A Short History of 3D Printing, a Technological Revolution Just Started

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Abstract **-The paper reviews the short history of 3D printing and points out the possible impact on society of this new revolutionary technology which may soon change our way of manufacturing but also of working, playing and living**.

Index terms **– additive fabrication, history of technology, 3D printing**

I. INTRODUCTION

In the 1980s a new way of industrial fabrication, which traditionally was subtractive fabrication, was proposed, the so called additive fabrication. According to it 3D objects are produced by adding layers of material starting from nothing, instead of removing useless material from a full block. This way of fabrication has been called 3D printing with reference to a similar technology used in ink-jet printers.

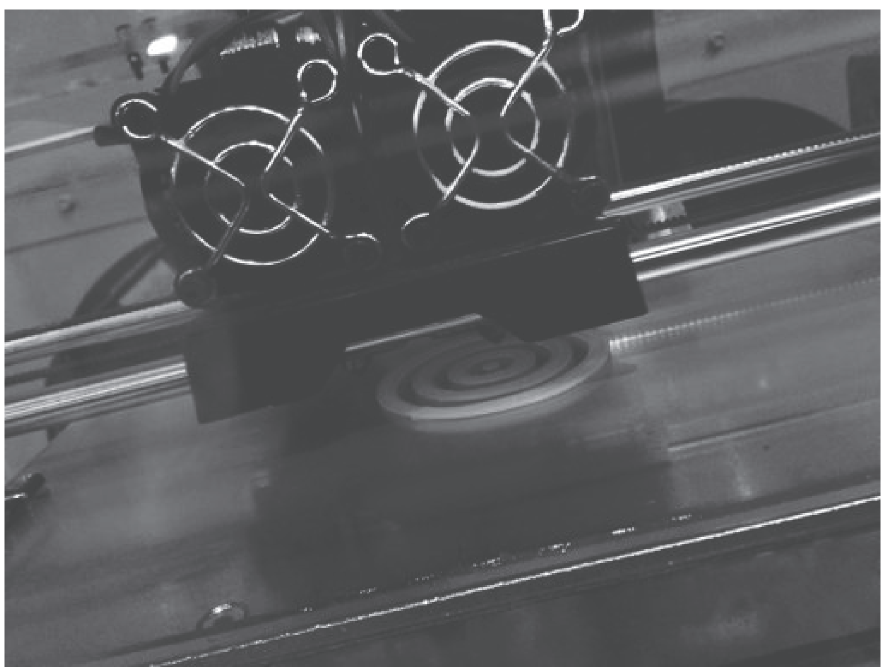

Fig. 1 Additive printer extruding ABS filament

Since then more than 30,000 patents about 3D printing are reported to have been published just in the U.S. Over the years various additive technologies have been continuously proposed from photo-polymerization to fusion deposition up to bio-printing recently. At the same time several open-source computer programs assisting the fabrication process have been made available on the web.
Nowadays the cost of a desktop 3D printer is affordable practically by everybody. Therefore probably we are at the beginning of a revolution in fabrication processes.

II. SUBTRACTIVE VS ADDITIVE FABRICATION

The traditional way for industrial fabrication of solid objects consists of removing material from a given solid block until the prescribed shape is obtained. It is called subtractive fabrication and uses tools like lathes and milling machines. Sculptors removing marble or other solid material from a block, potters shaping vases or craftsmen carving wood manually operate in a similar way.

The reverse way, i.e. adding material layer-by-layer to build up the three-dimensional object is called additive fabrication and is similar to the way of constructing buildings by adding bricks on bricks. Industrially it has not been used up to recent times.

A third way of fabrication of three-dimensional objects exists, i.e. forming liquid or plastic material into the required shape and then producing solidification of the material.

This last way used to be often employed in prototyping.

In research and development of new products, in fact, it is often required to design and then create prototypes, that are working models to be tested.

The advent of computers in the second half of the 20th century and the development of advanced computer software for computer-aided-design (CAD) and manufacturing (CAM) have revolutionized the ways of design, prototyping and fabrication.

III. COMPUTERS FOR DESIGN AND FABRICATION

As early as in the 1940s J.T. Parsons pioneered, and later in 1957 P. Hanratty developed, the numerical control manufacturing. The subtractive automatic fabrication of components in the aero-space industry was among the first application.

The past 40 years have been characterized by huge and fast progress both in computer hardware and software.

