Augmenting Architecture Through Desktop Manufacturing

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Abstract

Personal desktop manufacturing, with its roots in hacker culture, is on the cusp of exploding into the main stream due to the advent of affordable personal 3D printers. This paper is an exploration of these advances in desktop manufacturing technology and their impact on our relationship with products and the built environment. The paper draws parallels to the personal computing and desktop publishing revolutions that offer clues to the future of personal desktop manufacturing. Four major themes have emerged from this exploration: Personal empowerment, remote printing and collaboration, full-scale digital construction, and, most intriguingly, architectural prosthetics. Based on an open-source philosophy and creative commons licensing, desktop manufacturing is redefining our relationship with large manufacturers and is beginning to convert us back from a consumerist culture into a creator one.

1. INTRODUCTION

Digital manufacturing is traditionally viewed as a way to close the circle of a digital design process from concept to construction [1]. It enables the physical realisation of digital constructs. The advent of desktop-based manufacturing has placed that ability in the hands of a very large number of architects, designers and students that now regularly use it to create physical models of their ideas. *Augmented reality* is traditionally associated with the concept of superimposing virtual data and imagery over physical reality. This paper, however, addresses a different notion of augmented reality: the augmentation of physical reality with *physical* rather than virtual artefacts produced through digital fabrication processes. As we will see later in the paper, this prosthetic notion is rooted in our primordial need to use tools to repair, augment, enhance, and extend our abilities. Compared to the amount of literature on traditional augmented reality, little has been seriously discussed and published regarding how this prosthetic technology augments and modifies our design process and the physical built environments we produce.

2. DESKTOP MANUFACTURING

One of the earliest desktop manufacturing machines is a self-replicating machine called the RepRap [2]. The RepRap machine (short for Replicating Rapid-Prototyping machine) is an open-source community project conceived at the University of Bath, UK. The project's aim is to spread the manufacture of the machine by having each parent machine print out the majority of its own parts to build children machines that, in turn, would print out parts to build more RepRap descendants. In addition to the ability to print 3D objects at home or the office, the project created a community of individuals that collaborated and helped each other build and improve the machines using open-source hardware and software. It created an empowered creator culture that could augment consumer products with self-manufactured ones. Being an experimental project, however, the robustness of the machine is questionable and, more disappointingly, there is a long waiting list to obtain the parts from another RepRap machine to build one's own. An alternative to the RepRap exists that is manufactured as an open-source kit of parts that one would assemble into a functioning 3D printer. The company that invented it is called MakerBot Industries [3] and the machine is called the Thing-O-Matic (ToM). The MakerBot ToM has a maximum printable size of approximately 100mm (4 inches). Given the ready availability of the ToM, it was used as the main vehicle for experimentation in the project reported on in this paper.

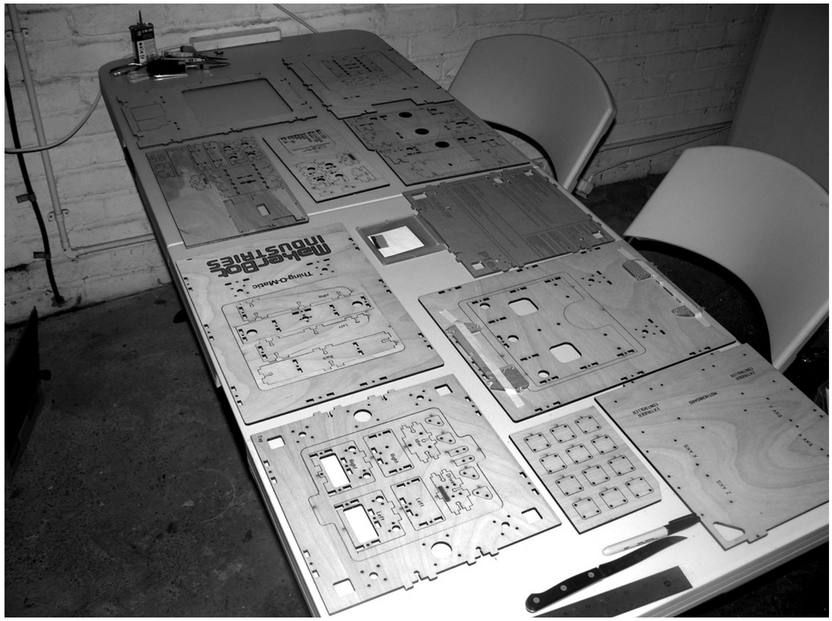
3. FROM HACKER CULTURE TO CREATOR CULTURE

