THEME ARTICLE: GRAND CHALLENGES

Citizen Manufacturing: Unlocking a New Era of Digital Innovation

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We have all come to expect—if not depend upon—the steady march of technology. All manner of pervasive computing devices, applications, and services increasingly support us at home and work. Thankfully, for those tasked with creating future generations of innovative digital technologies, the design and prototyping process continues to get easier. But for hardware, the transition from device prototype to production presents a bottleneck that is restricting the rate and nature of innovation. Imagine instead a world of citizen manufacturing, where individuals are empowered to turn their ideas not only into working prototypes, but also to evolve them organically and seamlessly into viable products. Such an approach could increase consumer choice, grow local and national economies, and facilitate more socially conscious production. We call on the community to join us in pursuit of this goal! We believe that overcoming the many challenges of transitioning from device prototyping to production will unlock a new era of digital innovation that allows more people to explore and benefit from pervasive computing.

STEADY MARCH OF TECHNOLOGY

The ongoing evolution of technology means that the things we do generally get easier, quicker, cheaper, more effective, and/or more enjoyable. Perhaps the most dramatic illustration of this comes from the remarkable growth of software applications, services, and solutions that we have seen over the past fifty years. As Marc Andreesen famously remarked, "Software is eating the world."[1]

Innovation is not just about convenience; in a market economy, it drives the growth that many societies have come to depend upon for prosperity. Since the second industrial revolution, the world has enjoyed 150 years of technical innovations and largely unchecked economic growth as a result.[2] Of course, technological innovation does not just happen: it arises from people having new ideas and creating new artefacts.[3] But the process of innovation is getting harder. Even though the worldwide investment in research and development continues to rise, research productivity is declining at 5%–10% per year.[3] Essentially, the low-hanging fruit has already been taken.

To use a specific example, in today's world it is no longer possible for two brothers working with just their personal resources to invent something as revolutionary as the airplane. Modern innovations of this magnitude inevitably require much bigger teams and much bigger budgets. It is not all bad news though. While ideas are getting harder to find, a steady stream of new tools and techniques ease the burden of searching for them, continually making the innovation process itself more accessible and efficient.

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NEW TOOLS AND TECHNIQUES FUEL SOFTWARE INNOVATION

Proliferation of Applications

A great example where innovators are empowered to pursue their ideas more effectively is the widespread adoption of software development tools and programming frameworks. A range of open-source libraries, online collaboration tools, and agile development methodologies—many of which were only developed since the turn of this century—have eased development and facilitated the rapid realization of new applications. Just looking at PC applications alone, an estimated 35 million titles have now been developed.[4]

Another key enabling technology behind many software products is cloud computing. Today's ready availability of cloud services removes the need for an up-front investment in server infrastructure, again lowering the barrier of entry to newcomers and allowing new ideas to be trialed quickly and easily.[5] Should a software product or service prove successful it is easy to dynamically scale and geographically redistribute the associated cloud services.

In the case of mobile apps—a relatively new category—the technologies listed previously combine for even greater effect. New products can be developed quickly and easily, the services that power them can be deployed with little up-front expense, and the "app store" marketing and distribution model provides a channel to millions of potential users.[5] In 2020, there were estimated to be nine million mobile application titles.[6] Even if a product only attracts hundreds of users a year, it can still deliver useful revenue for the producer.

Rise of the Citizen Developer

Despite the growth of the software industry, we can no longer rely solely on established models of app development: there simply are not enough developers to build all the worthwhile applications.[7] There is a projected need for more than 100 million new apps annually,[8] i.e., more applications must be created every year than were created in the entire history of computing—up until very recently, that is.

Citizen development, an emerging paradigm that provides a solution to this, is being adopted widely and quickly.[10] Citizen developers are professionals with no computer science or IT background who are, nonetheless, empowered to write software. They are using powerful development environments to build "low-code" and even "no-code" solutions that automate and assist with tasks at work. While their motivation is making their jobs and the jobs of their colleagues easier, they are at the same time making their companies more efficient and productive.

