The Wise Chisel:

The Rise of the Smart Handheld Tool

A recent spur of academic and industrial efforts has given rise to a new field of research in HCI devoted to smart handheld tools. This survey discusses such tools' origins and reviews prominent related work in fabrication, painting, printing, and maintenance.

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The vision behind smart handheld tools isn't new; stories and legends abound about tools whose capabilities extend beyond their native performance. Moses' staff, Thor's hammer, King Arthur's Excalibur, and the many gadgets of the Japanese manga character Doraemon are all archetypes of instruments that empower their possessors. These instruments often have their own intelligence and purpose and perform in a unique, extended way that far surpasses the standard tools of their kind. These tools also reflect cultural narratives of technology and its limitations, contrasting technical appearance with fictional capabilities.

Twentieth century science fiction contributed a new twist to smart tools lore: devices that allow for extended operation using highly sophisticated technology. In his 1950 short story, "The Little Black Bag," Cyril M. Kornbluth describes a smart medical tool kit. The kit's tools assisted a surgeon by preventing him from hurting healthy tissue during operations. This fictional vision foresaw a factual revolution in the medical field that both changed medical technologies and let experts work in symbiosis with technological assistance. Later, in a 1988 episode of *Star Trek: The Next Generation*, we were introduced to an "unusually shaped wood-sculpting tool" that let unskilled people sculpt wood (this tool was one of the inspirations for the hand-held devices we discuss later).

Today, digital technologies let us augment handheld tools, creating new capabilities and interactions. New research is underway to develop and study smart, handheld devices that augment the precision of autonomous tooling with on-the-fly creative expression and critical human judgment (see Figure 1).

Here, we trace and explore the emerging field of smart handheld tools that have been inspired by mythical images, technical need, and new technological opportunities. We also present a survey of contemporary and early work in the field (by industrial and academic groups, including our own), focusing on smart handheld devices used for fabrication, painting, printing, and maintenance.

Smart Handheld Tools

The Oxford dictionary defines a tool as "a device or implement, especially one held in the hand, used to carry out a particular function." James K. Feibleman adds that "a tool is a material object intended to move other material objects."[1] He continues, noting the connection between tools and skills:

> *The more complex the culture, the greater the knowledge needed to develop the tools and the lesser the manual skills… Automation tends to build skills into the machine so that it does its work without an operator. Thus the perfection of tools may act to eliminate the necessity for skills.… In certain cases skills can be transferred from men to their tools.*

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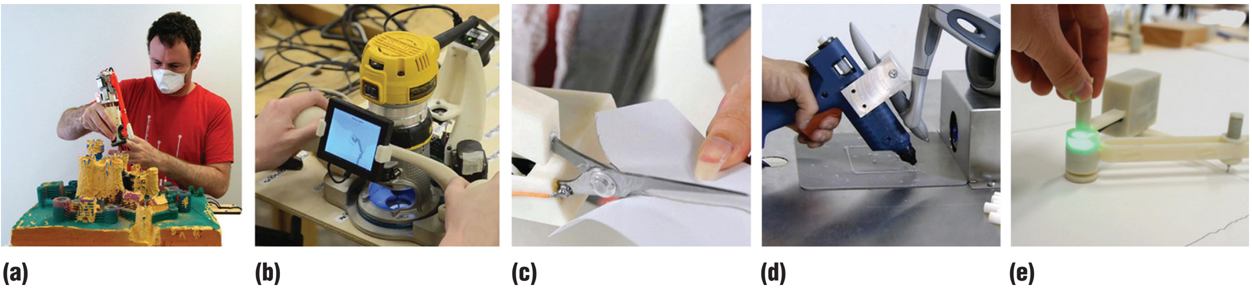


Figure 1. Smart tools for fabrication and printing. Tools enhanced with digital technologies include (a) FreeD, a 3D smart milling device; (b) a position correcting tool, which achieves accurate cuts on large-scale surfaces while letting users freely guide the tool; (c) enhanced scissors, which restrict the user to only cuttable areas on a paper; (d) Haptic Intelligentsia, which uses a haptic interface arm and an extruding gun; and (e) COMP*PASS, a compass-based digital drawing device.

