Digital Fabrication

Manfred Lau, *Lancaster University, UK*
Jun Mitani, *University of Tsukuba, Japan*
Takeo Igarashi, *University of Tokyo, Japan*

For the first time in history, laypeople can participate in the product design and manufacturing process by directly interacting with the underlying hardware and software.

Many of the items that we use on a daily basis are created by professional designers, mass-produced at factories, and then transported, through a complex distribution network, to regional warehouses and local retail sales outlets.

In the past, consumers often had to physically go to a neighborhood store to browse through existing products and make a purchase. Although mail-order catalogues have been around since the mid-eighteenth century, the number of goods that could be shipped directly to homes was extremely limited, and it was difficult to evaluate offerings without seeing them in person.

The Internet has made it possible for consumers to easily compare and buy competing products, with websites providing up-to-date textual descriptions, photos, videos, and customer reviews. Items purchased online can be shipped to the consumer from the nearest available distribution center rather than to local stores, reducing costs and increasing convenience. Online shopping has also made it easier to customize products—there is a dizzying array of choices for everything from T-shirt logos to sofa fabric patterns—although for most goods, consumers are still restricted to established designs.

A PARADIGM SHIFT

The next stage in the evolution of consumer product design and manufacturing is *digital fabrication*, in which individuals design products to meet their unique needs and preferences. These products are then manufactured and delivered to them on demand (N. Gershenfeld, *Fab: The Coming Revolution on Your Desktop—From Personal Computers to Personal Fabrication*, Basic Books, 2005; J.A. Landay, "Technical Perspective: Design Tools for the Rest of Us," *Comm. ACM*, Dec. 2009, p. 80).

Emerging digital fabrication technologies, such as desktop 3D printing, are increasingly affordable and might soon make what some observers have called the next industrial revolution a reality (C. Anderson, "Atoms Are the New Bits—The New Industrial Revolution," *Wired.co.uk*, 1 Feb. 2010; "The Third Industrial Revolution," *The Economist*, 21 April 2012).

For the first time in history, laypeople can participate in the product design and manufacturing process by directly interacting with the underlying hardware and software. The notion that average people—not just professionals—can leverage their unique creative skills and ideas to create real, physical objects is fun and exciting, and will open up a world of innovation.

Because digital content is weightless and can be moved instantly on a global scale at little cost, digital fabrication will lead to a paradigm shift not just in product design and manufacturing, but also in the storage, transportation, and energy sectors.

INTERFACES AND MODELING TOOLS

To fully realize this transformation, users need to be able to create digital 3D shapes before they can be fabricated into physical objects. Thus, a critical research challenge is developing 3D modeling tools for use by people with little or no experience in modeling and design. We have explored two types of user interfaces and modeling tools for this purpose.

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Modeling-in-context

We have developed an easy-to-use interface that lets users sketch a new object using a photo of an existing object as a reference (M. Lau et al., “Modeling-in-Context: User Design of Complementary Objects with a Single Photo,” *Proc. 7th Symp. Sketch-Based Interfaces and Modeling* [SBIM 10], Eurographics Assoc., 2010, pp. 17-24). The photo provides a background context for the user to draw a 2D sketch of the new object and annotate its 3D geometric properties. The system then creates a 3D digital model of the 2D sketch that matches the real object’s dimensions.

Figure 1 illustrates the use of modeling-in-context to design a replacement lid for a teapot. The user first takes a photo of the teapot and uploads the photo to the system. The user then draws 2D lines and curves on the photo to represent the new lid, and annotates the drawing with the lid’s geometric properties. An algorithm expands the 2D sketch into a 3D shape. A 3D printer fabricates the resulting digital shape into a real teapot lid that fits well with the original teapot.

Situated modeling

We have also developed an augmented-reality-based interface that lets users create models for digital fabrication by manipulating small real-world shapes, such as wooden cylinders, spheres, and prisms; the user “stamps” digital 3D copies of these shapes and combines these into a single, life-size model (M. Lau et al., “Situated Modeling: A Shape-Stamping Interface with Tangible Primitives,” *Proc. 6th Int’l Conf. Tangible, Embedded, and Embodied Interaction* [TEI 12], ACM, 2012, pp. 275-282).

The user wears a head-mounted display to visualize the creation of the digital model and its placement in virtual space. Instead of stamping in empty space, the interaction between the small primitive shapes and the real-world environment allows for tactile feedback, and leads to a more precise overall digital shape.

Figure 2 illustrates the use of situated modeling to design a table that will fit in the empty corner of a living room. Wearing a head-mounted display, the user manipulates a set of wooden primitive shapes that are outfitted with markers for identification purposes (Figures 2a and 2b). The user stamps digital copies of these physical shapes in the virtual 3D environment, which the user sees on the display. The corner of the room, including the physical ground and walls, serves as a background reference to create the digital model, which is later used to assemble a real table (Figure 2c).

FABRICATING PHYSICAL OBJECTS FROM DIGITAL MODELS

Fabricating physical objects from digital 3D models is another major research challenge. Although there

WHERE THE PHYSICAL AND DIGITAL WORLDS COLLIDE

We surround ourselves with manmade objects that range in scale from tiny pieces of jewelry to the huge buildings where we live and work. Historically, the separation of the physical and digital worlds has been very clear, but digital fabrication is blurring that dividing line.

Thus far, digital printing technology can only generate relatively simple objects. However, artifacts in our modern world can in many cases be seen as an instantiation of a plan, which can be data or software, and fabricating programmable devices that have complex physical characteristics and functional parts is the next logical step in the technology’s evolution.