The hacker community started in the 1940s and flourished in the 1960s at places such as the Massachusetts Institute of Technology where a *hacker* was not viewed as a malicious person that hacks into protected networks as it is often portrayed in today's popular media, but rather someone who pushed the envelope of what a technology could do through inventive and sometimes unorthodox methods. Ironically, many early hackers that created interesting solutions and projects in their garage moved on to become the CEOs of the largest consumer companies in the world. In 1937, William Hewlett and David Packard started their company (HP) in the garage at 367 Addison Ave. in Palo Alto, California. Steve Wozniak and Steve Jobs also started Apple Computers in Jobs' parents' garage at 2066 Crist Drive, Los Altos, California building computer kits that needed to be assembled at home. Wozniak and Jobs got their notoriety at one of the earliest hacker groups, the Homebrew Computer Club, where hackers and enthusiasts met regularly to share their accomplishments. We see similarities with the Makerbot online community, *Thingiverse* (http://www.thingiverse.com/), where modifications and improvements to the 3D printers are shared as well as computer files of 3D objects that can be printed by anyone owning a 3D printer.

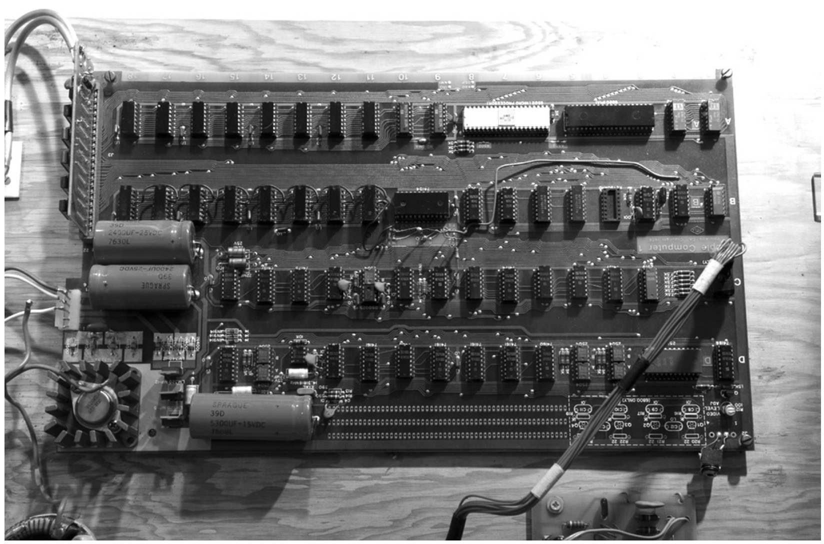
Yet, following a hacker mentality in some academic departments can be a challenge. Health and safety concerns such as the flammability of ABS plastic (the ingredient 3D objects are made of on the ToM) and the possibility of emitting toxic fumes causes many health and safety managers a lot of concern. Being a kit of parts rather than a tested consumer product, the ToM even fails the basic electrical safety testing conducted by the university to prevent electrical fires. To approve the use of the ToM, the university has to regard it as an experimental piece of equipment that requires close supervision.

4. ASSEMBLAGE

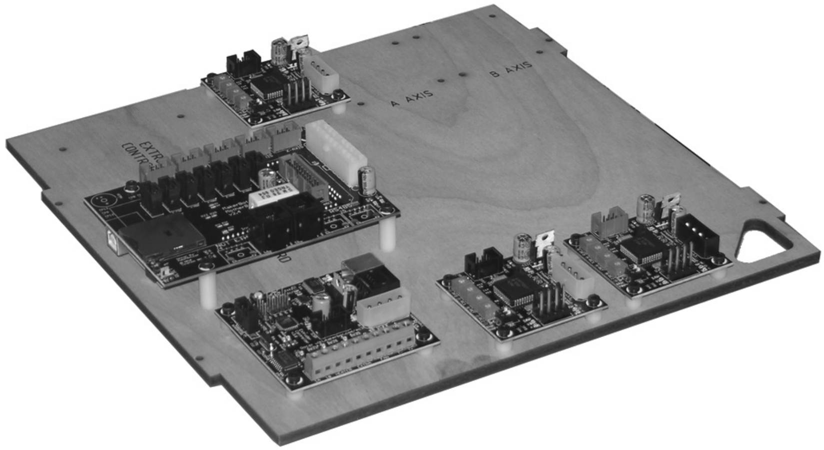
The current do-it-yourself and hacker communities have advanced the idea of building open-source laser cutters [4], CNC machines [5] and other machinery that traditionally was only affordable to large organisations. One of the first things that were intriguing was the fact that the MakerBot ToM is mostly made out of precision laser-cut parts [Figure 1]. The full list of parts is available online and can be either sourced or laser cut and assembled. The MakerBot ToM printer has a strong similarity to the early Apple I computer from the 1970s [Figure 2]; its circuit board is also mounted on wood [Figure 3]. If the Makerbot ToM follows the same trajectory as Apple Computers, advances in its technology, speed, precision and capability, and an inevitable streamlining of its form are surely to follow. The late Dean of the school of architecture at MIT, William J. Mitchell, once said at a conference I attended several years ago (paraphrasing): "Do not take into consideration current technology, it will change before you know it. Design [it] the way you ideally would like [it] to work and technology will soon follow."