We define a smart handheld tool as a handheld instrument that provides a functional or informative augmentation to assist its native operation. Our definition doesn't insist on a standalone tool; it might be part of a bigger computational environment, tracking technology, augmented reality system, or any other digital technology that transfers manual skills to the tool (see Figure 2). However, as handheld devices, most of the technologies we describe here are compact or at least have a central operational agent that can be held in one hand. Typically, the main design decision in developing a new smart tool is choosing which skills require manual control and which are automated; Figure 3 shows a comparison of various tools and their features.

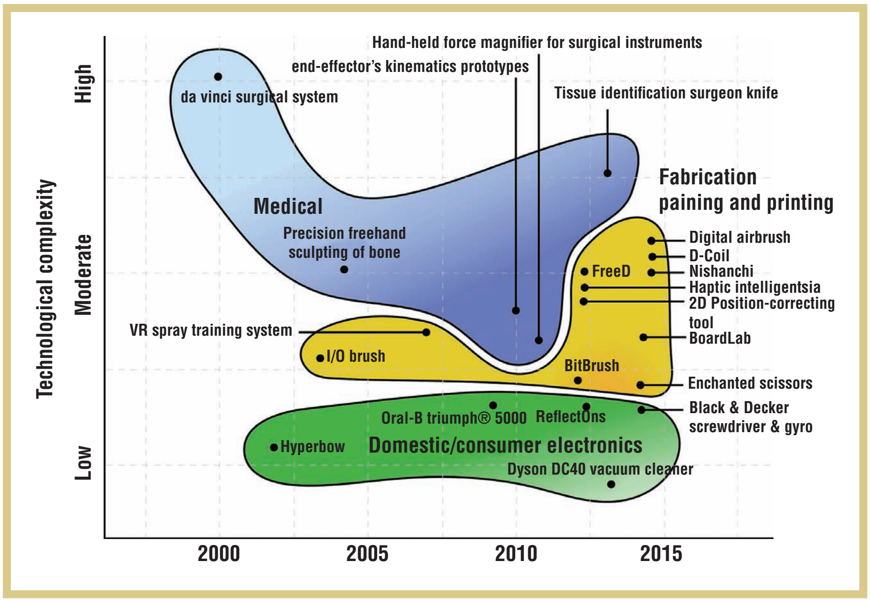
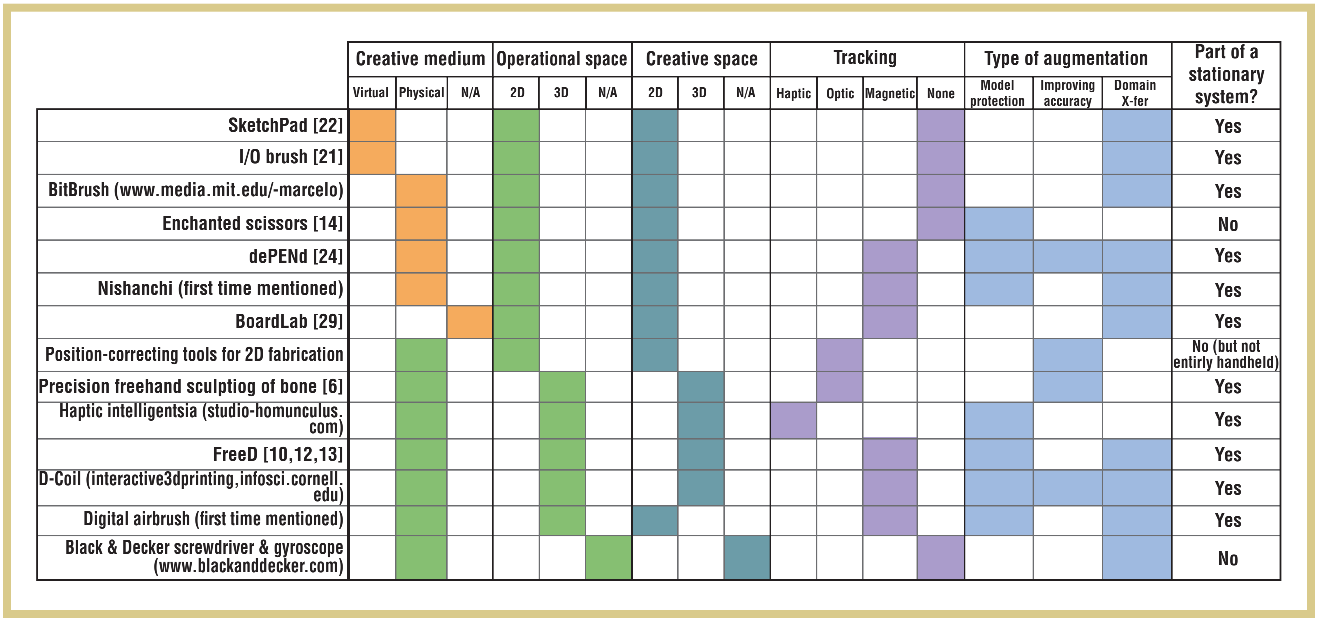


