Design-to-Fabricate: Maker Hardware requires Maker Software

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Abstract

As a result of the increasing availability of consumer-level 3D printing devices, the audience for 3D design tools has grown considerably. However, current 3D design tools are ill-suited for these users, both in that they have steep learning curves, and in that they do not take into account that the end goal is a physical object rather than a digital model. In this article we propose that a new class of "maker"-level design tools are needed to accompany this new commodity hardware. We provide several examples of recent "maker" tools, which achieve accessibility primarily by constraining functionality. We then describe recent developments in the meshmixer project, where we are building a tool which attempts to provide both accessibility and expressive power, by leveraging recent computer graphics research in geometry processing. We discuss our positive experiences with several 3D design/print workshops, and present several "design-to-fabricate" problems that we are currently exploring.

Introduction

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 - 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" for their new devices. 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.

CAD Tools for Makers

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. However, the democratization we are seeing in digital fabrication hardware brings with it a much larger community interested in designing their own 3D objects. Even if they are professionals by day, when they put on the "Maker" hat these individuals have the freedom and desire to explore novel and unconventional tools. As a result, digital fabrication provides an ideal playground for researchers and software developers - the tool makers - to experiment with entirely new approaches to 2D and 3D design. This is spurring the development of new types of design tools; particularly those in which the knowledge that the end goal is a physical object is deeply integrated into the system.

While academic computer graphics researchers have always been interested in easy-to-use design tools, recently we have seen an increasing number of works which incorporate fabrication constraints into the design process. These design-to-fabricate systems enable the rapid creation of complex physically-realizable designs which would otherwise be well beyond the capabilities of even moderately skilled users. A notable example is the guided furniture design tool developed by Umetani et al [UIM12] (Figure 1). In one potential usage, the user is free to explore any number of wildly complex bookshelf designs, with the system providing subtle hints to guide the virtual design towards one that is physically stable and manufacturable.

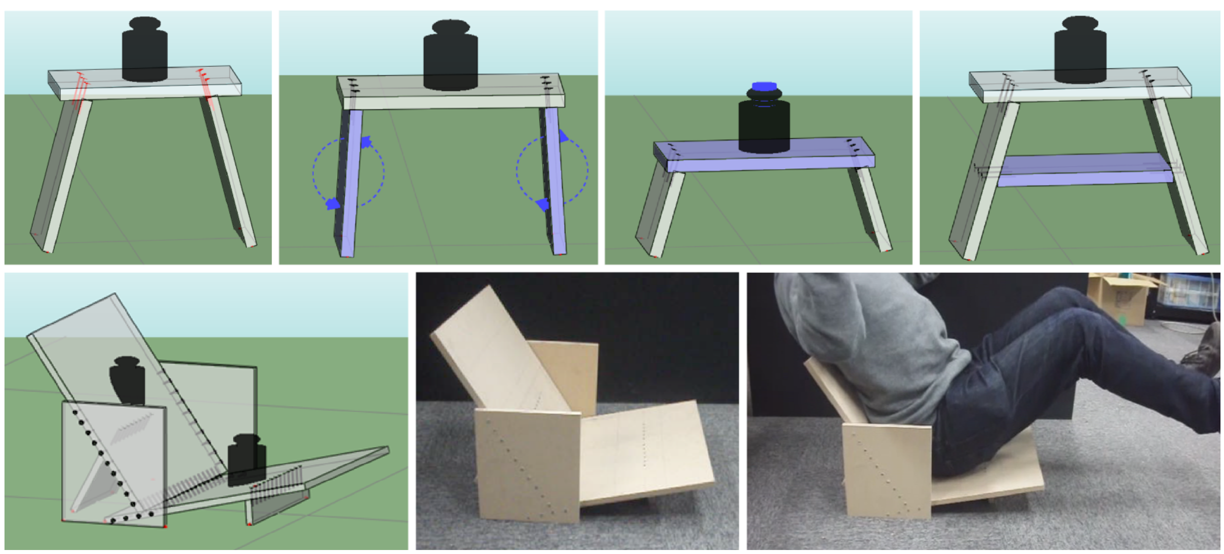

Figure 1*: The guided furniture design system described by Umetani et al [UIM12] can determine that an initial design (top, left) is physically unstable, and suggest various alterations to satisfy robustness criteria (top, right). In the bottom row the system is validated using a simple chair design. (Images copyright © Nobuyuki Umetani, used with permission)*

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. In the Sculpting-By-Numbers project, Rivers et al [RAD12] help novices create clay sculptures of given 3D models by analyzing and displaying guidance information directly on the current sculpture, using a projector-camera system.