► Figure 1. Laser-cut Makerbot body parts.



► Figure 2. Apple I circuit board.



◀ Figure 3. MakerBot ToM circuit board.

The MakerBot ToM is made up of several major parts:

1. The Build platform (with an automated delivery belt)
2. The horizontal (X and Y) axes
3. The vertical (Z axis)
4. The extruder motor
5. The sensors
6. The motherboard
7. The enclosure

4.1. Fused Filament Fabrication

The MakerBot ToM is in the class of 3D printers and a manufacturing technology known as Fused Filament Fabrication that uses an additive manufacturing process. A nozzle heats a filament of plastic and extrudes it unto a table or bed that moves horizontally in the X and Y-axes. It builds the 3D object in layers of molten plastic by moving the nozzle up on a vertical Z-axis. As the plastic cools, the layers adhere to each other.

4.2. X, Y, Z … and A and B

The MakerBot ToM is basically a 2D plotter with three extra dimensions. The basic bed is an automated heated build platform that moves on the X-axis via a stepper motor and belt. The heated platform is then mounted on another stage that moves in the Y direction using another belt and stepper motor. So far, this is exactly like the old-style pen plotter. The nozzle that extrudes molten plastic moves on a vertical axis (the third dimension) using a threaded rod mounted to a stepper motor. The fourth dimension is the extruder motor that pulls in a filament of plastic and starts and stops on command. Lastly, the fifth dimension is a conveyer belt controlled by a motor that delivers the 3D object when it is done. With future modifications, this conveyor belt could be used to print extra long pieces and to replace the current Y-axis in a fashion similar to traditional plotters.

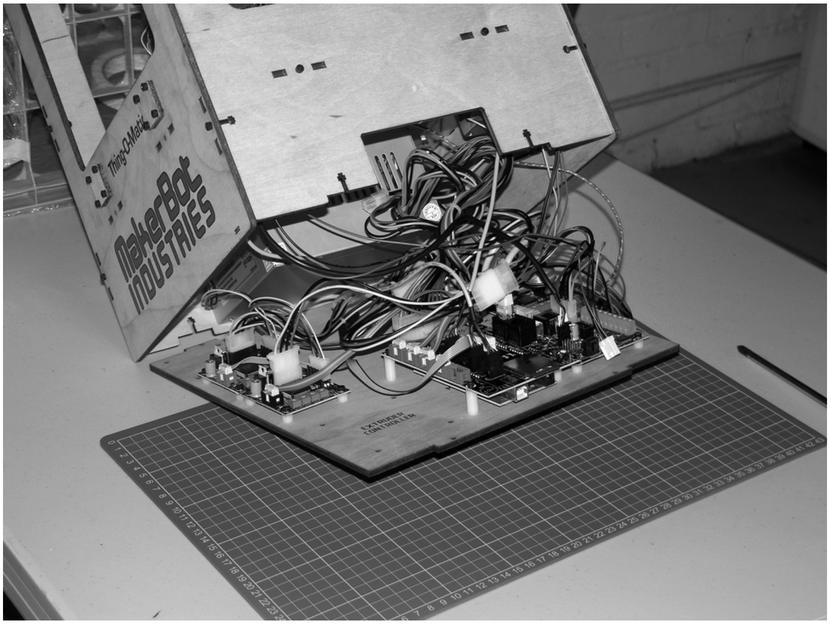
4.3. The extruder and heated core

The extruder is made of two parts: the step motor that pulls in the plastic filament from above, and the heated nozzle that melts the plastic and produces the molten material needed to build the object layer by layer [Figure 4]. The heated element needs to reach a temperature of 220 Celsius. It is, thus, insulated with ceramic tape and wrapped with Kapton tape (the golden-colour element in the centre of the image).

► Figure 4. Extruder and heated element (the plastic filament is fed from above).

