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Author:
Park, Miles

Publication details:
IDEN Industrial design educators network
v. 1
Chapter No. 2
pp. 24-33
22006834 (ISSN)

Publication Date:
2013

IDEN

ISSUE 02

MAKE

INDUSTRIAL
DESIGN
EDUCATORS
NETWORK

EDITED BY BERTO PANDOLFO AND MILES PARK

Enabling Technologies: The Promise of Low Cost DIY 3D Printing

MILES PARK
UNIVERSITY OF NSW, 2013

ABSTRACT

This paper investigates recent developments in low-cost 3D printing and offers a case study on the practicalities of commissioning a low-cost, kit based 3D printer. It discusses a range of practical considerations and possibilities on how it can assist in reconnecting students to making in an educational setting. The promise of digitally printed parts and models from an affordable desktop machine has many perceived advantages in complementing the more established 3D printing and traditional methods of model making. In addition, low-cost 3D printers have opened up new making possibilities for a wider community of non-professional designers and makers. In design education settings the integration of low-cost 3D printers can offer new making opportunities earlier in the design process by integrating with existing digital design tools.

INTRODUCTION

3D printing, along with other digital making technologies, capture an emerging theme for the 21st Century—a biological century where things are 'grown', unlike the 'heat, beat and treat' manufacturing processes of past centuries.[1] Many designers and makers have eagerly awaited the relatively recent availability of low-cost DIY 3D printers.

3D printing fits within an evolving ecosystem of low-cost design and prototyping enabling technologies. This includes, in addition to 3D printers, 3D scanners, laser cutters, CNC routers and simple to program devices (such as, Arduino, Raspberry Pi and Twine). These tools bring enormous creative opportunities to designers, students, design educators and individual makers enabling them to experiment and create technically advanced outcomes. The affordability and availability of these enabling technologies democratises ownership and redistributes access to sophisticated equipment that has, until relatively recently, remained the domain of large organisations or the well resourced.

Some claim 3D printing and associated technologies are nothing short of a 'third industrial revolution', disruptive and revolutionary.[2] Others take a more precautionary approach that 3D printing is still at an early stage with hackers and early adopters still figuring out what to do with it.[3] While much attention has been focused upon the possibilities of what digital disruptive technologies can offer in transforming aspects of design, making practices and manufacturing, the depth of this transformation remains speculative. It is still at a relatively early stage of development. The emerging possibilities of 3D printing and allied technologies are akin to the early days of rapid technological and market development of the Personal Computer during the 1980s. As such, the experiences of users are usually mixed and often depend upon technical aptitude, knowledge of 3D CAD and realistic expectations. To 'print' a 3D CAD file is inherently more complex than the ubiquitousness process of printing a paper document. Their portability makes them ideal for student use, university open days and recruitment events. Their low-costs enables student ownership, and their flexibility enables them to be modified, upgraded and repaired.

RISE OF THE MACHINES — THE ARRIVAL OF LOW-COST 3D PRINTING

Within the last year alone there has been a dramatic increase in the availability of low-cost 3D printing machines. These machines can be defined as costing less than $4000 (USD) and generally marketed to individual users who do not require high frequency use or high performance materials. The explosion and, to some degree hype, around 3D printing has been remarkable. Not least because it is less than ten years since the availability of the first low-cost 3D printing machine as an open source DIY project. The 'self-replicating rapid prototyper', or RepRap advanced early research into low-cost 3D printing.[4] Its developer, Adrian Bower from Bath University, UK, conceived it as a machine that could print and self-replicate its own parts from downloadable files. He envisioned a system that enabled communities around the world to ultimately bypass traditional manufacturing and

1. Benyus, Janine M. (1997). *Biomimicry: Innovation Inspired by Nature.* William Morrow

2. Anderson, Chris. (2012). *Makers: The New Industrial Revolution.* Crown Business

Markillie, Paul. (2012). 'The third industrial revolution.' *The Economist.* 21 April 2012

Marsh, Peter. (2012). *The New Industrial Revolution: Consumers, Globalization and the End of Mass Production.* Yale University Press

3. Hollbrook, Steve. (2012). The promise of 3D Printing. *Make: Ultimate guide to 3D Printing.* O'Reilly Media. [www.makezine.com]

4. *RepRap.* (2013). [http://reprap.org/wiki/Main_Page] (accessed 31. 05.2013)

distribution structures.[5] By 2007 RepRap and Fab@home, another open source 3D project, became available as a kit of parts and self-assembly instructions. These kits required a degree of technical competency to construct, commission and operate.

