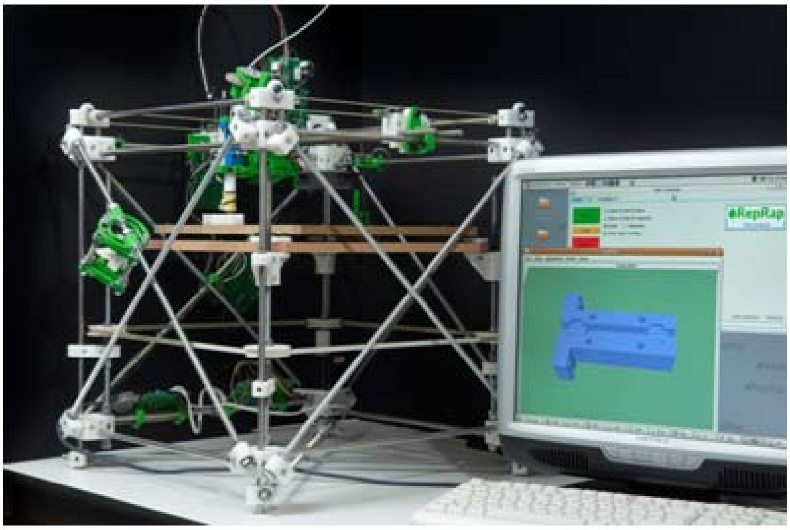

Figure 1: RepRap Darwin.

Mendel is the second model developed by the RepRap community, and it is the most popular to date, at least in terms of number of variants. The support structure is a triangular pyramid, formed by M8 threaded rods and printed pieces (Figure 2). The most widespread variant is the RepRap Mendel Prusa, created by Josef Prusa.

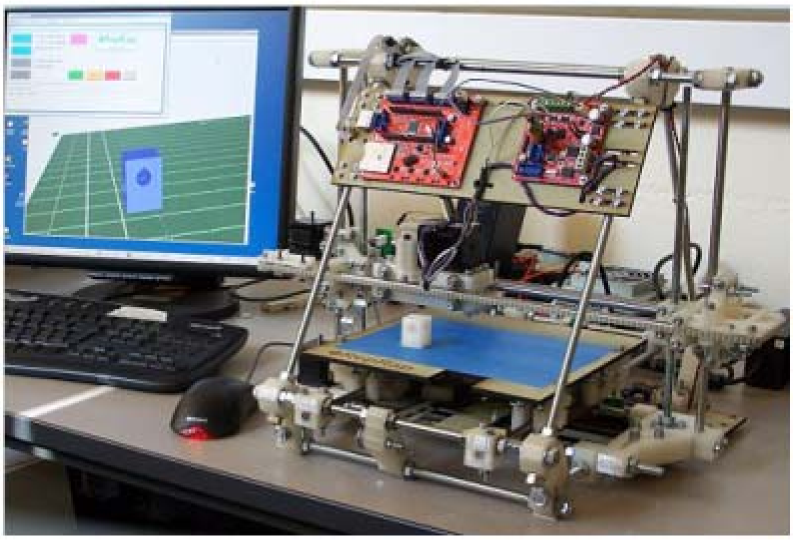

Figure 2: RepRap Mendel.

There is a Mendel variant with the pyramidal structure formed by aluminum profiles (MendelMax) which was created by Maxbots in December 2011. These profiles provide easer assembly and greater rigidity, with a small increase in price.

A variant with three extruders has also been developed: the RepRap Tricolour Mendel which was created by RepRapPro Ltd in 2013. The extruders use Bowden tubes which reduce the total weight to support.

Huxley is the third model and it was created by RepRapPro (Figure 3). It is the small and transportable variant of the Mendel Prusa, using M6 rods and NEMA 14 motors, like the RepRap Wallace.