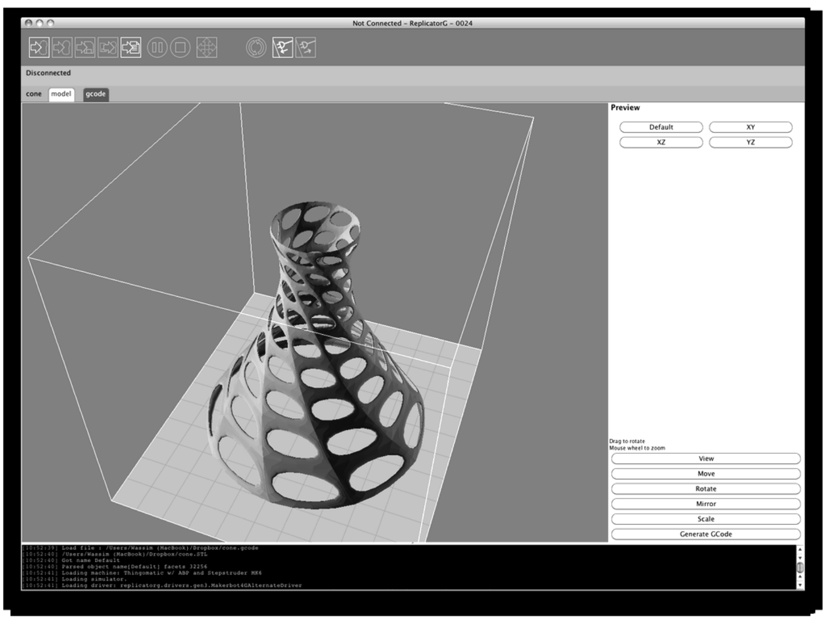
4.4. The electronics and the software

The MakerBot maintains its focus on open-sourcing most of its components. Thus, the main driver under the Motherboard is an *Arduino* prototyping board popular with the open source community [7]. The board communicates with several stepper drivers with potentiometers that control the current and speed of the stepper motors [Figure 5].



◀ Figure 5. The electronics components and power supply.

The software, called Replicator-G [7], is based on MIT's open-source *Processing* environment [8] and can create the necessary tool path (GCode) from an imported 3D model [Figure 6].

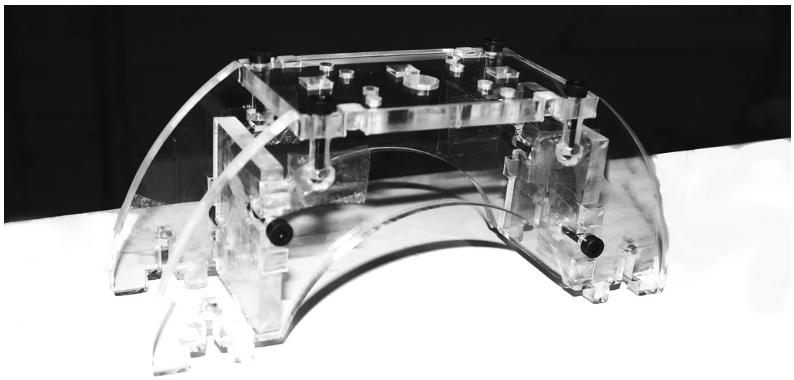


◀ Figure 6. The Replicator-G software interface.

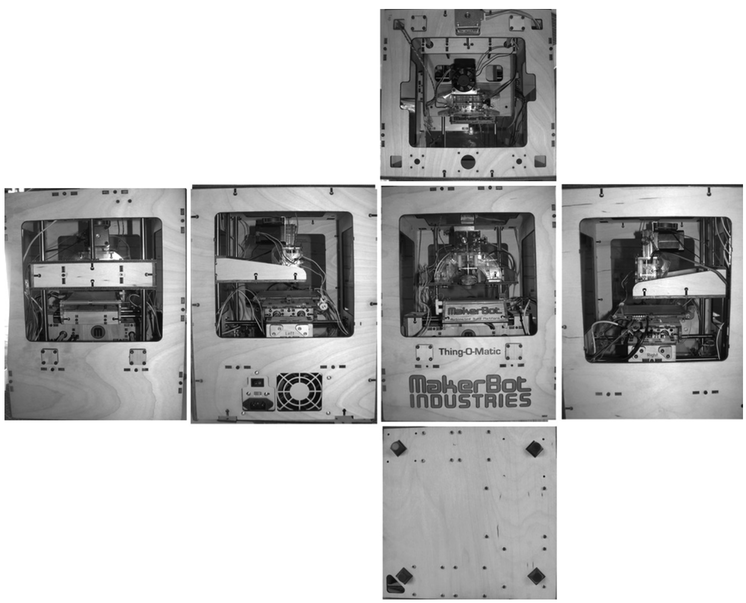
► Figure 7. "Bridge" structure for the MK6 extruder.

5. THE ARCHITECTURAL LANGUAGE OF THE MAKERBOT TOM

The ToM's construction bares a similarity to the language of architectural construction [Figure 7]. For example, the ToM can be viewed as a model for constructing a house. It has four elevations, a top and a bottom that are secured to each other structurally [Figure 8]. The main assembly technique is the T-connection. Two tabs are inserted into corresponding holes; a bolt and a nut are then used to secure the connection. Glue is used only in a few places to secure bearings. The accuracy of the construction is surprising. The precision laser cut panels forced a certain architectural logic (or language) through asymmetry where male and female parts would meet and connect; cross-bracing elements would naturally be fitted between walls to secure their orthogonal integrity.



► Figure 8. The MakerBot ToM unfolded.