In short, on the one hand mainframe computers of the 1970s were followed by minicomputers and workstations in the 1980s and finally by personal computers in the 1990s, not to speak of smart phones, since 2007 combining computation and communication facilities in a single device.

As a result, increasing computation power at decreasing cost was offered practically to each engineer: a trend towards diffusion, and so to say democratization, of computation and communication resources.

On the other hand, computer aided design has radically changed the way of design. Solid modelling of 3D objects introduced in the 1970s and MicroCAD, later known as AutoCAD, appeared in 1982 made it possible to create models of 3D objects of any size by single architects and engineers. Again a trend towards the diffusion of tools of artificial intelligence.

But the new revolution in computer-aided manufacturing had still to occur in the 1980s when the computer-assisted additive fabrication of 3D objects was proposed.

IV. 3D PRINTING

A. *The origin*

Up to the 1980s additive fabrication strategies had no practical application in industrial context except in electronic industry for the fabrication of microchips.

In the late 1970s various methods for computer-assisted additive fabrication using different technologies started to be proposed. They were the subject of early patents. More comprehensive patents were developed in the 1980s. Here the main achievements are reported chronologically and with reference to the fabrication technology. Charles Hull invented stereolitography (STL), a process making liquid polymers harden under ultra-violet light. He described a method and an apparatus for making solid objects by depositing layer-by-layer of this material in a patent issued on

August 1984 /1/. The first object he was able to build was a cup 5 cm tall and the fabrication process lasted months! /2/. Two years later he founded 3D System, a company producing and selling the fabrication machinery.
The Laminated Object Manufacturing (LOM) technology was developed towards the end of the 1980s /3/. By this method cross-sections of an object are cut from paper using a laser, then a plastic coating is melted on the bottom side of the paper layer. Applications were not particularly successful over the years. Producers were Helisys (USA), Solido3D (Israel) and Kira (Japan) among others.
Another technology for additive manufacturing was invented at the University of Texas. It was called Selective Laser Sintering (SLS) and consists of melting particles of powder by a laser beam. The relevant US Patent by C.R. Deckard was issued in 1989 /4/. After producing academic machines, DTM Co., a start-up of the University, started to build commercial machines cooperating with 3D Systems by which it was acquired in 2001.
In the early 1990s at the Massachusetts Institute of Technology technologies for 3D printing with the trademark 3D printing were developed. The fabrication technology adopted was inspired by ink-jet technology first developed by Canon Co. in 1979. The US patent by E.M. Sachs et al /5/ was commercialized by Z Co. The term 3D printing popularly started to be used in a broad sense.
Already in the late 1980s C.S. Crump developed the Fused Deposition Modeling (FDM) technology based on the deposition of thermoplastic material layer-by-layer using a 3-axis robot /6/. He patented this method and apparatus in 1992 and founded Stratasys Inc. In 2012 Stratasys merged with Objet Ltd a leading manufacturer of 3D printers based in Israel. The Fused Deposition Modeling then became the fabrication process on which most of desktop printers rely.

B. *The large expansion*

Up to the early 2000s 3D printers were expensive machines normally employed in industries for prototyping.
About in the year 2005 initiatives started with the goal of offering individuals low-cost and non-proprietary printers. In that year a project was carried out at the University of Bath by A. Bowyer in order to develop a 3D printer which was able to produce most of its own parts /7/. The name of the project was Rep Rap (Replicating Rapid prototyping). The Rep Rap printer consisted of a 3-axis robot mounting one or more extruders using Fused Filament Fabrication derived from Fused Deposition Modeling. Software and hardware were open-source, including the electronics based on Arduino platform. The addressed market was that of individuals (Do It Yourself (DIY) or Makers) who were invited to modify and produce parts of their own printers.

Fig. 2 Spare parts of a 3D Printer designed and produced in laboratory

A similar initiative took place in 2006 at Cornell University, USA. Fab@Home was the printer developed by open-source hardware and software /8/. It consisted of a 3-axis system moving multiple extruders depositing a broad range of materials. The purpose was that of evolving from industry to home fabrication, replicating the revolution occurred in the field of computation from industrial mainframes to desktop computers.
Based on the Rep Rap project, in 2006 MakerBot Industries were established in New York City providing do-it-yourself kits for anyone with just basic technical skill. Over the years MakerBot moved from open to closed source hardware. In 2013 it was acquired by Stratasys Inc.
The open-source revolution produced a sort of large diffusion and democratization of additive manufacturing so that practically people could afford to create objects by their own /9/.
The true revolution was the impressive expansion of consumer 3D printing. Herald of this process towards personal fabrication was N. Gershenfield who since early in the 2000s at the Media Lab in the Massachusetts Institute of Technology has been teaching a class on "How to make (almost) anything" /10/. A movement promoting diffused FabLabs (Fabrication Laboratories), creating communities of makers (do-it-yourself enthusiasts, hobbists, artists and crafts people) originated. A number of Makers Faires followed the first one held in 2006.