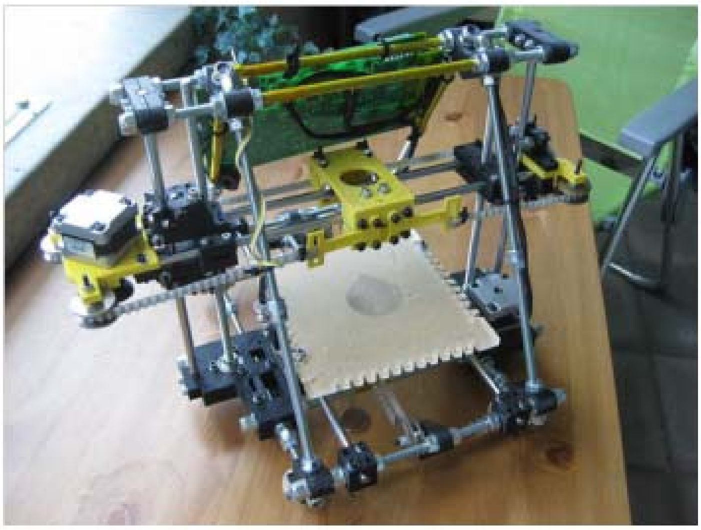

Figure 3: RepRapPro Huxley.

Wallace is the smallest model of the RepRap family. It is designed with M6 threaded rods and NEMA 14 motors. It is the most simple and easy to assemble variant (Figure 4). It is an evolution of the Printerbot, the simplest and cheapest RepRap printer.

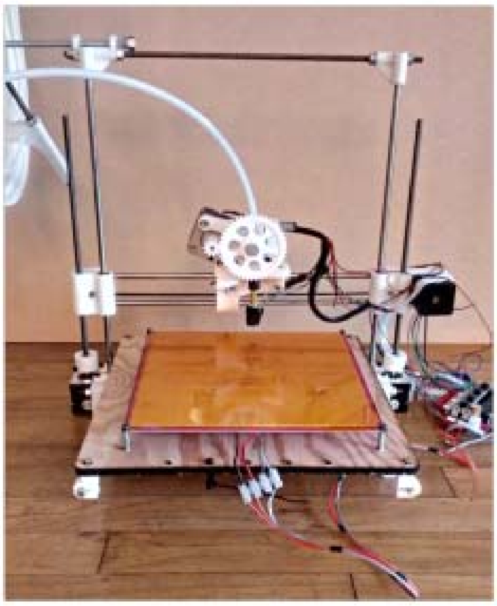

Figure 4: RepRapPro Wallace.

3. Basic components of RepRap machines.

The basic components of RepRap machines can be classified according to the type of components or the function that they execute.

a) Components by type.

There are four groups in this category:

Plastics components: They are replicable components. They can be manufactured by a RepRap. In Darwin and Mendel machines, the plastic components represent 48% of the total of the elements [3]. The material that forms them is normally PLA (polylactic acid) or ABS (acrylonitrile butadiene styrene). They include structural components, extruder components, carriage print components, etc.

Figure 5 includes a picture of a complete set of printed parts. The printer has been designed in order to use metal bearings which are easy to find: circular metal bearings are used by skates' manufacturers and they are sold as spares in sport equipment stores

Figure 5: Complete set of printed parts

Non-replicable structural components ("vitamins"): includes threaded and smooth bars, washers, nuts, circular and linear bearings, special parts for the extruder, belts... They are usually made of metal, steel or aluminum, except the belts that are usually plastics or flexible rubber.

Electronic components ("more vitamins"): they are the necessary electronic components for the printer operation, like microcomputer and electronic board, stepper motors, temperature and end stop sensors, resistances and cables.

The movement of the machine axes is achieved by stepping motors. The axis of these motors takes a turn with a fixed angle whenever it receives an electrical impulse. The motors that are often used are the NEMA 17, which is a standard of the National Electric Manufacturers Association (NEMA).