Citizen development is a form of prosumption, an established model where individuals generate artifacts for themselves—and sometimes others—breaking the traditional split between producers and consumers.[9] As with other forms of prosumption, citizen development is relatively low-risk compared to a more traditional approach for several reasons. It avoids an onerous requirements gathering and specification process, and it side-steps the need for contractual engagement of professional services. Instead, the end-user develops a new application themselves, as and when their other responsibilities allow. The application can be iterated, enhanced, deployed, and scaled as prudently or as quickly as befits the circumstances.

Software development is no longer restricted to professional programmers; it has become truly democratized, opening up a long tail of software applications.

HARDWARE INNOVATION IS ALSO CRITICAL

It is not just about the software of course; evidence suggests a strong need for new hardware devices too. These provide the critical gateway through which all our software applications and systems receive input and provide output.[5] Whether it is intentional user interaction, continuous context sensing, situated information display, autonomous control, wearables, or environmental sensing, electronic devices form the eyes, ears, and brains of our increasingly connected world.

It is not only companies that want to pursue new hardware. Sichela and von Hippel[11] have demonstrated the extent of what they term "household innovation." This refers to the use of household resources to create a product or process with future benefits for the household, and often other households too. Examples range from modified sporting equipment to niche medical devices. In the United States, for example, prosumers collectively spend around half as much on product innovation as all U.S. companies.[11]

Hardware Prototyping is Easier Than Ever

Prototyping, invariably the first step in the hardware innovation process, has become easier and more accessible since the turn of the century[12] thanks to numerous innovations from the research community and from industry. A variety of off-the-shelf modular electronics platforms[13] coupled with rapid prototyping equipment and services, such as laser cutting and 3-D printing, allow experienced practitioners to build prototypes of hardware devices quickly and cheaply.

At the same time, nonexperts are also empowered to work in this domain, using the platforms and tools cited previously and assisted by the global presence of 1400 makerspaces.[14] Makerspaces are physical spaces that provide social and technological resources to support people creating new technologies.[15] They have led to a community of hobbyists and tinkerers—makers—who have moved beyond their roots working with more traditional materials using techniques like woodworking, metalworking, and needlework and into functional digital device creation. Even high-school students can design and build useful and innovative hardware by combining an off-the-shelf microcontroller board, some external components, and a 3-D printed enclosure.[5]

These folks who are now empowered to build functional prototypes of all manner of interactive and embedded devices as prosumers—or "citizen engineers"—often leveraging them for personal use.[16] Some go beyond this notion of personal fabrication,[17] building on their prototyping skills and using craft production techniques to replicate their prototypes for sale. However, fieldwork by Corbin and Stewart indicates that this transition to viable production is very much the exception,[18] while other researchers argue it is actually a technomyth.[19]

Making is not Manufacturing

So why is the transition from prototype to production rare within the maker community? Well, first, making is a separate cultural practice to manufacturing,[20] and many makers primarily pursue it as an enjoyable pastime and nothing more.[19] But second, for makers who seek to transition from a working prototype to a reliable and financially viable product, challenges abound.[5]

To the uninitiated, this may seem counterintuitive. After all, moving from a prototype to production seems like it should be a straightforward process: just replicate the prototype as many times as necessary. However, the iterative process used in prototyping may include meticulous manual assembly and adjustment steps that are tedious and difficult to reproduce. As a result, even if the prototype works reliably, copies of it may not. Conversely, the copies may be more robust and reliable than is necessary, but prohibitively expensive or time-consuming to create. Lindtner *et al.*[15] observed this first-hand: they report that creators embarking on the transition from prototype to consumer product soon realized that the requirements of the two differed significantly. Working with factories in China, the makers quickly needed to learn about the specific affordances and limitations of the machines used for production. Khurana and Hodges[16] made numerous similar observations.

Successful Production Relies on Manufacturing Expertise

Moving to production typically requires key decisions made during prototyping to be revisited. These include the choice of components and materials, the architecture of the solution, and sometimes even the look and feel of the product. Somewhat paradoxically, the challenge of moving to production is often harder at low volumes than at very high volumes where the up-front cost of the productization process can be amortized over a great many units.[5] But either way, detailed knowledge and experience of a wide range of production processes is essential. As mentioned previously, this often results in long and involved interactions with manufacturers[15] to make suitable alterations and finalize manufacturing plans.