Interest in digital fabrication is not limited to academic researchers. Design-to-fabricate capabilities are also appearing in commercial systems with increasing frequency, particularly in the form of simple web-based and tablet/mobile applications. For example, the Shapeways Creator tools (http://www.shapeways.com/create) enable unskilled users to create customized 3D models for printing (Figure 2). With the Cufflink Creator the user need only type in their initials and pick a font, while the Ring Creator takes a grayscale image as input, wraps it around a ring template, and then extrudes in the normal direction. This workflow allows a novice to use familiar image-editing tools to create a unique 3D object.

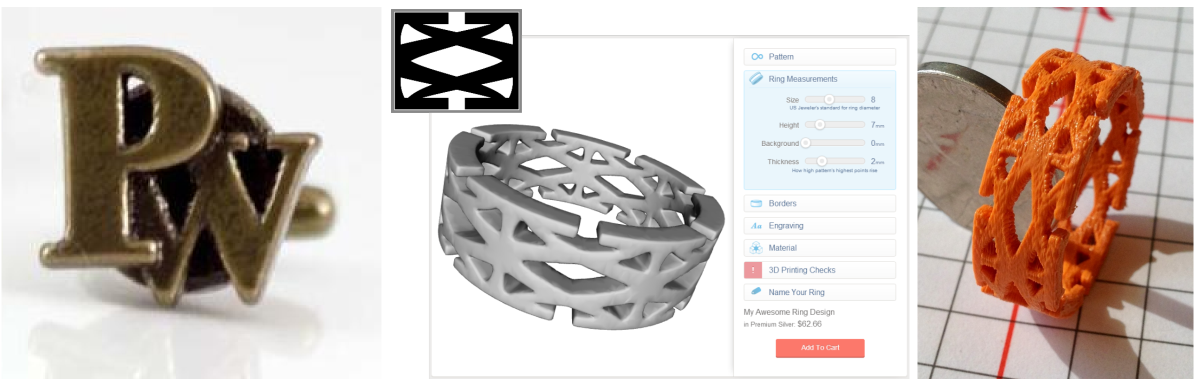

Figure 2*: The ShapeWays Cufflink Creator (left), converts letters into a 3D object, while the Ring Creator takes a bitmap image (middle, inset) as input and generates a corresponding 3D model (middle) which can then be 3D printed (right). (left image copyright © Shapeways Inc, used with permission.)*

Other recent tools include Cookie Caster (http://cookiecaster.com) for designing custom cookie cutters (Figure 3), and Crayon Creatures (http://crayoncreatures.com), a web service which converts childrens drawings into 3D prints (Figure 4). Many of these tools tend to focus on 3D printing, where the object is printed by a service bureau and mailed to the user. However laser cutting is also becoming increasingly available, and software like Autodesk 123D Make (http://www.123dapp.com/make) allows unskilled users to convert arbitrary 3D models to laser-cut fabrication plans with a push of a button (Figure 5).

Finally, as the library of freely-available and easy-to-use design tools grows, users are beginning to combine them in interesting ways. Figure 6 shows an example from a recent Valentine's Day event in Toronto, Canada entitled “3D Printing Kissing Booth”, created by the design studio HotPopFactory (http://www.hotpopfactory.com). At this event, participants were 3D-scanned using the Microsoft Kinect, and then directed a quick design session to turn the scan into a custom, printable design, which was fabricated with 3D printing.