Software: The RepRap microcomputer (firmware) and the external computer (for sectioning parts and calculating the GCODE), which are necessary for the equipment operation.

b) Components by function.

From a functional point of view, the components of RepRap printers can be divided as follows:

Support structure: is the structure that supports the whole body of the RepRap.

Y, X, Z axes. Y axis movement is forwards/backwards movement; X axis movement is side to side, left to right; and Z axis movement is up and down along the vertical plane. Linear movement is generally accomplished using one of 2 different methods: Belt/pulley driven motion and threaded rod, or lead screw motion.

The extruder: is responsible for feeding filament through a nozzle and melting it as it's deposited into the bed where the part is made [4]. The extruder (Figure 6) consists of two parts: The cold end and the hot end.

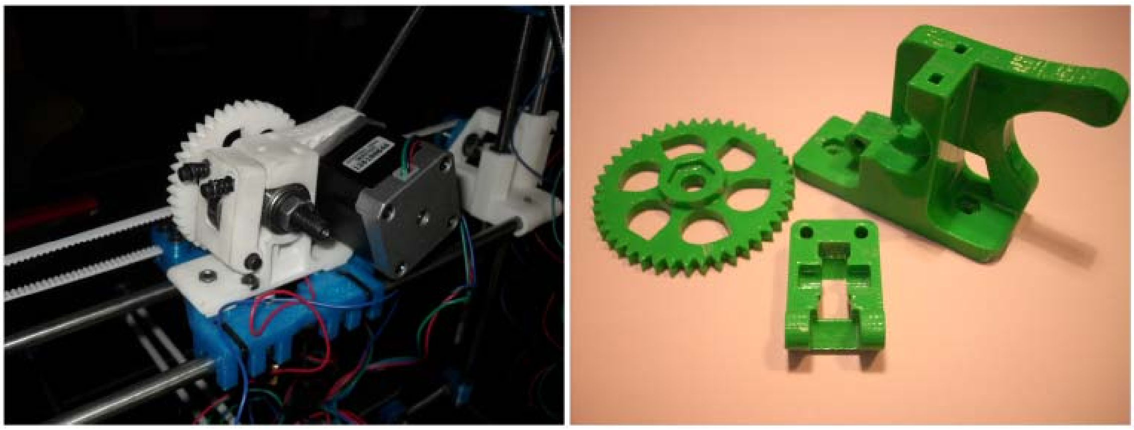

Figure 6: Extruder and extruder parts made by a FFF machine.

The print bed: is what the RepRap extrudes plastic into, where the plastic parts are built up. The print bed may be stationary, like the original reprap Darwin, or it may move along one of the x/y/z axes. The bed usually consists of two plates: the upper plate and the lower plate.

The heated bed. While a heated bed is considered an optional component of a RepRap, it often becomes necessary for operating a RepRap long-term because, without a heated bed, parts have a tendency to cool down too quickly.

The fusor: melts the fiber and puts it through the nozzle.

The end stop: is a very small and simple circuit board with a switch that tells the reprap when it has moved too far in one direction. Thus, there's normally 6 of these: 2 for each axis. A single end stop connects via wires to either: The controller or a stepper driver board.

The controller: is the brain of the reprap. It receives orders from outside, processes them and sends them to the printer.

Almost all reprap controllers are based on the work of the Arduino microcontroller. The most used controller are the Arduino Mega (with RAMPS expansion plate), the Sanguinololu (a Arduino variant which includes Pololu controllers and don’t need expansion plate) and the Generation 6 (a design made for the RepRap machines on one plate). All of them have 8-bit microcontroller of the ATMega family.

Figure 7 shows a picture of an Arduino Mega [5], with a expansion plate RAMPS v1.4 (Pololu expansion plate of RepRap Arduino Mega).