6. THE FUTURE OF DESKTOP MANUFACTURING

By conducting this experiment in personal desktop manufacturing, several issues emerged regarding the impact and the future development of this technology in the field of architectural design and direct digital fabrication. The themes that emerged can be categorised into four topics: personal empowerment, remote printing and collaboration, full-scale digital construction, and prosthetics.

6.1. From desktop publishing to desktop manufacturing: Empowering individuals and communities

Before 1985 the only method for producing one's own documents was the typewriter. A professionally printed pamphlet, magazine, or book needed the services of a large and expensive printing press. The arrival of the computer, personal WYSIWG publishing software (mainly Aldus PageMaker), and personal dot matrix, inkjet, and laser printers revolutionised the publishing industry. The Apple LaserWriter, introduced in 1985, is specifically credited with bringing high quality desktop publishing to the masses [Figure 9].

◀ Figure 9. An Apple Mac and LaserWriter, circa 1985.

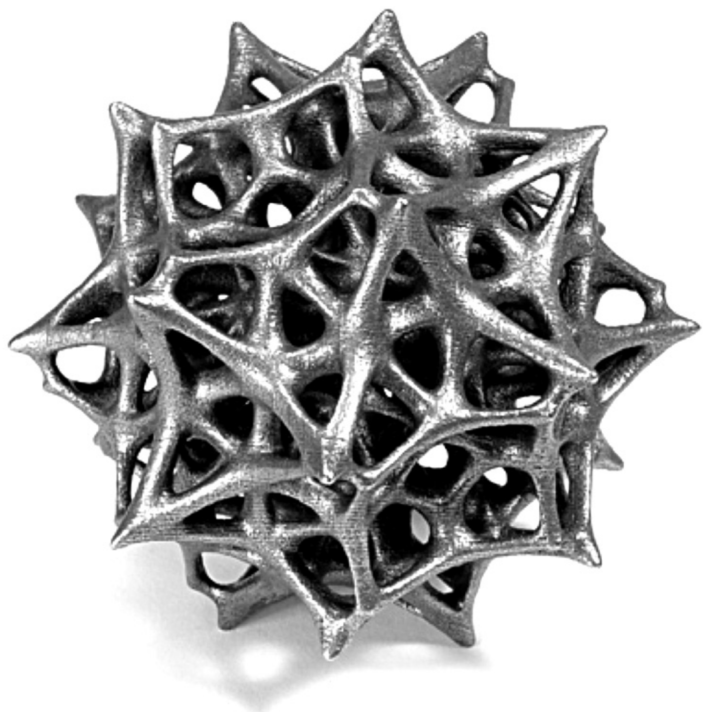
The parallels between personal desktop publishing and the current personal desktop manufacturing are striking. The 3D manufacturing technology as it stood just a few years ago required big, heavy, and expensive machines (laser cutters, CNC machines, 3D Printers etc.) and only commercial companies or universities could afford to purchase them. They were and, in many cases, still are housed in centralised *Fab Labs* that are not dissimilar to spaces that house printing press machinery. Access to this equipment is severely limited when compared to access to a personal laser printer that now costs only a small fraction of what it did a few years ago. Similarly, personal desktop manufacturing is on the cusp of exploding into the main stream due to the advent of relatively inexpensive personal 3D printers. Imagine a scenario, in the very near future, where students have the machine connected to their laptops. They design a building component, print it out to test its physical appearance and performance, and re-iterate.

The artist Bathsheba Grossman is exploring that process by investigating the region between mathematics and art. She uses 3D printing as the main vehicle for her design creativity [Figure 10]. She writes:

> "In the last years of the 20th century, 3D printing was developed to a level that could do my work, and then, quite suddenly, I began to be an artist" [9].

If a 3D model can be designed and printed within the span of a few hours currently, one can expect to be able to do that in minutes in the future and that means that 3D printing can enable rapid design iteration and thus be more tightly integrated in the design process at earlier stages. The personal manufacturing capability thus transforms the technology from a method for final output to an augmentation to an iterative design process at a personal level.

► Figure 10. *Vorocube*, Bathseba Grossman. (metal, 3D Printed).



This compression of time will be important to the fluidity of the design process much as rendering farms, more powerful computers, and advanced analysis software have made it feasible to iterate through design proposals, test their performance and feed the results back into the process. Larry Sass of MIT, for example writes: "The speed in production does change our understanding of the design and inspire us to extend our interests in building new design variations of previous ideas" [10]. Personal 3D manufacturing will level the playing field between big and small firms such that any individual, and not only large firms, can have access to printing out their models.