Initially, digitally fabricating such smart objects will rely on combining 3D printing with functional and programmable components (A. Schmidt, T. Döring, and A. Sylvester, “Changing How We Make and Deliver Smart Devices: When Can I Print Out My New Phone?,” *IEEE Pervasive Computing*, Oct.-Dec. 2011, pp. 6-9). Using computing component platforms such as Microsoft .NET Gadgeteer, it’s possible to build a fully functional digital camera or game console within hours (S. Hodges et al., “A New Era for Ubicomp Development,” *IEEE Pervasive Computing*, Jan.-Mar. 2012, pp. 5-9). In the long term, digital fabrication will become more sophisticated and enable direct printing of circuits as well as displays into objects.

In the not-so-distant future, the distribution and payment processes established in software—for example, app stores and in-app billing—might be applicable to physical objects as well. Concepts well researched in software engineering, such as versioning and product lines, could play a major role in all sorts of products.

Albrecht Schmidt, ***University of Stuttgart***

(a) (b) (c)

Figure 1. Using modeling-in-context to design a replacement lid for a teapot: (a) original photo of the teapot and 2D user sketch and annotations of the new lid; (b) 3D digital model of the new lid; (c) new physical lid from 3D printer that fits well with the original teapot.

Figure 2. Using situated modeling to design a table to fit in the empty corner of a living room: (a) tangible primitive wooden shapes with markers for identification purposes; (b) a user wearing the head-mounted display and holding one of the shapes; (c) digital table model created by the system, and corresponding physical table later assembled from wood pieces.

are many 3D model datasets, such as the Princeton Shape Benchmark (P. Shilane et al., "The Princeton Shape Benchmark," *Proc. Int'l Conf. Shape Modeling and Applications* [SMI 04], IEEE CS, 2004, pp. 167-178) and Google 3D Warehouse (www.sketchup.com/3dwh), as well as various software tools for creating and editing digital 3D shapes, it is not obvious how a digital 3D model can be fabricated into a physical object.

As one possible approach to this problem, we introduced a method that converts 3D furniture models into usable real-world furniture, specifically cabinets and tables (M. Lau et al., "Converting 3D Furniture Models to Fabricatable Parts and Connectors," *Proc. SIGGRAPH 2011*, ACM, 2011, article no. 85). The principal challenge is that the input models are triangular mesh models that only contain information about a shape's surface, as these models are typically used for display and visualization; they contain no information about the shape's semantics.

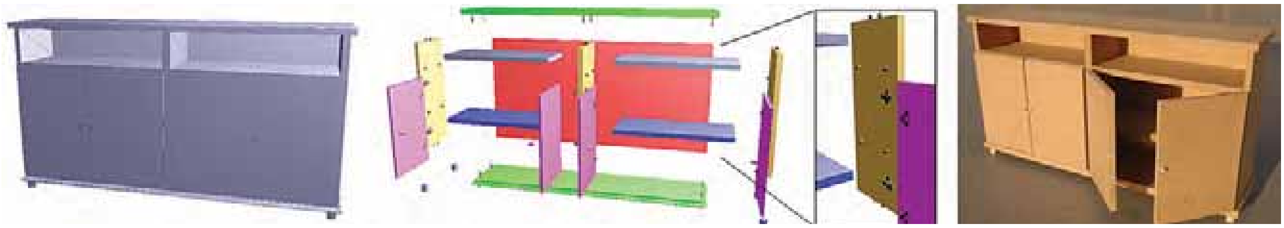
Our solution calls for defining formal grammars that describe how different types of cabinets and tables are constructed from individual parts and connectors (such as screws and nails). We then use these grammars to analyze a given model to extract its parts. After extracting the parts, we use data obtained beforehand from real furniture to generate the connectors. Figure 3 shows an example of the process applied to a 3D cabinet model, along with the equivalent real-world cabinet based on the structure and dimensions of the digital parts and connectors.

Despite the progress we and other researchers have made in advancing digital fabrication technology, many open challenges remain.

Current 3D digital modeling interfaces only allow for designing static objects, not objects with dynamic functional parts such as a closet door or a foldable chair. Researchers must develop more general user interfaces for handling these cases.

In addition, such tools do not consider the integrity of the resulting physical objects. Constructing a digital model doesn't guarantee that the object fabricated from it will be structurally stable, which severely limits the technology's usefulness. More research is required in this area.

New business and manufacturing models are also needed. If products



(a) (b) (c)

Figure 3. Converting a 3D cabinet model into usable real-world furniture: (a) digital model of IKEA ALVE cabinet from Google 3D Warehouse; (b) fabricatable parts and connectors generated by our algorithm; and (c) equivalent real-world cabinet based on the structure and dimensions of the digital parts and connectors.

can be created locally on demand, less storage, transportation, and energy will be required. The related industries must accordingly adapt to changes in demand.

Intellectual property issues must be addressed. Emerging commercial services such as Ponoko and Shapeways offer the ability to design, buy, and sell user-created 3D digital models. As more of these models are shared online, there must be adequate mechanisms in place to protect IP rights and prevent copyright infringement.

***Manfred Lau** is an assistant professor (lecturer) in the School of Computing and Communications at Lancaster University, UK. Contact him at m.lau@lancaster.ac.uk.*

***Jun Mitani** is an associate professor in the Department of Computer Science at the University of Tsukuba, Japan. Contact him at mitani@cs.tsukuba.ac.jp.*

***Takeo Igarashi** is a professor in the Department of Computer Science at the University of Tokyo, Japan. Contact him at takeo@acm.org.*