The first truly self-assembly kit based 3D printers, the CupCake, and soon after the Thing-O-Matic both developed by MakerBot Industries in the US, only became commercially available in 2010.[6] In parallel, MakerBot launched a website—'Thingiverse'.[7] The service offers contributors to upload stl CAD files to share and remix design files for use on a variety of digital making machines; not dissimilar to music file sharing services such as Soundcloud. Another service, Shapeways[8] offers an alternative model where uploaded files of a design, typically design prototypes, sculptural and jewellery pieces, gadgets for technologies and hobbies, can be purchased and dispatched as printed object in a selection of materials.

Since 2010, many other low-cost 3D printing machines have been launched into the market. A recent estimate (January 2013) found that there are in excess of twenty commercially available low-cost 3D printing machines with at least another half a dozen machines close to market. A number of the latest crop of low-cost 3D printing machines are still emerging from open source community start-ups offering an array of options from kit build to 'out of box' ready built solutions.

5. Randerson, James. (2006). Put your feet up, Santa, the Christmas machine has arrived. *The Guardian*. 25 November 2006. [www.guardian.co.uk/science/2006/nov/25/frontpagenews.christmas2006]

6. Dougherty, Dale. (2012). Dreaming Of 3D Printers. *Make: Ultimate guide to 3D Printing*. O'Reilly Media. [www.makezine.com]

7. *Thingiverse*. (2013). [www.thingiverse.com] (accessed 31. 05.2013)

8. *Shapeways*. (2013). [www.shapeways.com] (accessed 31. 05.2013)

PRINTING TECHNOLOGY

Most low-cost 3D printers utilise a printing method based upon fused deposition modelling (FDM). This is achieved by feeding PLA or ABS plastic filament through a precisely located heated nozzle that extrudes a thin stream of material to build up successive layers of plastic into a 3D object. These machines do not, yet, offer the tight tolerances, reliable finish resolution or material performance of their larger and more expensive industrial counterparts. Incumbent 3D vendors, who have traditionally supplied 'high end' rapid prototyping 3D printing technologies for industry, are also moving into the low-cost 3D printing space. 3D Systems, the developer of Stereolithography or SLS, was one of the first commercial 3D printing technologies claim to offer 'plug and play simplicity' with their low-cost 'Cubify' FDM printer.[9] Conversely, another but much lower-cost stereolithography machine has recently been launched. The 'Form One' 3D printer is touted as an affordable, high-resolution 3D printer. It was developed at the MIT Media Lab and raised over $2 million (US) on the crowd-funding platform Kickstarter. However despite positive reports emanating from the technology press, the Form One start-up and Kickstarter have been challenged for an alleged patent infringement by, unsurprisingly, 3D Systems the developer of Stereolithography.[10] Given the open source structure for a significant number of the low-cost 3D printer start ups, the prospect of infringing intellectual property seems an anathema to the many advocates for low-cost 3D printing and the collaborative nature of the communities behind the technologies.

LOW-COST 3D PRINTING IN PRACTICE

As a means to develop a greater understanding of the opportunities for low-cost 3D printing for design education, a research project commenced mid-2012 to evaluate of a 'representative' low-cost 3D printer. The research investigated utility, practicalities of commissioning and using a machine for student use. The printer chosen for the task was the Ultimaker 3D Printer.[11] This kit based machine became available in the second half of 2011. The machine is reliant upon open source hardware (Arduino), standardised components (stepper motors and bearings) and is fabricated out of laser-cut plywood. A key feature is a low-mass 'hot end' extruder that is claimed to enable fast and accurate printing.

"Why did we choose the Ultimaker? We considered many different models ... MakerBot Replicator, the Bits from Bytes 3D Touch, the PP3D Up! and the 3D Systems Cube ... we concluded that it wasn't a practical requirement for the average student. Instead we focused on the three main attributes we judged as important for common use: print quality, speed and cost.