V. AN OVERVIEW OF MATERIALS, TECHNOLOGIES AND APPLICATIONS

The landscape of 3D printing materials, technologies and applications has become so large that it is hard to summarize even its main characters.

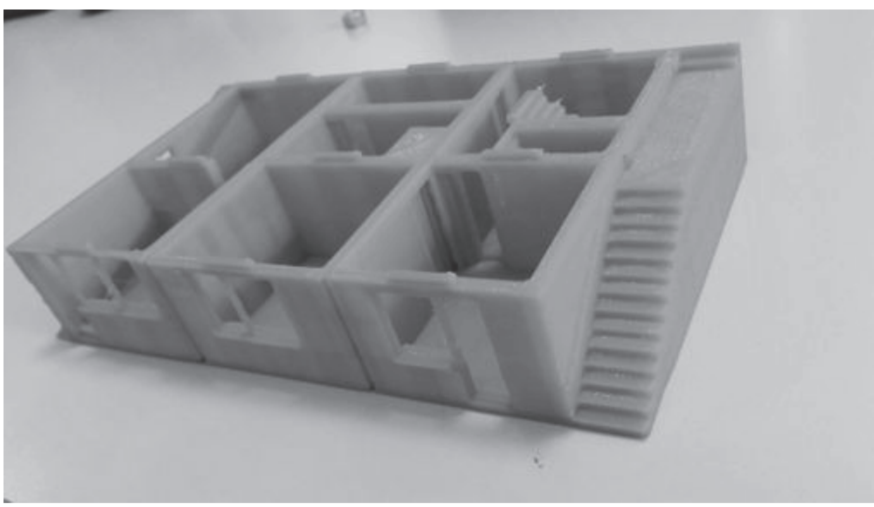

Fig. 3 Section of a house printed in PLA for architectural variations

It has been reported that the number of US patents about 3D printing techniques amounts to over 20 000 since mid 1980s. The first patents expired a few years ago; since then an explosion of new patents took place including improvements of known technologies and introductions of new ones. New materials are being introduced, tested and used in addition to traditional ones (photopolymers, wax, aluminium, thermoplastics, paper, etc.). Among others, metals (titanium, nickel), ceramics, epoxy resins are increasingly used, not to speak of unusual materials for new applications like clay for constructions and e.g. chocolate for food. The re-use of waste plastic material is also under investigation.

Among technologies for printing, Stereolitography, Selected Laser Sintering and, particularly, Fused Deposition Modeling with its variants are still the most frequently employed techniques, while, for instance, Laminated Object Manufacturing is less used and new technologies are

emerging like Electron Beam Melting and Laser Engineering Net Shapes.
The areas of applications of 3D printing are practically borderless. Traditional areas are: i) aircraft and automobile industries using mainly metals and plastic materials; ii) electronics for printed circuit board employing epoxy and other resins; iii) robotics and mechanical tools using metals, ceramics and plastics. A fast growing area is prosthesis and tissue engineering (bones, blood vessels, kidney, liver, teeth, regenerative medicine) which uses a variety of materials (wax, ceramics, plastics, etc.). Other developing areas are fashion (jewels, clothes, shoes), toys and leisure and food. Finally one has not to forget education and the broad domain of home fabrication.

