Design Tools for the Rest of Us: Maker Hardware Requires Maker Software

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The evolution of computing is in large part driven by the development of novel hardware capabilities, which can only be fully exploited by new types of software interfaces. This is particularly evident in the early history of digital fabrication, where the development of CNC machines at MIT lead to an interest in Computer-Aided Design (CAD) tools, essentially to "create content" for this new hardware. Sutherland's seminal SketchPad system [Sutherland63] - and hence the first Graphical User Interface - was one of the fruits of this endeavour.

In recent years we have seen a significant leap forward in rapid prototyping hardware, particularly in the domain of 3D printing. At the high end, 3D printers now have micrometer resolution and can blend between flexible, rigid, and transparent materials. Consumer-level systems have output quality similar to machines that cost tens of thousands of dollars just a few years ago. And mail-order 3D printing houses provide affordable access to a wide range of material options, from metals to ceramics.

Now that 3D printing hardware has become vastly more accessible, there is a growing userbase looking for software that enables them to "create content". Of course such tools do already exist, in the form of professional CAD software. However, much like early digital fabrication hardware, the cost and complexity of these tools is beyond the reach of the hobbyist "Maker". Traditional CAD packages are designed to support the pipelines and practices of professional engineering and industrial design. In the face of these rigid processes, innovation in "easy-to-use" CAD tools largely ground to a halt outside of academic research.

The democratization we are seeing in digital fabrication hardware brings with it a much larger community interested in creating their own objects, and hence their own 3D designs. Even if they are professionals by day, when they put on the "Maker" hat these individuals have the freedom - and desire - to try novel and unconventional tools. As a result, digital fabrication provides an ideal playground for experimenting with entirely new approaches to 2D and 3D design. This is spurring the development of new types of design tools - tools which take into account that the end goal is a physical object.

Recently we have seen an increasing number of interesting systems which attempt to assist novices in creating complex physically-realizable designs [IIM12, UIM12]. We have also seen works that take the reverse approach, applying geometric analysis to augment the fabrication abilities of an individual in the real world [ZP12,RMD12]. That such systems are of more than just academic interest is revealed by the increasing number of commercial forays into this space. Interest in digital fabrication is not limited to researchers; commercial systems are also breaking new ground in purpose-built design-to-fabricate interfaces. For example, the Shapeways Creator tools allow users to easily customize simple models such as a napkin holder or cufflink. More recent tools include Cookie Caster [DF12] for designing custom cookie cutters, and Crayon Creatures [Cuni12], a web service which converts childrens drawings into 3D prints (Figure 1).

Figure 1: 3D-printed objects created using Crayon Creatures (left) and the Shapeways Custom Cufflink Creator (right)
(note:copyright permission for these images has not been cleared)

In our own work, we are developing and applying a system which attempts to support a wider range of 3D design tasks, while still providing a high level of accessibility and utility to users with varying skill levels. The meshmixer system includes tools for easy 3D “mash-up”, virtual sculpting, and 3D scan “cleanup” and repair, alongside more traditional shape modeling interfaces such as boolean composition and 3D transformations. One of the underlying motivations for bringing this disparate toolset together in a single interface is to simplify workflows. In particular, the goal has been to make life easier for those who are not professional 3D artists, such as “Makers” and digital fabrication hobbyists. For this userbase, the 3D design is a means to an end rather than the end itself, and the tools should take this into account.

An important aspect of this research highlights the requirements of 3D design for physical fabrication. For example, the usability of many 3D tools is compromised to some degree by limitations of the underlying mathematical shape representations in use (for example NURBS or SuBD surfaces). In meshmixer we discard these structured formats in favor of a more flexible unstructured high-resolution triangle mesh. In doing so we have made trade-offs that leave meshmixer somewhat unsuitable for digital-only uses such as high-end film production or purposes that require extremely tight tolerances such as aerospace engineering. In return we gain greatly increased utility - and usability - for those who are primarily focused on making something awesome. As a result we routinely find 3D design novices using meshmixer to perform tasks such as repairing scans of museum objects and creating 3D mash-ups.