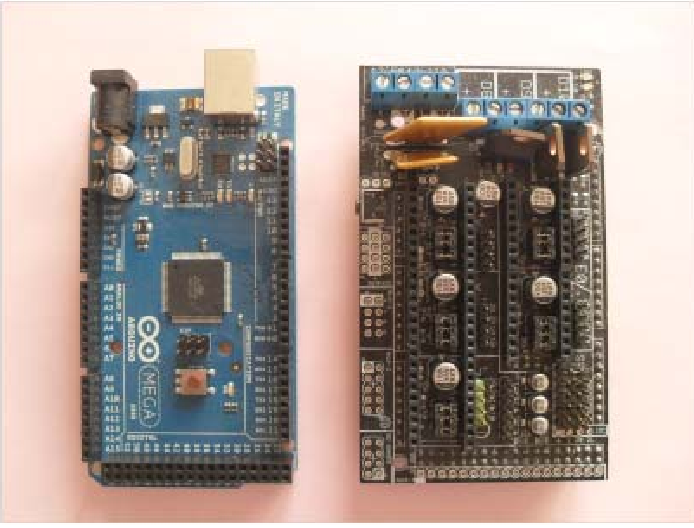

Figure 7: Arduino Mega and plate RAMPS v1.4.

The stepper motor: is a type of electric motor that can be accurately controlled by the controller. Most repraps use 4 to 5 stepper motors. 3 to 4 motors control the x/y/z axis movement and 1 motor is used per extruder.

The stepper driver: is a chip that acts as a kind of middle-man between a stepper motor and the controller. It simplifies the signals that need to be sent to the stepper motor in order to get it to move.

The software. There's specific software used for the machine operation, which can be divided into the following parts:

- *Firmware:* is the software installed on the microcontroller, which translates the GCODE received in motor movements, and it controls sensors and heaters. There are several alternatives for the Arduino, the most used being Sprinter [6], Marlin [7] and Teacup [8].
- *GCODE generator:* is the program that divides the piece printed in layers and generates the needed GCODE to build them. Installed on the external computer, it transmits the GCODE to the printer via USB or an SD card. The most used GCODE generators are Slic3r [9] and Skeinforge [10].
- *Printer control:* is the program for basic control of the printer. It allows you to pause and resume printing, set temperatures, control the motors, send GCODE commands and send gcode files with parts to print. The most widely used is the Pronterface [11].

The filament. Generally, people use one of two types of filament: ABS or PLA. ABS stinks and warps but is pretty strong, like legos, and PLA smells like waffles and is biodegradable. ABS fumes are also not good for your health. ABS will bend before it breaks and PLA is tougher but breakable as well. So, if you need a gear for instance, use PLA because it will preserve its shape longer.

4. User and exchange communities.

The social draught of this technology has been enormous and, as we have already said, its development is growing exponentially, allowing that design students and small architecture studies from all the world can test and perfect their creations before building them to real scale.

Accessibility to the technology has linked a number of user communities which exchange knowledge and experiences with the purpose of perfecting the printing system.

These user communities have developed various exchange platforms to download and print pre-existing 3D models. Thingiverse and Rascomras are two examples of platforms for loading and downloading of models.

Clone Wars is a group within the RepRap community, which seeks to document in Spanish everything in order for anyone to build their own 3D printer [12]. The Clone Wars project seeks disclosure of the RepRap technology, while it brings out new designs and new avenues of research, but not so much in the sense of being self-reproducing. This community was born in 2011 at the Universidad Carlos III of Madrid with Juan González, robotics professor who had previously attended a workshop taught by Adrian Bowyer. At the beginning of 2012 there were only 10 machines or clones; nowadays there are more than 223 clones which more or less actively participate in the community.

During the last 3 years, a series of workshops, called FabLabs (Fabrication Laboratories) have been held and promoted by the Center for Bits and Atoms (CBA) of the Massachusetts Technologic Institute (MIT). FabLabs are equipped with a series of machines controlled by computer "to build (almost) everything": printers in three dimensions, cutter laser, numerical control (CNC) milling machines and an electronic laboratory. The global computation of FabLabs is led by the United States which boasts more than thirty, followed by the Netherlands (with 9), France (with 8), Spain (with 7) and Germany (with 6).