Makers and citizen developers who do not have experience of production naturally focus on the prototyping process. But the technical, physical, and economic characteristics of prototyping platforms and tools support *ad hoc* exploration and evaluation rather than efficient and reliable manufacturing. A prototype, therefore, represents the outcome of the creator's learning journey, not an optimal expression of a product. So, somewhat ironically, prototyping platforms and tools can conspire to make the transition to production harder.

CITIZEN MANUFACTURING OF DIGITAL DEVICES

What if a creator with no knowledge or prior experience of hardware manufacturing was able to design a prototype device, and then produce and deploy as many as they wanted? This process of "citizen manufacturing" would be somewhat akin to the citizen development of software applications described earlier. It would build on the processes used by today's hardware prosumers, but it would need to extend them—to make them accessible to a broader range of creators rather than those who might consider themselves as makers—and it would need to support a much more seamless transition from prototype to production.

Our goal is to create a set of device design tools and services that eventually become sophisticated enough that anyone can cost-effectively produce hardware that matches what is today developed by experts—whether it is a one-off for personal use, a small series of long-tail hardware products, or an ongoing device manufacturing business.

Although we believe this vision of citizen manufacturing is achievable, we acknowledge it could be a way off. The more immediate value of citizen manufacturing lies in augmenting the traditional development process, just as citizen development already does for the creation of software applications. In this way, individuals will be empowered to evolve their ideas organically and seamlessly—first into prototypes, and from there into reliable and viable products. When it comes to the physical aspects of manufacturing, sophisticated design tools will take care of all the details, while a distributed network of manufacturing partners who provide real-time quotes for low-volume orders will fulfill the various production requirements.

Device creation, therefore, becomes a peer production process, lowering the cost and the risk of development when compared to a more traditional approach. It allows a more flexible schedule where development can be sped up or delayed to suit the circumstances of each project. It also allows new models of production to emerge, whether for commercial or social benefit.

Here, we give a flavor of new solutions that citizen manufacturing might enable.

Novel Connected Devices

The number and variety of connected devices that form the burgeoning Internet of Things are predicted to carry on growing. But it is not clear exactly what form these devices will take, or indeed how many different forms are needed. For example, is there a "universal" environmental sensor that will suit all scenarios, from urban air quality measurement to river defense flood detection, or does it make more sense to adopt a bespoke design for each new deployment? What about in-building occupancy sensors: should they simply detect the presence of "people," or should they be smart enough to count the number of people? And should they identify mask-wearing, detect window opening, and measure CO_2 levels to aid social distancing? A final example might be the choice between wrist-worn displays and shelf-mounted displays to assist warehouse workers.

What if the people deploying and using new solutions like those described previously could iteratively explore device form and function to answer those questions for themselves? This would surely accelerate the process of identifying which applications and which approaches bring the most value. Some of these may evolve into widely adopted solutions while others will likely remain as low-volume applications, but in both cases, a way to organically scale from prototype to product using a citizen manufacturing paradigm eases the transition.

Customized Accessibility Technologies

Although estimates vary, about 15% of the world's population lives with some form of disability or impairment,[21] a fraction that's increasing as the global population ages. Many assistive technology (AT) devices have naturally been developed to help these 1.2 billion people with disabilities (PwD), but there is an enormous range in the type and extent of disability, and many PwD struggle to find AT devices that match their requirements. To take a specific example, Siebra *et al.*[21] conducted a comprehensive review of AT devices for a variety of mobile platforms and observed a need for more variety and further research to improve accessibility for impaired users.

What if, as Mankoff *et al.*[22] suggest, AT stakeholders, ranging from clinicians and physiotherapists to friends and family members, as well as those with disabilities, could design, modify, and produce AT devices themselves? This support for the creation of customized functional solutions, as espoused by the notion of citizen manufacturing, could have a significant impact on the lives of the growing population of PwD.