The Ultimaker surprisingly came first in all of these key attributes by quite a large margin. It was therefore an easy choice as our test machine. More on these attributes as we begin testing."

JOSH FLOWERS, STUDENT RESEARCH ASSISTANT

9. 3D Systems. (2013). *Cubify*. [www.cubify.com] (accessed 31. 05.2013)

10. BBC News. (2012). *Kickstarter sued over 3D Systems' printer patent*. 21 November 2012. [www.bbc.co.uk/news/technology-20434031] (accessed 15.02.2013)

11. *Ultimaker*. (2013). [http://ultimaker.com/] (accessed 10. 06.2013)

12. Time-lapse construction film can be found at http://lowcost3dprinter.wordpress.com/2012/07/18/time-lapse-ultimaker-assembly/

13. An account of various tests and outcomes is available at http://lowcost3dprinter.wordpress.com

CONSTRUCTION AND COMMISSIONING

The kit requires approximately 16 hours to construct and is supported by an online wiki instructions inclusive with various tips, updates and improvements offered by users. This part of the process was relatively straightforward. A time-lapse film was made documenting the construction.[12] With the construction complete, initial tests revealed a fault with the extrusion mechanism that was traced to a faulty main circuit board. With a new replacement circuit board and a firmware upgrade the first test prints were achieved. Initial results were crude but looked promising. Necessary adjustments to the tension of the belts and extruder head travel end-stops would enable more accurate printing, however this was not a straightforward matter.

"First step: tighten the belts! If the belts are loose (and they were) the print head responds sluggishly and with less accuracy ... but there was no simple way to tighten the larger axis belts on the Ultimaker without getting really fiddly. I ended up printing the solution using a pre-made design from Thingiverse. They are tiny clips that fit on the edges of the existing belt support blocks. Incredibly simple, yet effective!"

JOSH FLOWERS, STUDENT RESEARCH ASSISTANT

Further test prints still failed to achieve a successfully complete print. The problems encountered involved the hot-end and extruder feed mechanism causing filament slippage and blockages. Many workarounds were devised leaving us to conclude that the current extrudion mechanism is clearly not fit for purpose. Around this time Utlimaker released an improved extruder heater nozzle (Hot-end):

"The release of a revised hot-end by Ultimaker is significant for two reasons, first it shows that they have acknowledged the poor design of the original, and second it means we'll hopefully be printing without blockages very soon!"

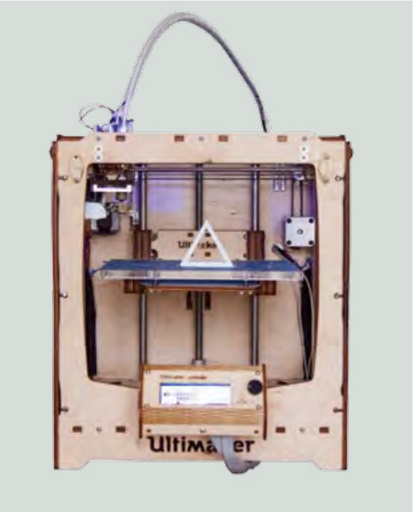
JOSH FLOWERS, STUDENT RESEARCH ASSISTANT

With the hot-end assembly problem solved, attention shifted to the other half of the problem—the extruder feed mechanism. The solution was to rebuild an entire new feed mechanism based upon a design posted on the Ultimaker forum. This required the printing of new 'replicated' parts from downloaded STL files.

"In preparation for the overhaul of the extruder, I researched all the viable alternatives. Dozens of fixes have been suggested and posted in the Ultimaker forums ... The challenge was to get the unreliable Utlimaker to print the parts, but with many failed attempts and some luck—it worked!"