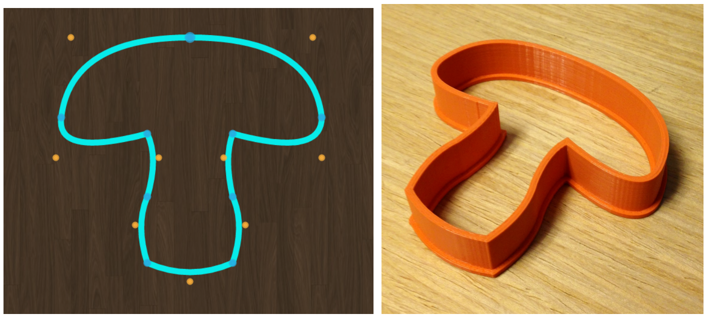

Figure 3*: With Cookie Caster, we designed a closed 2D polygon using a web-based curve editor (left). Standard design rules for cookie cutters are then automatically applied to create a 3D model suitable for printing (right).*

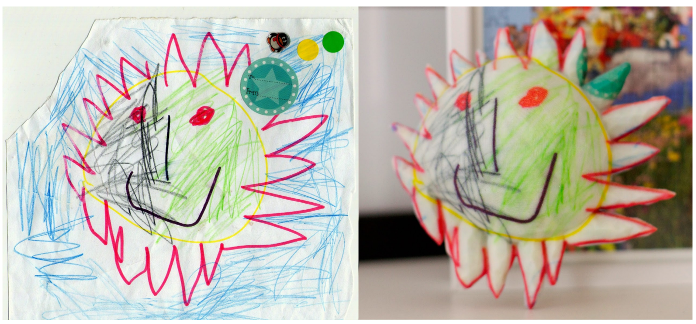

Figure 4*: The Crayon Creatures web service allows a user to easily take a childs drawing and inflate it in the third dimension, then create a color 3D print of the result (images copyright © Crayon Creatures, used with permission).*

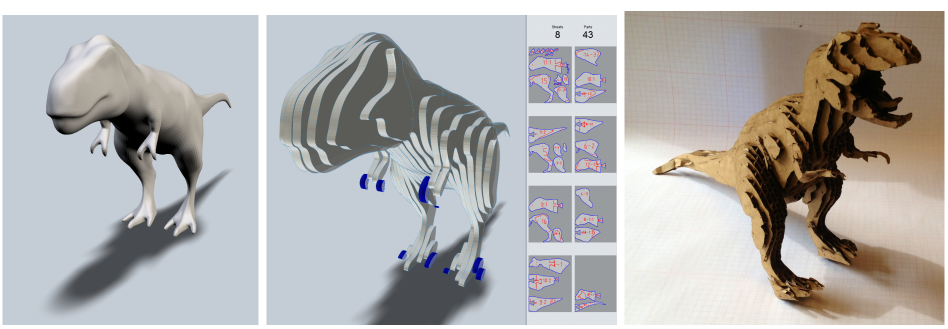

Figure 5*: 123D Make takes an arbitrary 3D models (left) and generates various types of slicing patterns (middle), so the object can be inexpensively fabricated at large scales using laser-cut cardboard slices (right, image copyright © Autodesk Inc, used with permission).*

Figure 6: *3D Printing Kissing Booth. A Microsoft Kinect is used to create a 3D scan of the participants (left), which is then quickly processed and combined with a base to create a unique 3D-printed keepsake (right). (images copyright © HotPopFactory, used with permission)*

Meshmixer: an Accessible General-Purpose Design Tool

The examples mentioned above are just a few of the many design-to-fabricate tools that have recently been created. At the broader level, we observe that the majority of these tools closely heed the maxim “do one thing, and do it well”, and hence focus on solving a single design problem. This approach is particularly effective when inexperienced 3D designers are the target audience. However, in our experience novices will inevitably (and often very quickly) master any given task-specific tool and begin demanding more expressive capability. Unfortunately these simple tools are difficult to “scale up” to more complex design tasks. One can find many online discussions which begin with a question “how do I do X...” and end with a suggestion that the user look into Blender or SolidWorks, professional tools of extraordinary complexity.