6.2. Remote Printing

One of the intriguing possibilities for 3D printers is the ability to print remotely. Imagine a scenario where a construction contractor finds out, on site, that a building component does not quite fit and requires changes. The designer, back at the office, can make the changes and send the file to the contractor's 3D printer that prints out a new and upgraded part. To make things more interesting, imagine that the construction was in a zero-gravity environment in space. NATO and NASA are interested in this question and have pioneered a rapid metal deposition process called Electron Beam Freeform (EBF) Fabrication [11]. This technology will enable the 3D printing of replacement parts on a space station without the need to re-send them as a payload on a rocket from Earth. One can imagine similar uses in remote areas on Earth, such the arctic region, where accessibility can be an issue. While still conceived as a fabrication laboratory, MIT's field fablabs are mobile units that travel to remote areas to empower communities to manufacture their own products [12]. Mobile fablabs have travelled to India, South Africa, and northern Norway to manufacture wind-powered turbines, instruments for agriculture and custom housing. It is perhaps not surprising that theses initiatives come from MIT where one can trace their roots to the hacker culture found at MIT's TechModel Railroad Club (TMRC) which was founded in 1946 and played an important role in creating the first example of hacker culture by finding out how things worked and sharing knowledge to empower a community rather than monopolise and patent technology to sell to 'consumers'.

6.3. Full scale digital construction

The idea of printing out full buildings digitally is certainly not new. However, we are seeing advances in the technology that are making it a reality. In the period 2006-2008, Larry Sass and Marcel Botha of MIT created the well-publicised House For New Orleans [13]. The house, exhibited at the Museum of Modern Art in New York, consists of 600 plywood and plastic sheets that are digitally manufactured and assembled using mainly friction joinery. The house for New Orleans is both mass-standardised as well as mass-customised to fit the needs and tastes of its inhabitants [Figure 11, Figure 12]

► Figure 11. Digitally fabricated *House for New Orleans* by Larry Sass et al (MIT).

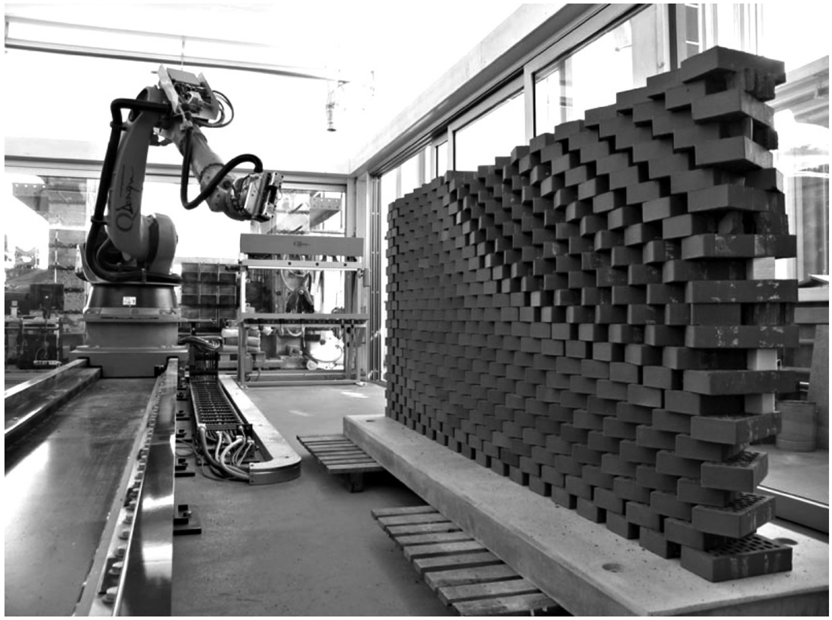
► Figure 12. Friction Joint Detail, House for New Orleans by Larry Sass et al (MIT).

While the House for New Orleans uses mainly a subtractive CNC process to cut sheets into the required shape, the Radiolara pavilion project is an intriguing example of direct 3D printing using an additive process [14]. Radiolara is an experimental structure developed by Andrea Morgante (Shiro Studio) and Enrico Dini (d-Shape). In 2008, d-Shape developed the first 3D mega printer that allows free-form construction of monolithic, large-scale structures. The printer builds the project in layers by depositing sand and then inorganic binding ink [Figure 13].

◀ Figure 13. 3D printed prototype for the Radiolara Pavilion.

Wes McGee and David Pigram from Matter Design Studio and the University of Michigan have also been experimenting with robotic technology inspired by the work done on the *Programmed Wall* at the ETH in Zürich [15] where a robot uses an additive process to build a brick wall [Figure 14]. Their project, *Periscope: foam tower*, is in fact a combination of a subtractive and an additive process that uses a robot to shape EPS foam into the required sections that are then stacked manually [Figure 15].

► Figure 14. *Programmed Wall*, ETH, Zürich, Switzerland.



► Figure 15. Periscope: Foam Tower by Matter Design (Wes McGee et al).

6.4. Prosthetics: Augmenting architecture through desktop manufacturing

The last envisioned use of direct personal 3D printing is that of augmenting architecture. Prosthesis is deeply embedded in our primordial need to use tools to repair, augment, enhance, and extend our abilities. One of the earliest prosthetic devices discovered is a large toe found on an Egyptian mummy dating from 1069 to 664 B.C. [Figure 16]. It is made out of wood and leather and is jointed which indicates that it was actually functional. It is thought to have replaced a big toe of a female about 50 to 60 years of age that may have lost her toe due to complications from diabetes [16].