Figure 2. Development and technological complexity of smart tool categories. Technological complexity includes 2D or 3D operation, degrees of freedom, virtual models, and the amount of sensorial and digital units. Category areas with darker shading represent stand-alone, handheld mobile tools. Medical projects tend to be more complex and stationary—and less handheld—compared to domestic and consumer electronics. Although our selections are biased toward fabrication technologies, this visualization is useful for comparing complexity levels between all territories.

Scholars have discussed the relationship between traditional craft and modern mass-production using concepts of meaning, engagement, and risk.[2] This inspired the creation of smart tools that act as a bridge between diverse making practices, with tools that work in conjunction with human operators without interfering with manual operations. We refer to this "native" operation as the device's *default function*, which remains unhindered even in its smart version. A wise chisel is first and foremost a piece of sharp steel that can cut softer materials, in the same way that Thor's hammer is first and foremost a hammer. In addition, smart tools can guide their operators, alerting them when a mistake is being made or extending their manual capabilities. In a sense, we can think of such instruments as prostheses, allowing for performance that extends the user's natural, manual potential.

Further, a device need not be electronic for it to be considered wise. For



	Creative medium			Operational space			Creative space			Tracking				Type of augmentation			Part of a stationary system?
	Virtual	Physical	N/A	2D	3D	N/A	2D	3D	N/A	Haptic	Optic	Magnetic	None	Model protection	Improving accuracy	Domain X-fer	
SketchPad [22]	🟧			🟩			🟦						🟪			🟦	Yes
I/O brush [21]	🟧			🟩			🟦						🟪			🟦	Yes
BitBrush (www.media.mit.edu/-marcelo)		🟧		🟩			🟦						🟪			🟦	Yes
Enchanted scissors [14]		🟧		🟩			🟦						🟪	🟦			No
dePENd [24]		🟧		🟩			🟦					🟪		🟦	🟦	🟦	Yes
Nishanchi (first time mentioned)		🟧		🟩			🟦					🟪		🟦		🟦	Yes
BoardLab [29]			🟧	🟩			🟦					🟪				🟦	Yes
Position-correcting tools for 2D fabrication		🟩		🟩			🟦				🟪				🟦		No (but not entirly handheld)
Precision freehand sculptiog of bone [6]		🟩			🟩			🟦			🟪				🟦		Yes
Haptic intelligentsia (studio-homunculus.com)		🟩			🟩			🟦		🟪				🟦			Yes
FreeD [10,12,13]		🟩			🟩			🟦				🟪		🟦		🟦	Yes
D-Coil (interactive3dprinting,infosci.cornell.edu)		🟩			🟩			🟦				🟪		🟦	🟦	🟦	Yes
Digital airbrush (first time mentioned)		🟩			🟩		🟦					🟪		🟦		🟦	Yes
Black & Decker screwdriver & gyroscope (www.blackanddecker.com)		🟩				🟩			🟦				🟪			🟦	No

Figure 3. A comparison of the smart handheld tools for fabrication, painting, and printing. The table lists and compares qualities and technologies of diverse tools from the last several years.