Currently the chasm between these simple task-oriented fabrication tools and general-purpose 3D design tools is simply too large, requiring a significant investment of learning time to cross. Hence, in our own work, we are developing and exploring design tools which attempt to support a wide range of 3D design tasks, while still providing a high level of accessibility and utility to users with varying skill levels. In particular, the first author has for several years been developing Autodesk meshmixer (http://www.meshmixer.com/), and together we have been exploring the usage of this tool in various fabrication-related contexts.

Meshmixer is a free 3D design tool, available for download on Microsoft Window and Apple Mac OS X platforms. Meshmixer includes tools for easy 3D “mash-up”, virtual sculpting, and mesh repair, alongside more traditional shape modeling interfaces such as extrusions 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.

In the meshmixer project we are re-imagining how a CAD tool should work at all levels, from the user interface to the fundamental data structures. For example, the usability of many 3D tools is compromised to varying degree by limitations of the underlying mathematical shape representations in use (for example NURBS or SuBD surfaces). These surfaces have desirable properties like intrinsic smoothness and compact data structures with minimal degrees of freedom, but achieve these properties via constraints on 3D structure which the user must explicitly manage. These constraints are completely opaque to the novice user, and lead to much frustration even for highly skilled users.

Spurred by much of the recent computer graphics research in geometry processing, with meshmixer we have discarded these structured shape representations 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 uses such as high-end film production or precision engineering. For example, with high resolution triangle meshes surface complexity is essentially free, while we can only achieve smoothness by applying computationally intensive variational mesh fairing techniques. It remains to be seen whether this approach will lead to a CAD tool that is viable for industrial design and engineering. However, we are already confident that with our mesh-based approach we have gained 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 a wide variety of tasks.

Figure 7 illustrates one interesting workflow in which meshmixer plays a critical role. A number of museums and galleries have hosted “Scanathons”, after-hours events where makers are invited to create 3D scans of the collections using photogrammetry software such as Autodesk 123D Catch (http://www.123dapp.com/catch). The meshes created via photogrammetric reconstructions often contain many artifacts which prevent them from being 3D printed, and users turn to meshmixer to repair these issues. The results are often posted to online model archives such as Thingiverse (http://thingiverse.com/), where others can download and edit them, for example to create mash-ups as shown in Figure 7.

Figure 7: *meshmixer plays a role in many scan-clean-print workflows (left), where a coarse photogrammetric reconstruction - in this case created with a cellphone camera - is postprocessed to convert the shell into a printable solid. Many such objects are now posted online, and are incorporated by others into interesting mashups (right, image copyright Brian Evans, 2012).*

To demonstrate a few of the tools in meshmixer, we took the fish scan in Figure 7 and created a keychain, shown in Figure 8. To work with high-resolution meshes, selection is based on a brushing metaphor, much like in image editing software. With this approach we could quickly select and delete the unwanted areas of the surface, and then use automatic hole-filling and mesh fairing algorithms to create an aesthetically-pleasing watertight solid. We then simply dropped in a ring connector from our part library, and positioned it using an interactive drag-and-drop composition interface. Variational mesh fairing was applied to convert the resulting sharp transition into a smooth one, similar to a traditional Fillet. During these operations the surface remains manifold and watertight, so it can be sent directly to the 3D printer.