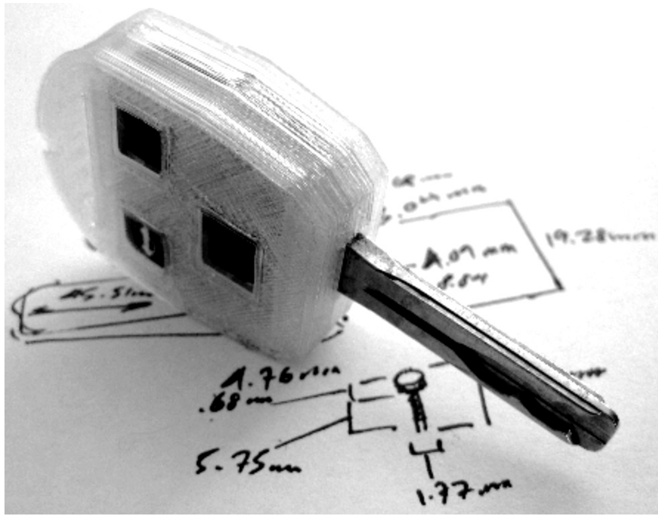
◀ Figure 16. A prosthetic toe, c. 950-710BC, Cairo Museum. (Image courtesy of J. A. Campana, Ph.D.)

3D printers are also currently being used for prosthetic reasons. The following is a true account from a user of the MakerBot ToM that was able to print out a replacement Key fob [Figure 17]. The writer recounts:

> "[My mother] came to visit on Monday night and left yesterday morning. Monday evening she mentioned her car key was broken. I measured the broken parts, printed up two prototypes, and printed out a fully functional replacement the following morning."

This is an indication of the revolutionary shift in our relationship with three-dimensional objects. Similar to the jailbreaking community (a modern version of the original hacker community) that customises consumer electronics by hacking into its software code, the empowering nature of 3D printing technology severs our dependence on large manufacturers selling us their statically defined products and transforms us from a consumer culture to a creator culture that tinkers with, hacks, enhances and even replaces the pre-made consumer objects we are given with custom designed and custom manufactured alternatives.

► Figure 17. A prosthetic for a broken car key.

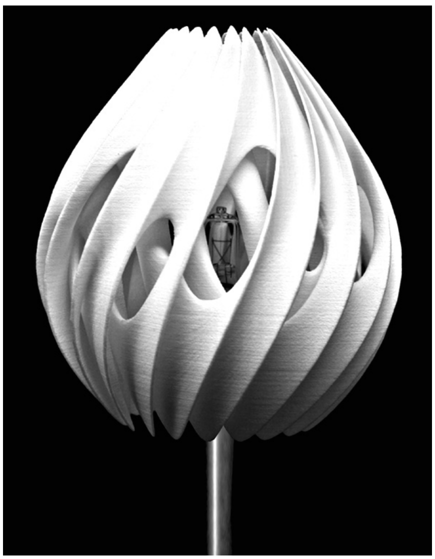


3D printed prosthetics is making amazing advances in the field of medicine. For example, we are already seeing advances in printing replacement blood vessels by 3D printers that use cells instead of ink [17]. The prosthetics company, Bespoke Prosthetics, is already using customised 3D printed prosthetics as a marketing advantage, elevating prosthetics to objects of desire [Figure 18]. Their marketing literature includes the following:

> "New technologies … allow us to rethink the dehumanizing mass-production, and return once again to a guild process, where a product can be created for an individual, unique to them alone."

► Figure 18. Bespoke prosthetics as objects of desire.

i.materialise is another company that is using customised 3D printing as a commercial enterprise where they allow their customers to design their own objects or parametrically customise pre-designed ones to create a unique product that is then shipped to them [18]. While i.materialise is a commercial enterprise, it allows individuals to upload their own designs that they can sell through the website [Figure 19]. Ponoko.com is yet another commercial enterprise that allows users to create 3D products, upload them and market them to others. They advertise themselves as "an online marketplace for everyone to click to make real things. It's where creators, digital fabricators, materials suppliers and buyers meet to make (almost) anything" [19]. In a sense then, the manufacturing model is fundamentally shifted from the few to the many empowering individuals and communities of designers and creators through shared access to otherwise inaccessible manufacturing technology.