example, the Dyson DC40 Vacuum Cleaner “automatically self-adjusts for different carpet types and hard floors,” yet while it uses electric power for the vacuum engine, it uses mechanical technologies alone for the self-adjustment and sensing mechanism (see www.dyson.com/Vacuums/Uprights/DC40/DC40-Origin.aspx). Nevertheless, the digital revolution has enabled easy and cheap digital augmentation of various handheld products by integrating control and sensing capabilities. For example, the Oral-B Triumph 5000 SmartGuide electric toothbrush alerts users if they’re brushing too hard and promotes an “optimized brushing performance” (www.oralb.com/products/professional-care-smart-series-5000). Black & Decker commercialized an electric screwdriver with gyroscopic motion-sensing technology that detects the user’s wrist movements to control the motor’s direction and speed (www.blackanddecker.com/power-tools/BDCS40G.aspx). In the hands of a skilled player, there is no more intimately connected a tool than a well-crafted musical instrument. Many research projects are exploring instruments' sensorial and digital augmentation, adding new "electronic" degrees of freedom to conventional instruments as well as imbuing them with knowledge of the piece that is being played and enormously amplifying the musician's sonic reach through dynamically mapped digital sound and effects.[3,4]

Cooking devices and utensils might be the most popular handheld devices. Among the new projects are smart utensils, such as HAPIfork (www.hapi.com), that support users who want to monitor their eating habits through instantaneous haptic[5] or long-term asynchronous feedback. The Liftware project stabilizes hand tremors, assisting patients with Parkinson’s disease by damping vibration in utensils and other handheld tools (see www.liftlabsdesign.com).

Although augmenting domestic tools is relatively new, extended research has been conducted on smart devices within the medical field, where digital technologies have already altered traditional human–tool interactions. The overarching goal is to heighten surgeons’ senses and provide superior precision, accuracy, dexterity, and force, as exemplified in projects such as the Precision Freehand Sculptor,[6] a robotic surgical device for laparoscopy,[7] and a method to increase the surgeon’s force.[8] Advanced sensing that extends far beyond the human sensorial reach has also been incorporated into medical handheld tools—including a system that identifies cancerous tissue by analyzing of smoke from the surgeon’s tool,[9] making Kornbluth’s sci-fi vision a reality.

Subjectivity, Control, and the Creative Experience

Although all the medical projects just described allow accurate operation, they don’t explore the domain of free-form fabrication or let users explore and create. Rather, they focus on accuracy and control—and often aim to prevent surgeons from making life-threatening mistakes. In contrast, shaping a cake, drawing and painting, or building a sandcastle are all open-ended activities, where accuracy isn’t necessarily as important as the expressive experience.

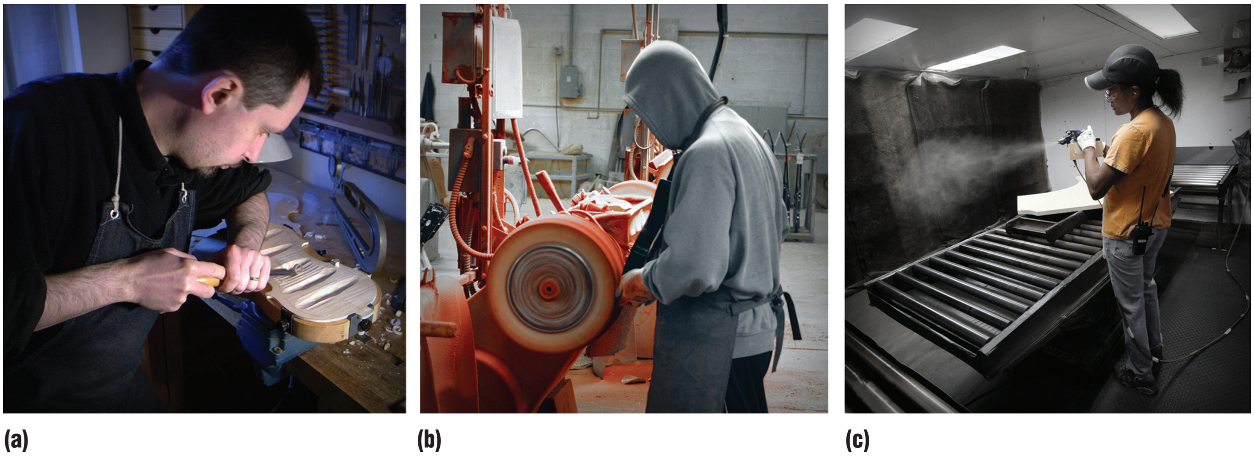


Figure 4. Manual practices. (a) Marco Coppiardi makes high-end handmade violins at his shop in Boston, even though mass-produced violins are cheaper to produce. (b) Buffing a guitar's finish is still a manual practice, even by major guitar manufacturers. (c) Wood staining for high-end tabletops can't be automated, as perfection is required.