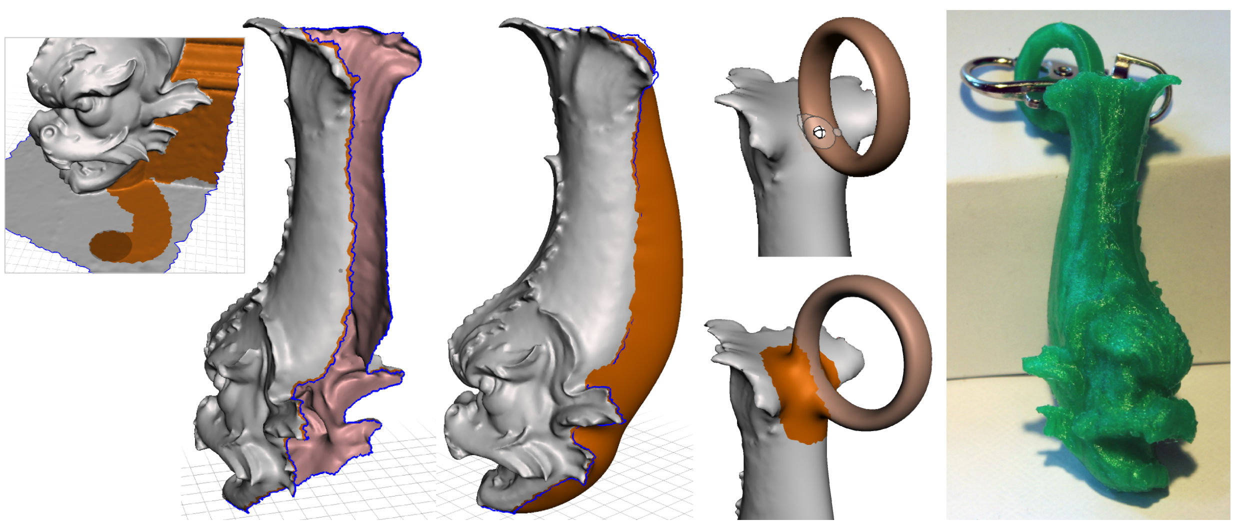

Figure 8: Our initial fish mesh is not a closed volume, and contains part of the background surface. Using a triangle-selection brush we can quickly get rid of those areas and then fill the large, complex hole with new triangles. A ring is then dragged onto the model and is stitched into the mesh along a small hole on the ring surface (not visible), so the surface remains a single, watertight connected component. Finally we applied variational mesh fairing in the region around this stitched transition to blend the ring into the fish, and sent it off to the 3D printer.

The drag-and-drop tool used in Figure 8 is a good example of the style of interface that we believe is suitable for the inexperienced “maker”. With this tool, arbitrarily-complex parts can be added to the mesh with a single click-and-drag. Novice users find this very satisfying, because they can create detailed models that would otherwise be beyond their technical or artistic capabilities. In the same vein, this tool enables users to easily share interesting parts. In a traditional CAD system one might perform a similar operation using a Boolean union, but that involves unconstrained 3D transformation - a very difficult task for novices - and assumes that the novice understands technical jargon like “Boolean Union”. By wrapping up multiple steps in a direct manipulation interface, with a live preview of the result, the drag-and-drop tool simplifies what would otherwise be a complex multi-step transaction.

Of course, the simplicity of our drag-and-drop interaction is enabled by complex underlying geometric algorithms [SS10], which make many decisions for the user and ultimately result in less “control” than an expert might claim to want (although so far experts seem to like this tool as well). This level of interactive control is something that we strive for in many of the meshmixer tools. In the best case, the many parameters of the underlying geometry processing algorithms are abstracted into a simple, intuitive interface, which the user interactively guides towards a desirable result.

Design-Print Workshops

Like most research systems, meshmixer has minimal documentation or training materials, and has a relatively spartan visual design. However, the interaction design has been iteratively guided through several years of feedback from skilled users. To more formally explore how novice users would respond to meshmixer, we developed and taught a “design-to-print” workshop. In this workshop we gave a one-hour introduction to meshmixer and 3D printing, which was followed by an hour of the participants designing an object, and then 3D printing the result. The workshop theme was focused on jewelry customization - we provided various basic models of pendants, which the participants personalized. Constraining the task and base models helped keep the designed objects small and flat, ensuring reasonable print times.

Many participants had never used a 3D user interface before, so our instruction had to cover basic concepts like “what is a 3D model” and how to manipulate a virtual 3D camera. We focused on meshmixer’s drag-and-drop part composition tool, as it allows one to easily add geometric details to a model from a part library that we provided. We also walked the participants through standard mesh selection and surface push/pull tools, and demonstrated the basics of the 3D sculpting tools that meshmixer includes. As design time was limited, we provided handouts with “cheat-sheets” for the meshmixer UI and workflows, and “meshmixer mentors” were available to deal with software issues and questions.