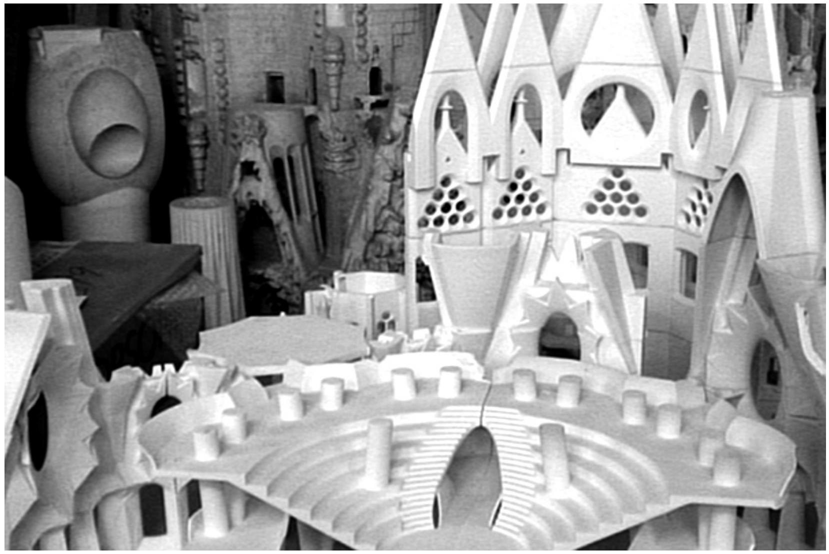


◀ Figure 19. Vova lamp by H+D Studio. 3D printed lamp in polyamide.

In the field of architecture, the most well known example of using digital fabrication as a prosthetic is the work of architects Jordi Coll, Jordi Faulí, and Mark Burry on Gaudi's Sagrada Familia [20]. They use both parametric digital models and digitally fabricated ones (using 3D System's 3D printers) to understand and complete the missing parts of Gaudi's church [Figure 20]. In discussing the relationship of physical modelling and parametric digital prototyping, Burry writes:

> " Interestingly, where the time honored iterative design approach using modeling in gypsum plaster provided the haptic interaction with the design for both critique and construction, the digital model has provided comparable haptic prototyping opportunities with accelerated production times commensurate with the overall increase in speed of design and construction."

► Figure 20. 3D printed models of the Sagrada Familia. (Image courtesy of 3D Systems)



In his conceptual project, *Prosthetic Rehabilitation*, in Miami Florida, Alex Lozano also employs a prosthetic strategy. He proposes that prosthetics can be subdivided into two categories: rehabilitation and enhancement [Figure 21]. According to Lozano, creating prosthesis in his project blurs the boundaries between existing spaces and proposed ones. Prosthetic architecture would then be able to replace unpleasant façades and weakened structures with a:

> "… formal species which will set up a dialogue between old and new." [21]

► Figure 21. Prosthetic Rehabilitation, Miami, Florida. (Image courtesy of Alex Lozano)

Prosthesis, however, transcends rehabilitation and enhancement into true extensions and exaggerations of our physical ability, senses, and collective consciousness. This was first fully explored by Marshall McLuhan, in his seminal book *Understanding Media*, in which he describes media and technology in prosthetic terms as extensions of our mind and physical senses and abilities:

> "During the mechanical ages we had extended our bodies in space. Today, after more than a century of electric technology, we have extended our central nervous system itself in a global embrace, abolishing both space and time as far as our planet is concerned." [22]

From the caveman's first use of tools, mankind will always strive to find ways to augment, replace, repair, enhance, and extend his body as well as his environment. Personal desktop manufacturing combines this possibility with a direct translation from virtually designed artefacts that can now be simulated and tested both digitally and physically. It is specifically this interlacing of digital design and personal physical prototyping that holds the most promise for desktop manufacturing as an additional design tool that deserves a place at the designer's workstation. In this age of patent lawsuits by large technology companies, personal digital fabrication plants a seed for personal and community empowerment through the circumvention of purchased technology. Open-sourcing 3D models and placing them in the public domain can avoid some of the copyright problems that would otherwise hinder the progress of these movements. Movements such as open design allow makers to freely distribute their creations along with documentation and permissions on their modification, derivation and re-distribution [23]. Creative Commons (CC) licensing models is one direction that shared desktop manufacturing could follow. According to their website, CC "develops, supports, and stewards legal and technical infrastructure that maximizes digital creativity, sharing, and innovation" [24]. By applying a CC license to one's shared creation, others can re-manufacture it, modify it or derive other products from it while protecting the rights of the original author of the work.

7. CONCLUSION

This paper points to the nascent field of desktop manufacturing as a tool for empowering individuals and communities by allowing them to design, manufacture, and share, locally and remotely, 3D objects from the smallest pieces of jewellery to prosthetic devices to full-scale shelters. The effect of this technology will be as revolutionary as the arrival of desktop publishing a few years ago that is now a habitual aspect of our digital life. Desktop manufacturing, with the proper consideration of the open source philosophy, copyright laws and the use of creative commons licensing, has the potential to augment our architectural environment with customised and distributed manufactured components, thus redefining our consumerist relationship with our built environment and returning us to a truly empowered hacker/creator culture.

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