A Revolution in the Making

Steve Hodges
Microsoft Research

Björn Hartmann
University of California, Berkeley

Hans Gellersen
Lancaster University

Albrecht Schmidt
University of Stuttgart

We're currently witnessing a revolution in the way pervasive computing hardware is designed, prototyped, and manufactured. A broad set of researchers and users now have access to a host of digital fabrication tools and techniques that empower them to create new devices and realize new concepts more quickly, cheaply, and easily.

Advances in both additive and subtractive physical fabrication processes, such as 3D printing and laser cutting, have dramatically increased the fidelity, quality and speed of prototyping for a variety of mechanisms and enclosures for pervasive computing devices. At the same time, these digital fabrication tools have become cheaper and easier to use, thereby increasing accessibility. Similarly, a plethora of electronic hardware toolkits and platforms are available to support the construction of electronic devices. Some of the latest developments include machines that print conductors, transistors, organic LED pixels, and even batteries, promising a future where digital functionality will ultimately be "printed into" physical objects.

In parallel with the development of mechanical and electronic fabrication technologies, a wide range of software tools and online services that support the design, development, and deployment of pervasive computing hardware have become available. For example, Web-based integrated software development environments integrate extensive and easy-to-use programming libraries, example code, and online documentation. These present a low barrier to entry for less experienced developers while providing headroom to support advanced use and even mechanisms to "graduate" projects to fully featured tools. Online communities provide an unrivalled support network for learning and troubleshooting. The diversity and sophistication of these software tools continue to grow.

Published by the IEEE CS ■ 1536-1268/14/$31.00

Related Work in Physical Fabrication

Like a great many people who fabricate pervasive computing devices, David Mellis makes extensive use of 3D printing and laser cutting. There are a number of creative ways to leverage these tools—for example, creating foldable cardboard enclosures for electronic devices or integrating with existing construction blocks.[1] Others in the research community, who aren't content with these approaches, are exploring ways of repurposing and extending the capabilities of rapid prototyping machines.

Frustrated with the time taken to produce a typical 3D print, Stefanie Mueller and her colleagues at the Hasso Plattner Institute have developed a way to integrate pre-manufactured elements such as Lego blocks into a 3D design so that the structural elements of a design can be assembled quickly and only the remaining "details" need be 3D printed.[2] Earlier work led by the same author extended the purely 2D fabrication capabilities of laser cutters into the third dimension by enabling gravity-powered folding of sheet acrylic following localized heating of bend regions using an out-of-focus laser beam, an approach called Laser Origami.[3] Another interesting technique, which this time involves using a 3D printer in an unorthodox manner, is that of printed optics. Here, a transparent material is used to incorporate light pathways within a prototype, enabling a variety of interesting applications.[4,5]

REFERENCES

1. S. Hodges et al., "Exploring Physical Prototyping Techniques for Functional Devices Using .NET Gadgeteer," *Proc. Seventh Int'l Conf. Tangible, Embedded, and Embodied Interaction* (TEI 13), 2013, pp. 271–274; doi: 10.1145/2460625.2460670.
2. S. Mueller et al., "faBrickation: Fast 3D printing of Functional Objects by Integrating Construction Kit Building Blocks," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 14), 2014, pp. 527–530; doi: 10.1145/2559206.2574779.
3. S. Mueller, B. Kruck, and P. Baudisch, "LaserOrigami: Laser-Cutting 3D Objects," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 13), 2013, pp. 2585–2592; doi: 10.1145/2470654.2481358.
4. K.D.D. Willis et al., "Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices," *Proc. 25th Ann. ACM Symp. User Interface Software and Technology* (UIST 12), 2012, pp. 589–598; doi: 10.1145/2380116.2380190.
5. E. Brockmeyer, I. Poupyrev, and S. Hudson, "PAPILLON: Designing Curved Display Surfaces with Printed Optics," *Proc. 26th Ann. ACM Symp. User Interface Software and Technology* (UIST 13), 2013, pp. 457–462; doi: 10.1145/2501988.2502027.