Our participants had no prior 3D design experience, and based on our observational experience of novices using other 3D tools, we had low expectations. In past experiments we have seen novices struggle with even basic camera manipulation. Subjects that do not have a strong personal interest in 3D design are generally unwilling to work to overcome the barriers that they inevitably encounter, particularly when what they see on the screen in no way resembles the shape that they are attempting to express.

Given this previous experience, we were stunned by how quickly the participants learned to use the meshmixer tools. Although many of the designs were relatively simple, all the subjects we talked to clearly enjoyed the experience. And several of the participants painstakingly created detailed 3D designs (which unfortunately were not always captured by the limited resolution of the consumer-level 3D printer). The success of this workshop has resulted in an ongoing series based on our materials (available online at http://meshmixer.com/help/index.html). The photographs in Figure 9 were taken from one iteration (taught by other instructors) where the participants were girls aged 9-13.

It seems unlikely that such an event, minus the 3D printing, would have been remotely as successful. 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 tool. We have had similar experiences on a smaller scale with consumer-level 3D printers in the office, where the initial response of co-workers is often an excited "...can I Make something?". To us, these experiences suggest that digital fabrication may provide a strong incentive for a level of basic "design literacy" that has not been present in the past.

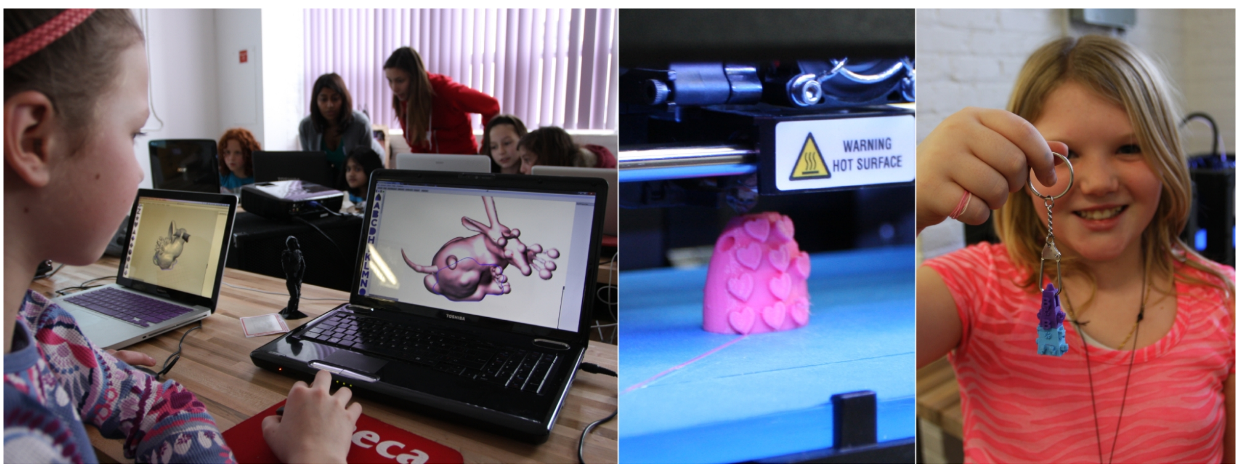

Figure 9*: These photographs were taken at a design-print workshop for girls aged 9-13, where they designed simple keychain and pendant objects in meshmixer, and then 3D-printed them (images copyright Ladies Learning Code http://www.ladieslearningcode.com)*

Fabrication Guidance for 3D Printing

The feedback and observations that we have gathered from 3D printing workshops has led to a number of usability improvements in meshmixer. But perhaps a more significant byproduct was an awareness of just how messy the transition from digital to physical still is. Although 3D printing does have an aspect of magic, the reality is that the machines have many limitations that are not immediately obvious, so a little bit of care taken in the digital stage can often lead to vastly improved physical objects.

For example, single-material consumer-level FDM printers (such as the popular MakerBots) print in layers, from bottom to top, essentially by extruding a tube of molten plastic. For this to work, there must be something “underneath” each layer, otherwise the plastic will simply fall into empty space. The rule-of-thumb is that parts of the model with draft angles less than 45 degrees are called *overhangs* and will “droop” when printing (Figure 10). This is a significant design constraint, which can be mitigated by printing *support* structures, which ideally will snap off easily in a postprocessing step, but in practice often lead to noticeable degradation of print quality.