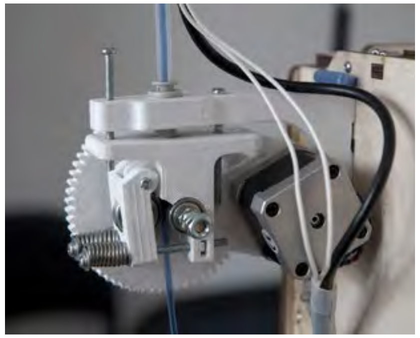
JOSH FLOWERS, STUDENT RESEARCH ASSISTANT

After these setbacks were resolved, the machine was finally calibrated and ready to print a series of test pieces. This involved printing simple and complicated forms with a range of different settings to understand the capabilities and limitations of the machine. The most challenging task thrown at the machine was to print an interlinking chainmail.[13] Critical to the success of any print is preparation of the machine. Belts, hot-end and filament feed require regular



◄ Ultimaker 3D Printer. *Ultimaker's low-mass print head promises fast and accurate printing.* (Photo: Josh Flowers)

◄ Thingiverse sourced belt tensioning clips (Photo: Josh Flowers)



◄ Ad-hoc adjustments and machine printed improved extruder drive (Photo: Josh Flowers) inspection. The print bed has to be taped, cleaned and levelled on a regular basis to ensure the correct amount of adhesion for the first print layers. An out of calibration machine will at best print distorted parts, out of tolerance, and at worst result in a clogged hot-end with a solidified lump of plastic spaghetti welded to the bed.

14. *Ultimaker Forums.* (2013). [http://umforum.ultimaker.com/index.php?/forum/28-troubleshooting/]

MakerBot Operators. (2013). [https://groups.google.com/forum/#!forum/makerbot]

DESIGN PREPARATION AND WORKFLOW

In addition to resolving the mechanical side of 3D printing, file preparation is a key element of the process. The digital workflow for 3D printing commences with the preparation and export of a STL file from a 3D design software package. This is then imported into a slicing software package to produce numerical control (NC) programming language known as G-code. It is G-code that determines all dimensional (x,y,z axis) movements and machine settings such as nozzle temperature, print speed, layer height and filament feed, retract and so on.

A primary consideration for a successful print is part design. As with other plastics manufacturing technologies, 3D printing has its own unique part design requirements. Part design considerations will also vary depending upon which slicing software and printer is used. The primary design variables are:

- Wall thickness—including top and bottom layers that can be independently specified
- Fill density—specified as a percentage of material density of the part cavity
- Support and Raft—creates support structures to prevent warping
- Skirt—a printed layer around the part to prime the extruder hot-end
- Orientation—to optimise print speed to avoid unsupported features

LIFE IN BETA

It is not unreasonable to claim that the experiences described above are typical in assembling and commissioning a low-cost 3D printer. They are broadly representative of the experiences many users have encountered. This is evident from the number of blog and forum posts[14] that either request help or offer tips and solutions. Periodically vendors will offer upgrades and revisions for their machines. For example, in late 2012 a new extruder nozzle assembly (hot end bundle) was offered for the Ultimaker in acknowledgement of an ongoing problem with nozzle blockages and leakages in response to the many forums posts on the problem. This is not so surprising as so many machines are new to market and remain a perpetual state of developmental evolution—akin to the state of beta issued software. There exists a spirit of 'work in progress' to which users, posting on various online forums, play an important and influential role in providing feedback and guidance for ongoing design development. This demonstrates a key attribute of the open source ethos that many low-cost printer start-ups and their supports embrace.

DESIGN EDUCATION STUDIO

In an industrial design studio setting an obvious benefit of low-cost 3D printing is as a supplementary, ready-at-hand, tool for model making tasks. Its affordability and portability offer an immediacy to design projects where low-cost printers can be located in the studio, adjacent making spaces or even student's personal study areas. Such arrangements enable design student to prepare and produce printed artefacts earlier in the design process where iterative, explorative and experimental design activities are encouraged.[15] Model making early in the design process is a valuable and often necessary exercise as a means for the designer to 'build to think' through a design.[16] This early experimental modelling stage is well suited for low-cost 3D printing where surface finish, colour and materials are not necessarily important. For example, concept models of control knob variants for a kitchen cooktop/hotplate design enable the designer to explore product forms to resolve aesthetic and ergonomic matters. As well, multiple prints of a control knob design can enable user testing of control function and spatial arrangement, such as cognitive mapping of which knob should go where. In a design studio setting, low-cost 3D printing can offer:

- Proof of concept—demonstrate physical functionality
- Ergonomic and aesthetic assessment of physical form
- Parts for user-centred design research tasks—user testing and prototyping experience
- Test parts—fit, interference and nesting with proprietary parts
- Duplication of parts—repetition of similar parts for assembly onto a model
- Incremental part variation—concept design variation

15. Cross, Nigel. (2011). *Design Thinking: Understanding how designers think and work.* Berg

16. Brown, Tim. (2009). *Change by Design: How Design Thinking Transforms Organizations and Inspires Innovation.* HarperBusiness

17. Coxon, Selby. (2013) pers. comm. 22 May 2013, personal interview with Coxon, Selby held at Monash University.

For final 'appearance models' 3D printed parts require a degree of finishing and post processing. Surface stepping needs to be removed through controlled sanding prior to painting with an appropriate primer and topcoat. Gluing printed parts together also requires knowledge and planning with ABS offering superior qualities over PLA.

Other project opportunities for low-cost 3D printing in the design studio could can be framed around themes such as utilisation of additive manufacturing technologies, electronics and mechanics, part fit and tolerances, up-cycling and working in teams. For example, studio projects devised to build an open-source 3D printer in teams from obsolete inkjet printers or assemble and commission kit based printers.[17]

RECONNECTING WITH MAKING

Workshop traditions and student expectations still often place model-making as a final stage event in design projects with the creation of a 'appearance model'. This is despite the increasing capability and ease for computer visualisation to fulfil a similar role. For many design students the computer has become the primary tool platform for design activity. As such, the role of making, to test and develop a design is often neglected and seen by design students as unnecessary extra work. Low-cost 3D printing offers a means to short-circuit these entrenched practices by uniting the predominance of screen based virtual design with the 'made' material world. It can assist in developing a fluidity of a back and forth workflow between digital design and physical modelling. It enables an experimental and iterative design process by offering physical feedback of the virtual design space of CAD.

WORKSHOP RESOURCES

For educational institutions the adoption and distributed ownership of low-cost 3D printers can reduce demand for specialist workshop equipment that is often under utilised. For example, model-making tasks that require milling and lathing tasks can, in certain instances, be achieved by 3D printing that can take place in spaces other than the workshop. This can reduce unmet demand by students and refresh training on equipment that may only be used intermittently. This reduces the burden of technician support in safety compliance, training and supervision. However, it must be stressed that this is not an excuse to diminish the importance of accessible workshop environments as a rich and vital contribution to a design education. If workshops can resist the temptation of expanding their suite of digital making technologies with their finite resources they will be able to better focus on creating an accessible workshop environments for existing students model-making needs. As digital making technologies increasingly become located in office or studio environments, it makes economic as well as pedagogical sense to empower students with these increasingly low-cost technologies through direct ownership or ready availability in the design studio where most design activity takes place. We are already seeing the seeds of distributed ownership with the emergence of student 3D Printing user groups and individual ownership of machines by staff and students.

CONCLUSION

Low-cost 3D printing offers an engaging and affordable making platform for design creativity and problem solving. For the design student, it can reconnect the preoccupying virtual world of CAD design and visualisation with making. Making, at any stage during the design process is a valuable and often necessary activity. Despite the predominance of digital design environments, making remains at the core of many design practices as a means for the designer to 'build to think', test and verify design propositions. Low-cost 3D printing does not replace the need for the traditional workshop or 'high-end' 3D printing services. It fits within an evolving digital making ecosystem of increasingly affordable technologies. This evolution is far from mature as low-cost 3D printers remain temperamental and experimental devices. They cannot be left unattended and often demand a degree of technical aptitude from the operator. However, as the rollout of new machines continues unabated with improved stability, usability and printing performance for lower cost, it appears inevitable that we will see a growing student ownership and utilisation of low-cost 3D printers.

ACKNOWLEDGEMENT

Joshua Flowers for his skill and knowledge in commissioning the Ultimaker. A blog account of the project is available at http://lowcost3dprinter.wordpress.com/

MILES PARK