New Types of Interactive Surfaces

Many researchers have predicted a future where today's digital display technologies are complemented with new forms of interactive surfaces. Examples include large-area conformal 3-D displays,[23] shape-changing interfaces,[24] and fashion apparel that responds to the wearer and their environment.[25] Determining the potential of each of these areas, and many others, is surely its own ongoing grand challenge![24] Which of the many possible technologies those researchers have explored will prove viable? What exact form will these future surfaces take? Which applications will provide sufficient value to bootstrap them?

What if the creation of devices that can be used to evaluate potential form factors and applications for new displays was quicker and more people could get involved? Seyed *et al.*[25] have already explored the idea of a platform that empowers avant-garde designers to prototype fashion-tech garments, but they found it challenging to make the platform sufficiently accessible to nontechnical end-users, and they did not need to scale up garment production beyond one-offs. What if fashion designers, to pick one example, could leverage citizen manufacturing to develop and scale-up new wearable technologies?

KEY RESEARCH CHALLENGES FOR CITIZEN MANUFACTURING

Some of the building blocks underpinning our vision of citizen manufacturing are already beginning to emerge. Powerful and well-documented electronics and mechanical design tools and techniques have been developed. Many are cheap—if not free.[a] For

[a]Examples include KiCAD, see https://kicad.org/ and Free-CAD, see https://freecadweb.org/.

example, printed circuit board (PCB) design, which was once very much the domain of the professional engineer due to the cost and complexity of the tools and the manufacturing process, is now a common activity for makers. Similarly, prosumers who want to leverage rapid prototyping techniques, such as laser cutting and 3-D printing, have access to powerful 3-D computer-aided design (CAD) tools that mirror the key functionality of professional alternatives and allow them to share their designs in formats that online manufacturing partners can readily consume.

It is also getting easier for less-experienced hardware developers to anticipate and work around potential pitfalls when using these powerful tools. For example, books and articles that provide guidelines and share insightful "war stories" about electronics production are emerging[16,26–28]. Online communities relating to engineering design[b] have also become established, providing an always-available sounding board that supports learning and troubleshooting.

Together, these tools and knowledge bases provide a way for less-experienced hardware developers to self-enable, reducing the need to work so closely with manufacturing partners. So why is citizen manufacturing not yet a reality? Here we give a flavor of some of the many challenges and opportunities associated with creating a viable product.

Supporting an Organic Transition From Prototyping to Production

The challenge of citizen manufacturing of digital devices starts with prototyping. Although—as described previously—the prototyping process is easier than ever, today's prototyping tools and processes are largely created with only the prototype in mind.

What if, instead, prototyping was always considered as just the first step in an ongoing process, a means to an end? In that case, tools should not overoptimize on just that first step. They would certainly facilitate creative and iterative exploration, and support the quick and easy creation of a functional prototype. But they would balance this with the anticipated transition from prototype to production. In other words, a prototype would be constructed in a way that naturally led onto organic scaling, in support of further evaluation and/or early adoption.[5]

[b]For example, EEVBlog, see https://eevblog.com/.

Production Means Quality as Well as Quantity

Perhaps because of the common phrase "mass production," we often think of the scale as the main differentiator between prototype and product: we expect prototypes to be single units whereas products are made in volume. However, another key difference between products and prototypes is reliability. For a prototype, it is usually sufficient that it "mostly works"—it largely does what's expected during demos and perhaps during a period of end-user evaluation. But the expectation of a product is that it can be relied upon; it must work every time and all the time, despite component tolerances, variations in manufacturing, and ongoing operation in different conditions. And when the inevitable failures do occasionally occur, a well-defined process to identify and rectify the fault, or if necessary replace the product, is important.

What if we had readily available and easy-to-use tools that could evaluate and optimize the reliability of a prototype, and highlight suitable mechanisms for dealing with faults? For example, a combination of software and hardware tooling—Strasnick *et al.*'s Pinpoint[29] is a good starting point—might automatically characterize the performance of a device across expected variations in component tolerances. Low-cost environmental chambers could then be used to perform worst-case temperature range evaluation; perhaps a programmable power supply could be incorporated to simulate different levels of battery charge. Specifics aside, the key point is to create tools that make it easier to assess and improve the reliability of devices, thereby easing the transition to the product.