Minimizing overhangs is a complex design constraint that novices have difficulty taking into account. Even for a skilled designer it is difficult to determine by visual inspection alone where overhangs exist on complex freeform surfaces. To help with this task, meshmixer includes a tool to identify overhang regions and visualize them via a surface shader (Figure 10) . For overhangs where small changes to the shape are acceptable, the user can often use sculpting brushes to slightly tweak the surface to meet draft angle criteria. Alternately, the user may choose to automatically generate support posts for a particular overhang. This guided approach scales with the users skill level: novices can simply auto-generate support geometry where needed, while experts can combine their design knowledge with the interactive feedback to optimize an object for 3D printing.

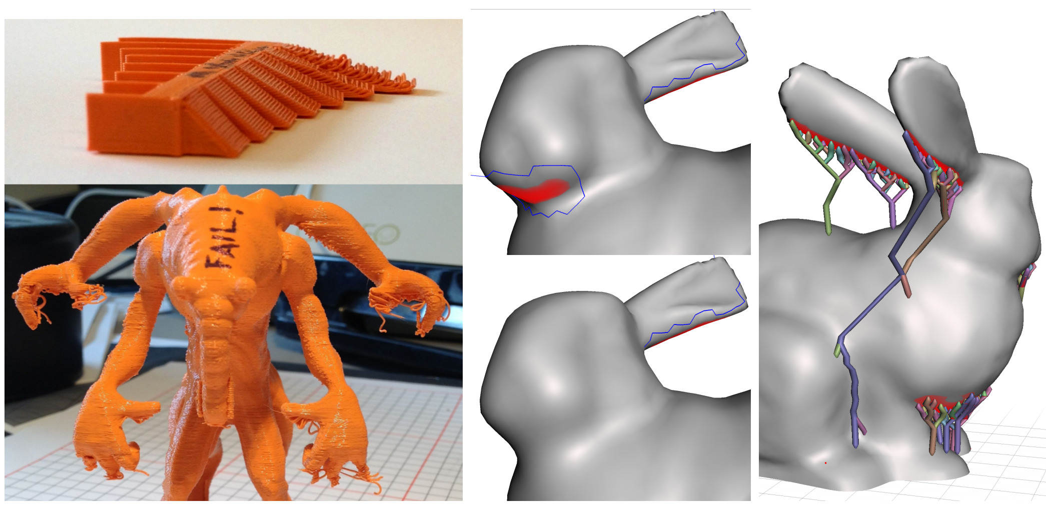

Figure 10: *If a model has (left, top) too shallow a draft angle, or (left, bottom) regions that are completely unsupported from below, “drooping” will result. Visualizing surface regions that violate draft angle restrictions (center, top) allows the user to make slight shape modifications to improve printability (center, bottom). Alternately, we can automatically generate snap-off support structures to improve print quality (right).*

At a global scale, the spatial orientation of the model determines total overhang area. Orientation can also have implications for model robustness, as between-layer bonds are weaker than those in-layer, so thin parts printed vertically are fragile. As a result, something as simple as changing the orientation of the model relative to the print bed can vastly affect the print strength. Currently some tools automatically determine an orientation which minimizes the total area requiring support, but this can result in support interfaces (which lower surface quality) covering important parts of the model. We are exploring support minimization techniques that will simultaneously attempt to minimize support while maximize part strength and surface quality for areas the user deems to be most important.

Another factor to take into account is whether a digital model will be stable in its intended orientation. Figure 11 is a screen capture from 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 its projected position relative to the convex hull supports analysis of how (un)stable the object currently is. In recent work, Prevost et al [PWLS13] describe techniques to automatically optimize an object to maximize stability.