5. Difficulties, development and assembly of a RepRap machine.

A common problem of the RepRap printers is the necessity of an external computer connected to the printer, usually by USB (Universal Series Bus), with the appropriate device controllers. This computer does the following functions:

- It processes files with the three-dimensional definition of the objects to print (usually STL files) and transmits orders to the printer (using the so-called GCODE commands). The computer must remain connected during the printing.
- It serves to load and modify the printer software, for example to calibrate it after a material change.

In order to avoid this dependence, there have been several variants of controllers that include memory card readers (normally SD cards), where you can burn files of GCODE orders from other computers and send them to the printer. In this case, it isn’t necessary to have external equipment, except for calibration.

In order to be able to identify the problems in the assembly of a RepRap machine and be able to propose alternatives that improve the process, we decided to build a RepRap Mendel Prusa, but with a number of modifications. This new machine was called RepRap Azara (Figure 8), following the custom of the RepRap movement in which are used names of personalities who contributed to the evolution study (in memory of Felix de Azara who was a Spanish naturalist of the 18th century).

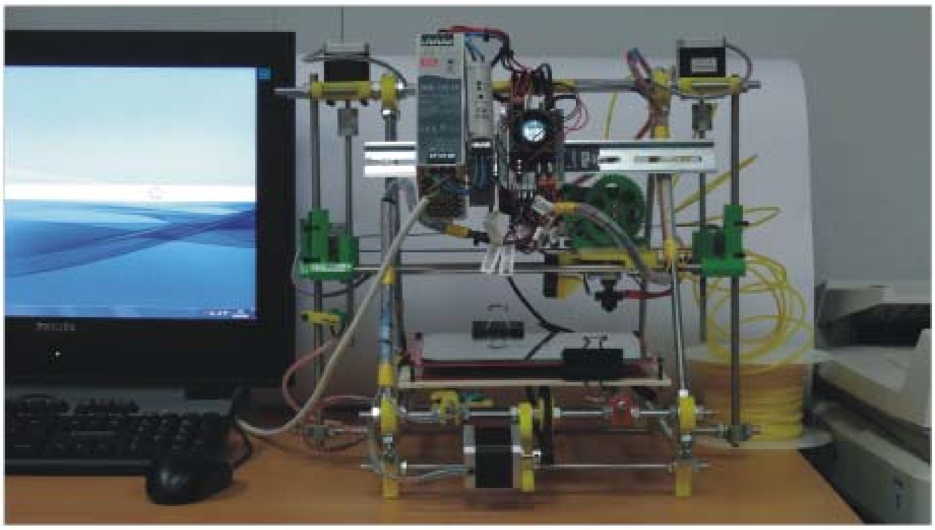

Figure 8: RepRap Azara.

Firstly, the controller was replaced by one much more powerful, with enough capacity to perform all the work that is currently done with the external computer. In this way, the necessity of an external computer connected to the printer has been completely removed.

For communication with the RepRap, an HTTP server is used (Hypertext Transfer Protocol, usually know as web server), installed on the new controller. In this way, the printer use and the calibration is done by web, so it is possible to use the machine with smartphones, tablets, etc.

In addition, it has made possible that the printer is able to transform three-dimensional designs in manufacturing orders, i.e., is able to transform STL files into GCODE instructions without external assistance. This prevents that users have installed special applications, properly calibrated for the printer.

Basically, the new RepRap variant replaces the electronics of the printer, replacing the original 8-bit controller (Arduino or similar) with a 32-bit microcomputer (Beaglebone) [13].