Building Electronic Devices

In this special issue, we've brought together four articles that describe recent research in this space of printing and fabrication for pervasive computing. The first article, "Do-It-Yourself Fabrication of Electronic Devices," is by David Mellis, a PhD student at the MIT Media Lab who is well known as one of the inventors of the Arduino electronics prototyping platform. Mellis discusses ways in which the growing number of digital fabrication technologies has made it possible for non-experts to design and produce their own working electronic devices. He presents a number of devices he has built—such as a radio, a mouse, and several cell phones—and shares insights he has gleaned from running workshops where he has led people through the process of assembling these electronic devices.

Despite all the benefits that modern fabrication tools and techniques bring, Mellis draws from his own experiences to highlight some of the difficulties that remain. He also discusses the meaning of DIY fabrication—why people are motivated to fabricate and customize their own devices rather than buy the mass-produced equivalent. The article concludes with some thoughts about the future of digital fabrication. (Also see the "Related Work in Physical Fabrication" sidebar for a discussion of other approaches for repurposing and extending the capabilities of rapid prototyping machines.)

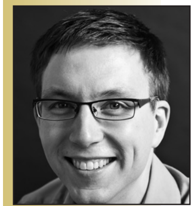
Printed Conductors and Sensors

A fabrication technology that's starting to emerge as an option to complement established tools is the process of digitally printing arbitrary conductive patterns. A number of variations of this basic idea have been explored by researchers, but an interesting recent development is the use of nanoparticle inks that can be ink-jet printed. The second article in this special issue, "Building Functional Prototypes Using Conductive Inkjet Printing," comes from Yoshihiro Kawahara at the University of Tokyo and his collaborators in Europe and the US—Steve Hodges (a coauthor here), Nan-Wei Gong, Simon Olberding, and Jürgen Steimle. The article shows how silver nanoparticle ink can be deposited using an off-the-shelf domestic inkjet printer. This allows single-layer electric circuits to be printed much more quickly, easily, and cheaply than the established alternative—printed circuit board fabrication.

The authors bring together and extend previous work that explores the conductive inkjet printing process and a variety of techniques that leverage the resulting flexible circuits and applications. They also provide practical information so others can replicate and build on their work. It's easy to imagine future conductive inks that can be

the AUTHORS

Steve Hodges leads the Sensors and Devices research group at Microsoft Research, Cambridge, UK, and is a visiting professor at the School of Computing Science, Newcastle University. The focus of his research is to create new interactive experiences for users, to seed new devices and technologies in the market, and ultimately to change people's perceptions of technology and how it can be used. Hodges has a PhD in robotics and computer vision from Cambridge University. Contact him at shodges@microsoft.com.



Björn Hartmann is an assistant professor in EECS at the University of California, Berkeley, where he co-directs the CITRIS Invention Lab. His research group creates design tools for pervasive computing and digital fabrication. Hartmann received his PhD in computer science from Stanford University. Contact him at bjoern@eecs.berkeley.edu.

Hans Gellersen is a professor of interactive systems at Lancaster University's School of Computing and Communications. His research interests include ubiquitous computing, physical-digital interactive systems, and user interface technology. Gellersen has a PhD in computer science from Karlsruhe University. Contact him at h.gellersen@lancaster.ac.uk.

Albrecht Schmidt is a professor of human-computer interaction at the University of Stuttgart. Contact him at albrecht.schmidt@vis.uni-stuttgart.de.

The FreeD smart milling device can empower novice users to create compelling 3D sculptures.

ink-jet printed onto 3D structures,[1] with the ultimate goal of fabricating enclosures with the wiring needed to connect a small number of electronic modules and an embedded power source.