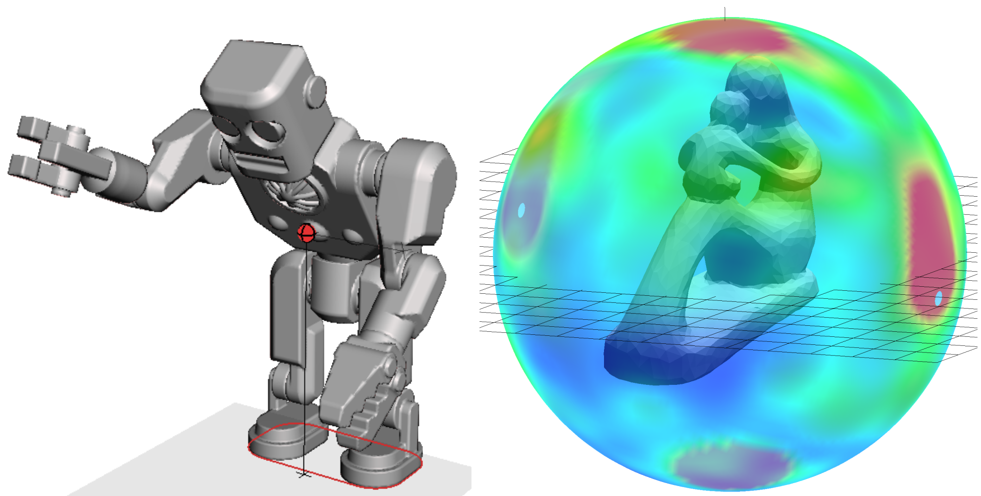

Figure 11*: A straightforward geometric analysis allows us to determine if this robot model (left) will stand up under gravity (in this case, the red ball indicates that it will not). In the image on the right, the color map on the sphere indicates the total surface area that would require support structures if the print bed is aligned with the corresponding normal direction.*

Finally, many of the exciting applications of 3D printing - fixing broken parts, printing entire functional assemblies, and so on - involve tolerances which may depend not only on the printing technology or particular model of printer, but on machine-specific factors and even ambient effects like room temperature. Our design tools need to be materials- and process-aware, to guide users through the complexities of adapting a design to different manufacturing techniques. In this direction, researchers have begun to explore interfaces which analyze the physical properties of a virtual design [ZPZ13], and can automatically optimize the model to improve printability [SVBCM12] or interactively guide the user towards a more desirable end result [UIM12].

These examples illustrate the complexity of helping novices design for fabrication in more general contexts, where the interface cannot strictly constrain the user to designs which are clearly “safe” for 3D printing. However, we have only scratched the surface of what might be useful in a design tool like meshmixer. For example, while visualizations of geometric analysis and simulation results are helpful, our novice users will likely not understand how to interpret the feedback without instruction, or know how to resolve tricky fabrication issues. So how do we improve the interface? More informative visual guidance will be necessary to enhance usability, while suggestions and automatic changes can help users to improve their designs. We will need both to really unlock the power of digital fabrication, creating new design tools - and entirely new approaches to design - by combining advances in user interfaces, geometry processing, and machine learning.

Conclusion

Digital fabrication is an active and exciting space, with new and interesting problems whose solutions will directly impact industry and society in ways we cannot yet imagine. While we are wary of the current “hype factor” around 3D printing, we also note that each of the 3D printing workshops we have observed here in Toronto has been larger - and sold out more quickly - than the last. As the price for entry-level 3D printers drops under $500, the critical question is “what will people do with them?” Regardless of the task, interactive 3D design tools are clearly going to play a key role.

Our goal is a system that can guide any user - from hobbyist to professional - through the process of creating a design suitable for direct fabrication. A key design criteria which we have not covered in this article is structural integrity, both during manufacturing and afterwards, when the object is put to its intended use. Current work in this direction is mainly treated as post-processing [SVBCM12, ZPZ13], but in our opinion, this sort of analysis needs to be integrated into the design cycle, running in the background and providing interactive guidance. Another critical and complex issue is tolerances. It is all too easy to design a part which is too thin to print properly, or an assembly that won’t fit together when 3D printed. Tolerances in digital fabrication often have complexities, for example in some sintering processes the tolerance on a small hole depends on local thickness. Similarly, cost and material usage are factors which need to be considered. New approaches to shape analysis will likely be needed to guide the user through the gauntlet of machine-dependent parameters.

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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