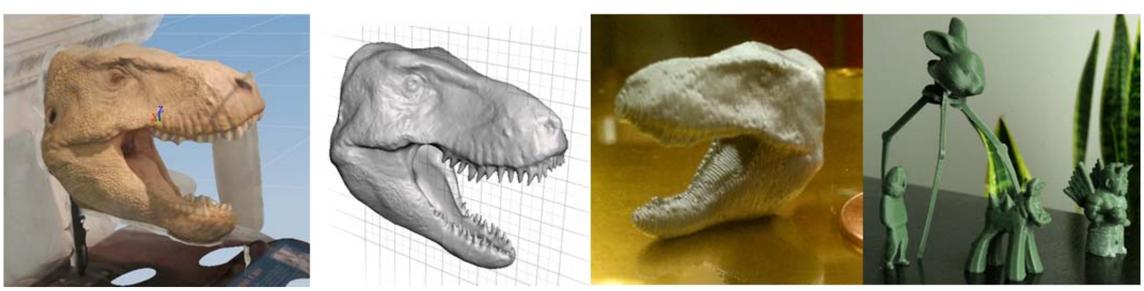

Figure 2: meshmixer was used in this scan-clean-print workflow of a museum artifact (left) and to create various creature mash-ups (right)
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To more formally explore how novices respond to our interactive design tool, we developed and taught the "design" half of a "design-and-print" workshop. In this workshop we gave a one-hour introduction to meshmixer, and then provided the participants with base models and a library of parts that could be easily added via drag-and-drop. The participants also experimented with more complex modeling tools, including 3D sculpting brushes, extrusions, and fairing.

Our participants had no prior 3D design experience, and based on our observational experience of novices using other 3D tools, we had low expectations. However we were completely blown away by how how quickly they learned to use the meshmixer tools. We strongly believe that because they were designing a real object - something that they were going to 3D-print and take home with them - the participants were much more motivated to learn to use the software. This suggests that digital fabrication may provide a strong incentive for a level of "design literacy" that has not been present in the past. The success of this workshop has resulted in several others based on our materials (available online at http://meshmixer.com/help/index.html).

Another byproduct of this workshop was an awareness of just how messy the transition from digital to physical still is [RR12]. Although 3D printing does have an aspect of magic, the reality is that a little bit of care taken in the digital stage can often lead to significantly improved physical objects. For example, something as simple as changing the orientation of the model relative to the print bed can vastly affect the quality of the final object. Similarly, different forms of 3D printing - FDM, photo-curing resins, SLS - as well as different types of 3D printers - makerbots, printrs, or Dimensions - create somewhat different results from the same 3D file. This knowledge should be encoded in our design tools. Researchers have begun to explore interfaces which support the analysis of physical properties of a virtual design, and can guide the user towards a more desirable end result [SVBCM12, UIM12].

In meshmixer we are exploring simple interactive tools to guide the user towards more physically-desirable results. For example, Figure 3 shows an interface which can tell the user if an object will fall over when printed. This is a straightforward geometric computation - an object is stable if its center-of-mass, when projected to the ground plane, lies within the convex hull of its ground contact points. Visualizations of the center-of-mass and convex hull supports analysis of how (un)stable the object currently is. However, analysis and visualization are just the first steps - the average Maker is unlikely to understand how to interpret this data. So how do we improve the interface? We may wish to provide more informative visual feedback, or suggest automatic changes that would improve model stability. Most likely we will need both to really unlock the power of digital fabrication, creating new design tools by combining advances in both user interfaces and shape analysis.

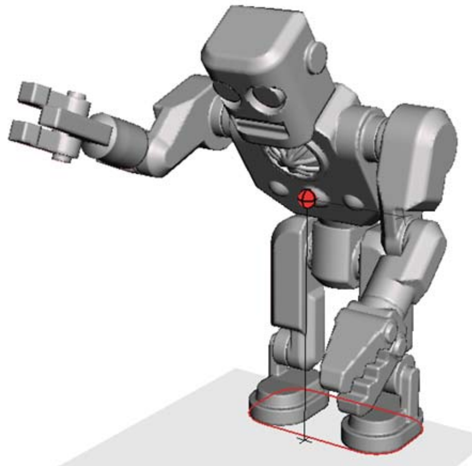

Figure 3: Screenshot from a tool implemented in meshmixer to analyze whether an object will be stable under gravity. The center-of-mass (red ball) lies just outside of the convex hull of the ground contact points, so this object will fall over.

Finally, it is important to note the intermediate term ramifications of new tools for digital fabrication. Get the tool chain right - easy to learn, scalable in terms of complexity, and accessible - and the vision of digital fabrication spurring wide-spread engagement in creative making is realizable. But if we get it wrong - hard to learn, limited in capability, and focused on restricted social groups - and we run the risk of digital fabrication becoming just another mechanism for delivering products to consumers.

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