Design Tools That Account for Manufacturing

The PCB and 3-D CAD tools mentioned previously apply a principle that's common to many tools: they encapsulate design knowledge and best practice in ways that help users to "do the right things" as their prototypes evolve. But there is much room for improvement! The research community is actively exploring many ideas that make electronics and mechanical design quicker, easier, and more collaborative[30,31] while start-ups try to commercialize new approaches.[c] But as yet, nothing beats an in-person discussion about design for manufacturing, assembly, or testing with a seasoned electronics designer, sheet metal fabricator, or injection mold tooling designer.

[c]Examples include Flux, see https://flux.ai/ and Circuit Mind, see https://circuitmind.io/.

What if commonly available tools were to address these aspects of "design for X"? Start-ups, such as Merifix and MagicDAQ,[d] have created an entry-point to electronics test automation, but ready access to such tools could profoundly change the prototyping workflow in a manner akin to test-driven development in modern software development, espousing a more natural transition to production. Another example would be a component sourcing and inventory management tool that helps creators track availability, pricing, and their own current stock of components—like a personalized instance of Octopart.[e] In short, we see many opportunities for tools that build on the established design packages in pursuit of the broader challenge of citizen manufacturing.

New Approaches to Producing Physical Parts

Very specific requirements for physical parts can often be met using engineering suppliers, such as McMaster-Carr,[f] who maintain an extensive catalog of mechanical components. While these may be suitable for internal components, they may not be suitable for user-facing applications—the form of a product often has to be "just right" in terms of size, shape, finish, and feel. Rapid prototyping tools, such as 3-D printing, can be useful here, especially at low volumes. But sometimes the constraints of 3-D printing—cost, material properties, resolution, finish, etc.—mean it is not a viable option for finished products. And unfortunately, consumers frequently associate "high quality" with manufacturing techniques that have high up-front costs and therefore naturally favor mass production.

What if a new approach to manufacturing physical parts, especially enclosures, and other housings, were to support some of the flexibility of injection molding but without all the drawbacks of 3-D printing? Perhaps a way of combining preformed or partially molded plastic elements could be developed to create enclosures that are aesthetically pleasing but also economical in low volumes. Alternatively, it might be possible to mold certain types of housing using lower temperature and/or lower pressure (and hence cheaper) processes.

Redistributed and Cloud Manufacturing

Redistributed manufacturing refers to technologies, systems, and strategies that enable smaller-scale manufacturing, reduce supply chain costs, improve sustainability, and tailor production.[18] Cloud manufacturing is a related idea,[9] where individual manufacturing tasks are outsourced to different partners, often mediated through a real-time online requirements specification and ordering process in a "pay-as-you-go" manner.

Early examples of cloud manufacturing services came from 3-D printing companies, such as Materialise and later Shapeways,[g] both of whom allow design files to be uploaded to a website that gives an immediate quote. Following online payment, delivery follows as quickly as the next day. Subsequently, custom PCBs have become similarly quick and easy to the source using cloud manufacturing portals where design files can be uploaded, verified, and dispatched to production instantly. Companies, such as EuroCircuits and JLCPCB,[h] also provide an online service for PCB assembly, where the bare boards are populated with soldered components.

What if this decomposition of design and manufacturing was extended beyond the established rapid prototyping and PCB production processes? This would require precise specification of each cloud manufacturing service, and also raises important questions about the consequential flow of production along a "service pipeline" of different companies.[9] But the problem naturally decomposes into constituent services, which could be developed independently. What if devices based on emerging printed electronics technologies that incorporate flexible substrates, organic semiconductors, and low-temperature processes could be ordered online like conventional circuits? What if EMC precompliance testing involved dropping a prototype in the mail and getting a report in your inbox a week later? What if the final assembly of a device—putting the electronics into the enclosure, testing it, and putting it into the packaging—could be out-sourced as easily as ordering a bare PCB is today? We envision all manner of pay-as-you-go cloud manufacturing services that serve citizen manufacturing.