This controller change has involved the development of:

- An expansion plate of Beaglebone, with capacity to control stepper motors, heaters, end stop and temperature sensors.
- A new resident software driver (firmware), which is capable of transforming the GCODE commands into motor movements, control temperatures, etc.
- A web server, allowing calibration, the sending of three-dimensional design (STL) files or GCODE files, direct control of motors and temperature, etc.

The new design has also added advantages which are linked through a web server using:

- The printer can be used directly from any computer connected to the local network.
- The printer may be used at a distance, by configuring the router that connects it to the internet.

- A remote printer management can be done, which facilitates the maintenance of the machine.

The website developed for the printer control allows its use from any computer which is able to visualize the models and send files through an HTLM form.

The printers with SD card readers only print independently. They still need an external computer to calibrate or modify the firmware, and it can't be administered remotely.

In addition, we have improved some aspects of the printer structure. We detected recurring problems in parts that allow the movement transmission of the z-axis motors to the threaded bars, called z-axis engines. The original parts, printed in PLA by a RepRap, don't support an intensive use. In order to solve the problem, we replaced these parts with others of aluminum which have perfectly fulfilled their function.

We also verified that the extruder blocked after using several hours because the melted plastic was too fluid and ascended by capillary action from the fuser to the extruder where the plastic fiber solidified and blocked. In order to solve the problem, we modified the design of the extruder and we incorporated an electric fan which can cool the upper fuser area, avoiding the melted plastic to ascend.

But this fan cools the hot zone of the fuser. This situation causes difficulty to get the temperature of plasticization and increase the energy consumption. In order to avoid this, we designed a piece adapted to the fan which diverts the air flow to the low area of the fuser. New parts have been manufactured with our own RepRap printer.

6. Improvements and possible application fields.

After analyzing the characteristics of RepRap printers and the complete assembly of one of them, we could suggest, in general, some changes of improvements:

- Edit the thermistors tables from the browser, and access to the complete skeinforge calibration.
- Add an user control to the web page. If you log in as an administrator you can manage print permissions, change of tail order, calibration, etc.
- Create a remote administrator of the machine which access a log to be able to monitor the printed parts, changes, problems, etc. This remote administrator may be used to diagnose remote problems suffered by the printer.
- Add a video camera that could be used as a complement to the remote administrator, or to visualize at a distance the progress in the printing of the pieces. The images would be transmitted by the website of the printer.
- Improve the algorithm that makes movements in the printer to achieve more appropriate speeds and accelerations.
- Vary the design of the RepRap MendelMax, made of extruded aluminium profiles.
- Add an emergency button which instantly cuts the movement of the machine.
- Modify the expansion plate to allow a touch screen connection. In this way, you can completely manage the printer without having to connect to its website.
- Develop simple visualization software to facilitate the use of this type of machines to users without technical knowledge.
- It could also be considered in future works to improve the machines with new drives based on linear guides.

Due to the self-replication potential of the machines, it is possible to cheaply distribute RepRap machines to individuals and communities (you can buy a complete kit of a RepRap printer by approximately $700), allowing them to create (or download from internet) products and complex objects without the need of expensive industrial machines. Application fields where RepRap machines could be used are: architecture, industrial design, engineering, robotic, education, toys, jewelry, medicine, feeding, etc, but it is always necessary to take into account part of the problems discussed above when we are developing new projects.

7. Conclusions.

The RepRap technology will allow many small companies and engineering or architecture studies to have their own rapid prototyping machine.

The low-cost, self-replicating character, GPL license, ease of assembly and existence of user and exchange communities are some of the features of RepRap machines that are valued very positively by users. The main problem is that RepRap printers have much less precision than other 3D printers.

The RepRap machines still have a long way to go on improvement and research fields. That is the reason why the people working in this area are continuously increasing during the last years.

In terms of social impact, this technology opens a wide range of possibilities for anyone can manufacture its spare parts without having to resort a technical service, or in the case of discontinued equipments, when it is not feasible to find that piece in the market.

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