Digital fabrication technologies now allow designers to easily create, download, and modify virtual models and outsource their fabrications to digitally controlled agents. As engineers, we seek optimal solutions, efficiency, and a reduction to a nonparametric approach to enable automation and repetition. However, qualities such as creative engagement in the making experience are markedly lost, especially when compared to traditional crafts. As Figure 4a shows, craftspeople engage in an intimate fabrication process that lets makers enjoy the experience of shaping raw material. As a result of this engagement, handcrafted products are unique and carry a personal signature.[10] These craft qualities inspire devices that work in conjunction with the intimate experience of manual operation: instead of a 3D printer or Computer Numeric Control (CNC) machine, makers can hold fabrication instruments that will actively assist them in the making process, while still permitting manual control of the details and intuitive design modifications.

The possibility of personalizing digital fabrication has motivated us and other academic researchers to explore the hybrid territory of augmented manual devices for creativity. Surprisingly, our publications have attracted growing interest from industries. Although automatic manufacturing technologies dominate the mass-production process, some tasks still can't be automated. Humans excel at adapting to changing fabrication conditions, integration and assembly tasks, and real-time adjustments to production lines. All such tasks require substantial spontaneous creativity, even though they might not be highly regarded as art and design processes. Tasks such as staining and finishing wood (Figures 4b and 4c), testing for quality and performance, repairing products, and debugging electronic products are evidently more efficient when performed with manual labor than with automatic procedures. However, we found the industry's need for a hybrid territory in opposition with our preliminary motivation: controlling the subjective performance, while upholding a certain quality in a manual operation. While working with a specific company, we were asked to "minimize subjectivity caused by manual labor," by adding computational monitoring and actuation to manual tools.

The quest for hybrid creative expression comes from polarized directions: personalizing digital fabrication and permitting subjective engagement in both the design and fabrication stages, and controlling the subjectivity in manual stages of mass production unsuited to automation.

Fabrication, Painting, and Printing Tools

Inspired by these polarized motivations, researchers have started to explore the hybrid territory of handheld smart tools for fabrication (see Figure 3), painting, and printing, pushing the making process into a new interactive domain. Here, we'll take a closer look at several projects before reflecting on future potential and the important challenges ahead.

Tools for Subtracting and Cutting

Two similar research projects—a 2D smart router and FreeD, a 3D smart milling device (see Figure 1a)—were developed simultaneously at MIT (a good indication of rising interest in smart fabrication tools). Alec Rivers and his colleagues developed a position-correcting 2D router that