Although printed conductors introduce a lot of new possibilities for the fabrication of pervasive computing devices, they're fundamentally limited to interconnection and basic sensing applications. Making more sophisticated devices requires integrating additional electronic functionality. In addition to the self-adhesive "circuit stickers" described by Kawahara and his colleagues,[2] Valkyrie Savage at Berkeley has been exploring this in her PhD work. Her Midas system supports capacitive sensing[3] and, more recently, the Sauron system integrates a camera into a 3D-printed prototype to detect various forms of interaction.[4]

In a similar vein, in our third special issue article, Jessica Lo and Audrey Girouard from Carleton University in Canada describe how they integrated bend sensors into a deformable arcade game prototype, which they call Bendy. They describe the techniques they developed while fabricating Bendy and offer practical advice that should help others who want to leverage silicone casting, flexible circuit etching, and bend sensing.

Assistive Fabrication Tools

The final article, "The Wise Chisel: The Rise of the Smart Handheld Tool," takes a very different approach to digital fabrication. Rather than striving to produce a high-fidelity physical rendition of a digital CAD model, Amit Zoran, Roy Shilkrot, Pragun Goyal, Pattie Maes, and Joseph A. Paradiso describe a class of fabrication tools where the human operator is fundamentally in control, albeit in conjunction with a digital sensing-and-control system that can guide and constrain them as necessary. The authors start by describing and categorizing a variety of previous research projects and commercial products that meet their criteria for "smart handheld tools." The second part of the article focusses on handheld tools specifically designed to help inexperienced users. The authors describe their own work in this space: the FreeD smart milling device can empower novice users to create compelling 3D sculptures, and a smart airbrush constrains the painting process to ensure a recognizable result. They also review other research in this area.

Others have taken the smart "assistive" tool concept in different directions. For example, Stefanie Mueller and her colleagues have developed a way of using a handheld laser pointer to direct the operation of a laser cutter, creating a highly interactive computer mediated experience.[5] Christian Weichel, a PhD student at Lancaster University, has built two different tools that help users match their 3D design with the components that will fit inside it or with other objects with which it's designed to work.[6,7]

As we look to the future, there's no doubt that the wide variety of printing and fabrication technologies will continue to evolve, enabling an even broader spectrum of users to design and construct custom artifacts. We hope that this special issue provides insight into several areas of active research in this domain, but we also encourage the interested reader to explore this fascinating and fast-moving field more deeply.

REFERENCES

1. J. Sarik et al., "Combining 3D Printing and Printable Electronics," *Proc. Sixth Int'l Conf. Tangible, Embedded, and Embodied Interaction* (TEI 12), Works in Progress, 2012; http://research.microsoft.com/pubs/189096/07-sarik.done.pdf.
2. S. Hodges et al., "Circuit Stickers: Peel-and-Stick Construction of Interactive Electronic Prototypes," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 14), 2014, pp. 1743–1746; doi: 10.1145/2556288.2557150.
3. V. Savage, X. Zhang, and B. Hartmann, "Midas: Fabricating Custom Capacitive Touch Sensors to Prototype Interactive Objects," *Proc. 25th Ann. ACM Symp. User Interface Software and Technology* (UIST 12), 2012, pp. 579–588; doi: 10.1145/2380116.2380189.
4. V. Savage, C. Chang, and B. Hartmann, "Sauron: Embedded Single-Camera Sensing of Printed Physical User Interfaces," *Proc. 26th Ann. ACM Symp. User Interface Software and Technology* (UIST 13), 2013, pp. 447–456; doi: 10.1145/2501988.2501992.
5. S. Mueller, P. Lopes, and P. Baudisch, "Interactive Construction: Interactive Fabrication of Functional Mechanical Devices," *Proc. 25th Ann. ACM Symp. User Interface Software and Technology* (UIST 12), 2012, pp. 599–606; doi: 10.1145/2380116.2380191.
6. C. Weichel, M. Lau, and H. Gellersen, "Enclosed: A Component-Centric Interface for Designing Prototype Enclosures," *Proc. Seventh Int'l Conf. Tangible, Embedded, and Embodied Interaction* (TEI 13), 2013, pp. 215–218; doi: 10.1145/2460625.2460659.
7. C. Weichel et al., "MixFab: A Mixed-Reality Environment for Personal Fabrication," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 14), 2014, pp. 3855–3864; doi: 10.1145/2556288.2557090.