Integrated Software Support

Today's electronic devices invariably contain microcontrollers, so device creation naturally involves the development of embedded firmware—a class of software that's "low level" and considered by many as particularly difficult to develop. And increasingly, these devices are connected—to other devices over

[d] See https://merifix.com/ and https://magicdaq.com/.
[e] See https://octopart.com.
[f] See https://www.mcmaster.com/.
[g] See https://materialise.com/ and https://shapeways.com/.
[h] See https://eurocircuits.com/ and https://jlcpcb.com/.

Bluetooth or to the Internet over WiFi, to pick two examples. This often necessitates the development of and integration with companion apps and cloud services. While the tools to create these different aspects of a connected device experience are all advancing, each is typically in its own silo. The necessary hardware, firmware, and software artifacts are developed independently by engineers with different backgrounds and skillsets.

What if embedded firmware, client software, and cloud apps could be created in parallel using the same toolchain and within a unified framework? What if no-code and low-code tools allowed drag-and-drop programming and/or simple software configuration to give devices the required functionality and interoperability with existing products? Combined with citizen manufacturing, this would empower creators to build, test, and refine integrated solutions more easily and quickly, easing the challenge of moving from a prototype to a robust and reliable product.

Overcoming the Nontechnical Barriers

While this article largely focuses on the technical challenges of citizen manufacturing, there are many nontechnical challenges too![16] For starters, a good product-market fit is an essential prerequisite to scaling up production and finding one can involve extensive customer engagement, evaluation, and iteration. This raises the important topics of regulation and consumer protection—in most countries, there are quite complex rules regarding the public deployment of prototypes, let alone the sale of products.

Having established product needs, effective mechanisms of marketing, distributing, and supporting it are critical. Crowdfunding platforms and online storefronts[i] certainly help to identify customers, take orders, and ship goods, but a steep learning curve and high costs cause many newcomers to struggle.[16]

What if relatively low-volume products were not held to the same rules and regulations as their mass-market cousins, especially at an early stage? What if citizen manufacturers could leverage "comparison" websites to determine the legislative requirements of different countries, a myriad of trade tariffs, and the relative cost of different product delivery services? We think that new tools can help citizen manufacturers navigate these complexities—optimizing the flow of components and finished goods, automatically managing the associated paperwork, and easing the customer support burden.

RISING TO THE CHALLENGE

Realistic Proposition or Utopian Dream?

In this article, we have aimed to present a grand challenge that strikes a balance between realism and ambition. On the one hand, we already see very practical ideas and solutions that make in-roads to the challenge of citizen manufacturing being actively explored in the research community and commercialized by start-up companies. And at the other extreme, we have alluded to a somewhat utopian dream of citizen manufacturing where literally anyone can use somewhat magical (and certainly yet-to-be-invented) tools and services to design and produce beautiful digital devices that are good value, seamlessly interoperate with existing products and meet all the necessary legislative requirements. We even mused that they might one day be as good as those designed by today's experts.

We hope that this vision for citizen manufacturing will inspire others in academia and industry as a bold endeavor that is both worthwhile and achievable. In many ways, we aspire to the middle ground. Perhaps the highly optimized designs necessary for keen pricing at high volume and for high performance in demanding applications will always rely on domain experts. But we believe a growing segment of citizen manufacturers will play an increasingly important role.

This article has focused on the citizen manufacturing of interactive and embedded electronic devices—which we argue is a natural progression from today's citizen development of software. But ultimately, the considerations and the roadmap we have discussed could apply to the citizen manufacturing of other types of product—from cars to clothing, and from home appliances to the homes themselves.[j]

There is certainly no silver bullet for any of these application domains; rather, we think it is possible to make steady, incremental progress by building a citizen manufacturing pipeline that progressively adds value as it evolves. At some point, we hope a network effect will emerge, where a critical mass of cloud manufacturing services is complemented by sufficiently polished tools that provide seamless interconnection between them. This would bootstrap citizen

[i] These include Kickstarter, Indiegogo, Crowd Supply, Amazon, Alibaba, and Etsy.

[j] In the case of cars, see Open Motors, for example, https://www.openmotors.co/services/.

manufacturing by providing a "minimum viable solution" for prosumers while naturally drawing in more service providers and further investment in tooling in a virtuous cycle. Common interfaces and open standards will be the key to success here.