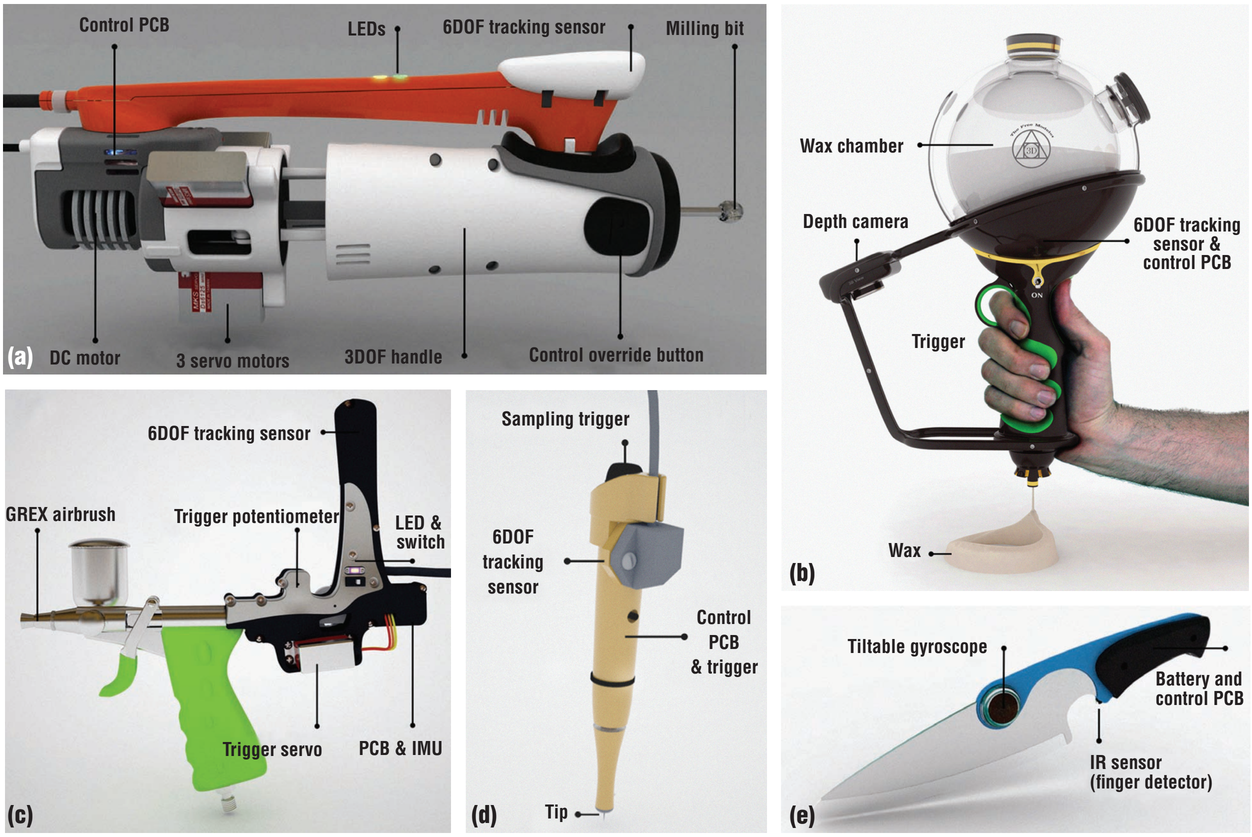


Figure 5. Working prototypes and concept designs of our smart fabrication tools. (a) The FreeD milling device and (b) a concept design the 3D additive modeler. (c) Our digital airbrush device and (d) the BoardLab probe for just-in-time information on board schematics, component datasheets, and source code. (e) A concept design for our smart kitchen knife.

achieves accurate cuts on large-scale surfaces while letting users freely guide the tool (see Figure 1b).[11] Motivated by the need for a cheaper, portable CNC machine that can cover a large cutting area, this smart router uses a smartphone for optical tracking and control. The project inspired ShopBot to develop a portable, compact CNC machine as a product.

Unlike the position-correcting 2D router, which must be aligned to a flat surface, FreeD is a freehand digitally controlled milling device that harnesses CAD abilities in 3D design and keeps the user involved in the milling process[10,12] (see Figure 5a). A computer monitors the 3D location-aware tool (using the Polhemus magnetic motion tracking system), while preserving the maker's gestural freedom (see Figure 6a–6c). The computer intervenes—by slowing down, diverting, or stopping the spindle—only when the milling bit approaches the 3D model. In addition, FreeD permits manual and computational design modifications of a virtual model while fabricating. As such, it can render a unique 3D model directly in a physical material while keeping the user's subjective tool path as a signature embedded in the physical artifact's texture.

Although digital practice separates design from fabrication, the FreeD suggests a synergy, allowing users to create unique artifacts from generic designs.

A recent user study undertook what is probably the first in-depth observation of design and creative style of hybrid tool use.[13] This form of involvement allows researchers and practitioners to discuss fabrication skills, design styles, qualities, and other issues that are often absent in digital fabrication discourse. Open-ended processes benefit considerably from such a hybrid system, letting makers control the computer's level of dominance over their work. Beginners can focus on honing their technique while the computer ensures they will reach a satisfactory result, and practiced makers can opt for only high-level control—letting the computer copy their method—or manually explore the material.