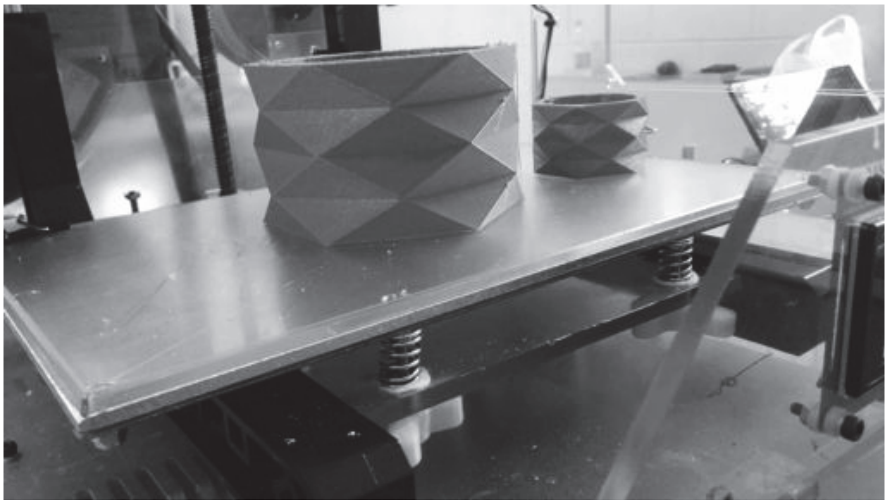

Fig. 4 Prototypes of jewels printed in silicone-based filament

A list of major achievements across the history of 3D printing since 2000 includes:

2002 the first functional kidney printed;
2005 the first self replicating printer;
2008 the fist 3D printed prosthetic leg;
2009 3D bio-printing using patient's cells to produce blood vessels;
2011 the first 3D printed unmanned aircraft flying;
2011 the first car with a 3D printed body;
2013 3D printed Terahertz waveguide of the size of 100 microm;

Among the latest news:
2014 zero-gravity on-board 3D printer;
2014 3D food printing;
2015 the first 3D printed cement stuck 3 m high.

VI. SOFTWARE, HARDWARE AND PRODUCERS OF 3D PRINTERS

The starting point of 3D printing is the creation of a geometrical model of the 3D object to be built. Modeling tools normally are based on geometrical shapes (CAD tools) or may receive data from a scanner of a real-life object. Other tools are based on free-form shapes. Once the model has been created, it must be "sliced" into layers. Then a code must be generated to feed into the 3D printer. The basic software including the above described processes may be offered by the producer or downloaded from the Internet free. For professional printers it is sold by the producer.

As concerns the hardware, one must think that a 3D printer is nothing but a mechanical robot

moving the device depositing the layer of material along 3 axes. The little motors are generally stepper motors. Typical layer thickness is about 100 microm down to 16 microm. The working space of the printer (assembled build envelope) normally ranges from 100x100x100 mm to 600x600x600 mm. Personal printers lay in the lower range. The weight of the smallest 3D printer is 21.5 kg. The time required to create an object depends on the shape of the object and the quality of the result. For pretty simple objects it is of the order of minutes.
Among the top companies in the market producing and selling 3D printers there are: 3D Systems Inc.; Stratasys Inc with its associated Objet Ltd and MakerBot Industries; Hewlett Packard and Hitachi. The number of producers is huge, especially if one considers the market of desktop personal printers. Some companies are specialized according to applications, like Organovo (bio-printing), Arcam (metals), Alphaform (art product) or huge machines (Voxeljet, ExOne).
Acquisitions, merging and alliances of companies are very frequent.
Leading country producing 3D printers remain the USA, followed by Japan and, increasingly, China, Israel, in joint venture with the USA, and European countries.

The cost of 3D printers has dramatically decreased in the past fifteen years. For instance, what previously cost 20,000 dollars now probably costs less than 1,000 dollars. At present the range of costs is from a few hundred dollars to hundred thousand dollars, moving from personal to industrial printers.

VII. A CROSS-INDUSTRY INNOVATION PATH

Another important aspect to be taken into account during the analysis of the historical steps of 3D printing technology is the one related to the ecosystem of players driving innovation in the 3D printing industry. Moreover, in order to perform a correct and precise study it is necessary to understand the origin of the actors participating in the innovation curve and to treat industry as a new one. Otherwise one could make the mistake of expecting the greatest innovation forces to be incremental innovations arriving only from already established firms operating in few of the industries mentioned earlier, such as the old printing one.

In our analysis we define two heterogeneous categories of actors operating in the 3D innovation field: producers and designers. The first category includes both hardware and software producers, that rely on their technical know-how to develop incremental and radical innovations. Large incumbents belonging to this category usually respond to the mass market needs and are therefore unable to foresee the increasing need of the smaller niche made of innovators and early adopters /11/. Smaller and more recent producers are more flexible in terms of product development capabilities and compete in a fierce market composed of other start-up firms that are trying to emerge in which usually breakthrough technology advances take place. Indeed, these players represent the connection between large firms, that potentially have the resources to strongly diffuse the new technology in the mass market, and the second category of actors defined, that is designers. More specifically, this category is composed of the large universe of small organizations and individuals that are driving innovation in the 3D industry giving new meaning and functionalities to innovative sets of hardware. In fact, these players often come from industries in which technology still represents an expensive tool available in the market for few, whereas in the newborn 3D Printing industry technology becomes a flexible and democratic solution to evolving needs.

