Guest Editors' Introduction

Fabricating Pervasive Computing Systems

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Electronic miniaturization has driven pervasive computing for decades. With the rapid progress of digital manufacturing however, new tools and methods are maturing that enrich the possibilities for ambient and wearable system design. While miniaturized technology remains a key feature, now pervasive system designers work holistically across engineering disciplines. Pervasive systems are getting more affordable because designers can bypass the nonrecurring engineering costs and laborious preparation steps of classic manufacturing, e.g., to create molds or physical templates. Eventually, new classes of pervasive computing systems become feasible: personal devices that are adapted to the preferences and needs of one user, and systems addressing niche applications, i.e., devices made for very small production volumes that could not be addressed before. With the maturity of printed electronics, the pervasive system design is no longer limited to mechanical devices only. Instead, we are witnessing digitally manufactured pervasive computing systems with new mechanical features, including shape, texture, flexibility, acoustics, and electronic components such as sensors, actuators, computation, and communication. We even see digital manufacturing in crafts with inspiring features of taste and sound.

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The growing variety and wide availability of materials drives makers, in particular those developing interactive wearable computing systems. The form factor of these new wearables ranges from smart accessories and textiles, to computing patches and electronic tattoos. Still, there are a variety of challenges in making pervasive computing systems. For example, key open problems for wearable systems are conductivity of new materials, achieving skin-like properties, and developing integrated manufacturing processes. The open problems on one side and the possibilities of digital manufacturing on the other are propelling computer-aided design (CAD) software development: What had been tasks of mechanical engineers become accessible to lay people and users. However, to fully support the possibilities of digital manufacturing, mechanical and electronic CAD, which have been distinct domains, must integrate with each other.

Conferences capture the growing interest in making pervasive computing systems in established formats (e.g., ISWC and Ubicomp), but new venues arise too (e.g., Symposium on Computational Fabrication, IEEE FLEPS). Moreover, large industry events push three-dimensional (3D) printing and printed electronics (e.g., LOPEC, IDTechX, and RAPID) and provide opportunities for academia and industry to meet. While there is a lot of momentum, the academic community that builds on those new options to make pervasive systems is still small and fragmented.

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In this special issue, we capture early but promising trends of making pervasive computing systems that highlight challenges and opportunities of this area. The selected papers emphasize the need to develop convenient software tools and accessible process chains, especially for people who are not familiar with manufacturing processes.

In the article "Exploring Pervasive Making Using Generative Modeling and Speech Input," Ballagas *et al.*, build on 3D printing and investigate how artificial intelligence (AI) methods could enable lay people to realize complex mechanical designs. They focus on a Sunglass Kiosk that can be voice-controlled by users to express their design intent. They employ a generative adversarial network to generate sunglass models based on user commands. With this AI-driven approach, the authors analyze attitude and behavior of users. The article of Huppert *et al.*, "Design Different: Pen & Paper for Laser Cutting," introduces an innovative digital approach to classic pen and paper interaction. Their effort aims to simplify the traditionally complex process of designing for laser-cutters. With the approach, users can focus on their design interest, rather than the toolchain needed to produce prototypes. The article of Tansaz *et al.*, "Printing Wearable Devices in 2D and 3D: An Overview on Mechanical and Electronic Digital Co-Design," focuses on the digital manufacturing process chain. They present a mechanics and electronics co-design approach for wearable devices and guide readers in the choice of multiprocess additive manufacturing for wearable devices.

In their spotlight contribution "Long Tail Hardware: Turning Device Concepts into Viable Low Volume Products," Hodges and Chen discuss product popularity and drivers that shape the long tail of increasingly niche products, leading to what they frame as "replication challenge." Although scaling hardware from prototype to production will remain more challenging than for software, e.g., a smartphone app, they see options to create long-tail hardware successes.

Two sets of interviews help frame and highlight themes around making. Interviews with researchers in pervasive systems highlight (among others) that dealing with electronics and battery waste, for example, through novel degradable materials and new approaches to noble metals recycling, will be essential for sustainability of the making field. Interviews with practicing artisans and technologists in the crafts of music and food (including the famous pastry chef Amaury Guichon!) highlight the increasing use of digital tools as part of the toolchain for traditional crafts as well as the increasing engagement in hybrid (virtual and physical) crafts. Through these interviews, we identify important topics for future research and guide new investigators, entrepreneurs, and artisans in their steps to enter the area of making and using pervasive computing systems.

We hope that the selected articles provide a useful insight into the novel opportunities of digital manufacturing and making pervasive computing systems. We aim to motivate new research and the discussion of new ideas on making systems to spur further development of the area.