Figure 6. Smart tools in action. (a) Using FreeD in balsa foam to create a model of a cat. (b) Another user creating the same model of a cat. (c) A user works on a deer project involving six makers. (d) An early test of our smart airbrush and initial results of its use painting (e) a bear's face and a wolf. (f) Marcelo Coelho's BitBrush tool and (h) an example of artwork produced using it. (h) Artwork produced using the tracked version of Nishanchi.

Recently, Mayu M. Yamashita and her colleagues at Keio University presented a new vision: digitally controlled scissors (see Figure 1c) that restrict the user to only cuttable areas on a paper, where, "unlike a completely digitalized cutting device, the user can freely apply improvisations within the permitted areas in real time."[14] While both the position-correcting 2D router and FreeD require a virtual model to guide and protect the design, with this tool, the protected area doesn't have a virtual identity—the area is simply hand-drawn on the paper using conductive ink to apply a digital version of Dyson's surface adjustment mechanism.

Additive Handheld Fabrication

Rotary milling devices and scissors operate on raw materials by cutting and/

or subtracting using a sharp edge, tip, or bit. In a way, controlling such devices is straightforward: if the subtracting element is allowed to reach a point in the material, we can assume the material in this location is cut.

Although most of the digital fabrication movement relies on additive technologies such as 3D printing, the implementation of additive handheld devices is an order of magnitude more complex than subtracting handheld devices. In an open environment (as opposed to a 3D printer chamber), it's difficult to monitor, manipulate, transfer, and apply an additive process without precise control of the "printing" head location. However, a few projects have tried to overcome this challenge, presenting some promising directions.

Prior to his work on FreeD, Amit Zoran (a coauthor here) created an early concept-design for the 3D additive modeler (Figure 5b). The additive modeler uses technology similar to fused-deposition modeling, manually layering thermoplastic or wax on a flat surface, while a computer tracks the device's location to control the manual trigger's operational range. A depth camera monitors the physical shape that appears on the workbench, updating the virtual model in real time.

As Figure 1d shows, the Haptic Intelligentsia 3D printing device—which uses a haptic interface arm and an extruding gun—shares a similar perspective. The user freely moves the gun, receiving real-time haptic feedback. If the gun's tip is moved into the volume of the virtual model, the arm generates haptic resistance. Although not entirely a freehand device, Haptic Intelligentsia and FreeD have a similar philosophy: both projects seek to personalize a digitally fabricated artifact during the making process.

Recent developments in additive fabrication have inspired researchers to create freehand devices such as 3Doodler (www.the3doodler.com), a freehand ABS plastic additive extruder, and the *Mataerial* (www.mataerial.com), which uses a robotic arm to create 3D curves of material in free space. Although, by our definitions, 3Doodler is not *smart* and Mataeriel is not *manual*, they define important hardware cornerstones for new smart additive tools by showing an alternative approach to additive manufacturing techniques. A recent example of this approach is the *D-Coil*, a digitally controlled freehand clay extruding tool that lets users interleave the design and fabrication process in an additive process using clay coiling (see interactive3dprinting.infosci.cornell.edu).

Digital Painting and Physical Graphics

Painting or sketching with a pen, paint brush, or airbrush is another form of additive fabrication. However, it is much subtler and aims to construct not objects but images. Similar to the fabrication methods we discussed earlier, painting is affected by a multitude of uncontrolled parameters, and smart handheld painting devices emphasize control over the extrusion of paint.

The paintbrush is an ancient technology and a pervasive tool in both traditional and digital painting. Researchers in the digital painting community sought to recreate the unique pattern of brush on paper in a simulated environment as early as the 1980s.[15] However, others weighed in on the side of augmented tools to capture the uniqueness of paintbrush strokes. The IntuPaint[16] and FluidPaint[17] systems use real tools to guide paint simulation. Before those tools emerged, other researchers used augmented paintbrushes (and other tools, such as a paint bucket) to create expressive paintings.[18,19] *Hiroshi Ishii and Naomi Miyake* postulated that the use of smart drawing tools dates as early as 1991,[20] and later conceived the I/O brush, a handheld camera-equipped faux-paintbrush that captures a texture and then applies it to a virtual canvas.[21] In addition, Random International's PixelRoller (www.random-international.com) is a smart roller brush that paints walls based on a digital image.