In this sense, our review aims at demonstrating how not only 3D Printing is affecting high-tech industries. Indeed, a number of low-tech sectors and consequently many traditional business models that most of marketers thought to be valuable in the long-term are rapidly evolving towards new forms that are surely going to change daily routines of people in the world.

VIII. LOOKING AT THE FUTURE

On speaking of 3D printing, the new manufacturing technology, the term revolution is often used. The technology has just come out of its infancy, is tremendously growing and it is incredibly hard to foresee the long-term impact on the manufacturing world and, in general on economy and society.
Someone expects as large an impact on the world as that, for instance, produced in the past by the invention of the steam engine which started the first industrial revolution or, more recently, by the diffusion of personal computers and smart phones.

“The industrial revolution of the late 18th century made possible the mass production of goods, thereby creating economies of scale which changed the economy – and society – in ways that nobody could have imagined at the time. Now a new manufacturing technology makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. It may has as profound impact on the world as the coming of the factory did.” /12/

The second industrial revolution will be probably characterized by production increasingly taking place not in large factories but in small laboratories, or even at home, thanks to 3D printers, powerful concentration of hardware and software. Delocalization, democratization and customization will be brought about by the progress of the new technology.

“Three-dimensional printing makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. It may have as profound an impact on the world as the coming of the factory did. Just as nobody could have predicted the impact of the steam engine in 1750, or the printing press in 1450, or the transistor in 1950. It is impossible to foresee the long-term impact of 3D printing. But the technology is coming, and it is likely to disrupt every field it touches.”/12/

Two years ago the President of the USA, to much surprise of lay people who never heard of this technology before, announced the commitment of the country in fostering this revolution /13/:

“There are things we can do, right now, to accelerate this trend. Last year we created our first manufacturing innovative institute in Youngstown, Ohio. A once-shuttered warehouse is now a state-of-.the-art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything. There is no reason this can’t happen in other towns.
So tonight, I am announcing the launch of three more of this manufacturing labs….And I ask this Congress to help create a network of (15 of) these hubs and guarantee that the next revolution in manufacturing is made here in America.
We can get that done.”

What is certain is that just twenty years from now the way of fabrication will probably be much different from that we can imagine right now.

REFERENCES

/1/ Apparatus for production of three-dimensional objects by stereolithography , C.W. Hull, US Patent 4575330A, August 1984.

/2/ Layer-by-layer: the evolution of 3D Printing. IEEE member Charles Hull invented the original process in 1983, IEEE Spectrum, 14 Nov. 2014

/3/ Apparatus and method for forming an integral object from laminations, M. Feygin, US Patent 4752352, 1988.

/4/ Method and apparatus for producing parts by selective sintering, C.R. Deckard, US Patent 4863538, 1989.

/5/ Three-dimensional printing techniques, E.M. Sachs et al, US Patent 5204055, December 1989.

/6/ Apparatus and method for creating three-dimensional objects (A system and a method for building three-dimensional objects in a layer-by-layer manner via Fused Deposition Modeling), S. Scott Crump, US Patent 5121329, June1992.
.
/7/ Bowyer A., The Self-replicating 3D printer – Manufacturing for the Masses, in Eight National Conference on Rapid Design, Prototyping and Manufacture (D.M. Jacobson et al ed.s), Buckinghamshire Chilterns University College, 2007.

/8/ Malone E., Lipson H., Fab@Home: the Personal Desktop Fabricator Kit, Proc. of the 17th Solid Freeform Fabrication Symposium, Austin, TX, Aug. 2006.

/9/ von Hippel E.A., *Democratizing innovation*., MIT Press, Cambridge, MA, April 2005

/10/ Geshenfeld N.A., *Fab: the coming revolution on your desktop – from personal computers to personal fabrication*. New York Basic Books, 2005

/11/ Rogers E., *The diffusion of Innovation*, The Free Press, New York, 2003

/12/ Print me a Stradivarius. How a new manufacturing technology will change the world, The Economist, February 10, 2011.

/13/ B. Obama, Address on the State of the Union, January 21, 2013

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