Social Responsibility

As technologists, we are naturally excited about the potential of citizen manufacturing to drive innovation. In addition to the economic benefits this could bring, we also hope to enable more socially conscious approaches to manufacturing as an alternative to large corporations who may not always prioritize the long-term interests of society and the environment. Our hope is that providing a more democratic process for realizing products will allow sustainable approaches to device production and consumption to emerge.

At the same time, citizen manufacturing also introduces new societal challenges. For example, if a product infringes on the rights or affects the safety of another person or organization, who is responsible—is it the fault of the designer, a cloud manufacturing partner, or perhaps the distributor? What would constitute fair and realistic remediation for such a failure? How do citizen manufacturers quantify and protect their investment and intellectual property in a world where tools and partners play such an important role? These are all questions that need to be addressed.

Pro^2: A Community-Driven Effort

Having set the scene for citizen manufacturing, explained the concept, illustrated some of the potential benefits, and described many of the challenges, an obvious question concerns the realization of this vision. How can and how should citizen manufacturing be made a reality? Is it possible to build open tools and run low-cost services that collectively form a distributed platform, mirroring many of today's leading software development resources? Can this be done in a responsible, sustainable, and politically acceptable way?

In the spirit of peer production, we would like to bring together a network of research organizations, commercial enterprises, and other interested parties who share our vision for citizen manufacturing of digital devices. We hope this community of stakeholders can work together to make significant in-roads to the challenge of citizen manufacturing in a collaborative and open way. We are calling this initiative, designed to accelerate the transition from prototyping to production, Pro^2. Acting at the interface of the established digital economy and manufacturing sectors, our hope is that Pro^2 will:

1) *connect people* with a common interest in manufacturing new digital devices using both conventional and emerging technologies, especially in low volumes;
2) *identify the established principles, techniques, and technologies* for device production—the best practices used today—and synthesize them into guidelines that can be readily consumed by others;
3) *develop new tools and processes* that encapsulate existing domain knowledge and facilitate innovative approaches, to make the transition from prototyping to production easier and cheaper, especially at low volumes;
4) *promote the benefits of citizen manufacturing* with end-users, the business community, and ultimately governments, and explore the challenges and tradeoffs compared with mass production.

A key characteristic of the planned Pro^2 community is a philosophy of collaboration across academia and industry, an inclusive and hands-on approach, and a desire to combine the agile processes that have become the norm in digital economies with the manufacturing know-how that underpins the production of digital devices. Throughout all four of the abovementioned activities, we aim to foster academic–industry partnerships that facilitate knowledge exchange, enable explorations, and initiate pilot projects. Ultimately, we hope that Pro^2 will seed new products and services that support the overarching goal of enabling citizen manufacturing.

CONCLUSION

Our vision for citizen manufacturing is a world where all individuals are empowered to turn their ideas for pervasive computing devices into reality, complementing today's high-volume mass production with low-volume manufacture of small batches and sometimes just single units. All these products would be cost-effective to make and reliable to use.

We imagine application areas from smart buildings to smart factories, from wearable technologies to assistive technologies, and across the growing Internet of Things. We hope to complement today's mainstream markets by serving user groups that are currently underrepresented, supporting emerging applications and markets, building products that are more sensitive to local contexts, and more effectively meeting customers' professional and personal needs. We envision redistributed manufacturing networks that leverage local supply chains and workforces, growing local economies. This infrastructure could also support remanufacturing and the right to repair, leading to more socially responsible alternatives to much of today's mass manufacturing.

We acknowledge that the success of this distributed approach to manufacturing will also depend on overcoming nontechnical challenges relating to business models and legislative requirements. Ultimately, we hope that citizen manufacturing will reduce friction and facilitate innovation, allowing more individuals, companies, and communities to benefit from pervasive technology solutions.

We welcome feedback from both practitioners and researchers on the ideas presented here and encourage individuals and organizations from all backgrounds and with all levels of experience to consider joining Pro^2. If you are excited by the vision of citizen manufacturing—as a researcher, a technology company, or simply as a prosumer—please get in touch via https://prosquared.org!

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