In contrast to a paintbrush, a pen constrains its ink extrusion with a narrow nib or ballpoint mechanism, allowing for finer drawing techniques. Ivan Sutherland's SketchPad[22] paved the way for digital handheld drawing and sketching tools. Nowadays, digital pens are a common sight, with products from a host of companies such as Wacom (www.wacom.com) and Anoto (www.anoto.com). Digital pens are, however, not smart; they act as regular pens with a digital canvas, where all the complexity (for example, a beautification of the curves) happens in virtual constructs rather than in the tooled artifacts. In contrast, Hyunjung Kim and her colleagues[23] and Junichi Yamaoka and Yasuaki Kakehi[24] have embedded sensors and actuators inside the pen itself to make it adhere to a premade drawing, sketch, or remotely communicated scribble. In addition, COMP*PASS is a compass-based digital drawing device in which the radius of the interface is regulated according to the rotation of the device, so the user only needs to rotate the device when drawing a specific figure (see Figure 1e).[25]

Airbrushes allow paint to freely mix with high-pressured air, creating unique spray patterns similar to paintbrush strokes.[26] Limited attention has been paid to augmented airbrushes for virtual spray painting.[27,28] However, Joseph Luk is attempting more interesting work, attaching a magnetic tracker to a computer-controlled paint-dispensing fuel injector that aims to reconstruct a painting through spray.[29]

Our novel smart airbrush design strives for a more intuitive operation method and continuous feedback (see Figure 5c and Figures 6d and 6e). Currently in the advanced stages of prototyping, our airbrush alters an existing airbrush product with custom-made controls, magnetic tracking, and feedback mechanisms. The brush connects to a computer, which governs paint output through the nozzle by limiting the amount of paint the user can extrude when facing the canvas at a certain angle, speed, and distance. A virtual environment simulates, given the brush and easel position, how much paint will hit the canvas based on a model of the airbrush's dynamic properties. The computer commands the handheld tool to open or close the trigger and provides the painter with feedback on the painting technique; it also lets users paint on unexplored canvas areas.

With the smart airbrush, we look to assist novice painters in their first steps of creating works of art, while still requiring manual control of the device to encourage skill development. This device is like a paint-by-numbers canvas embedded in a manual device. However, it's designed for more than simply offering instructions to paint a particular graphic; it can also help users learn painting techniques and develop their style.[30]

The Handheld Inkjet Printer

In contrast to manual painting, an inkjet printer relieves the painter of the need for brush skills. In return, it provides high precision. The inkjet printhead is simply a miniaturized, digitally controlled, steerable brush that applies paint to the workpiece by shooting small ink droplets from a series of miniscule nozzles. In a conventional inkjet printer, the printhead is mounted on a gantry mechanism, limiting the printout to flat surfaces. With open source tools like inkshield for Arduino (www.nicholasclewis.com), hobby electronics enthusiasts can build custom applications using inkjet printheads, which are otherwise closed proprietary systems. Marcelo Coelho's BitBrush (www.media.mit.edu/~marcelo) uses an inkjet printhead to create a handheld drawing device. However, it doesn't constrain or guide the painter in any way or alter the printed texture dynamically (see Figures 6f and 6g).

Pragun Goyal (also a coauthor here) designed Nishanchi, a handheld printhead that can digitally print on numerous nonconformable surfaces and materials (see Figure 6h). Using six degrees-of-freedom printhead tracking, Nishanchi can be programmed to imprint mapped textures at the correct surface areas; this lets users decide whether to turn the device on or off, move fast or slow, pull the device away from the surface to create a blur effect, and so on. The inkjet printhead's highly accurate yet local printing abilities let users interplay between fine intricate painting and rough texturing.

Maintenance and Verification with Clever Probes

Although not a making process, maintenance, repair, and verification are still important aspects of fabrication, particularly over the long term. Often, manufacturing and fabrication processes are followed by manual verification to ensure that the finished product achieves expected quality and performance levels. Parts with a long life expectancy are often tested regularly for performance; when such parts are complicated, many parameters can go wrong. Electronic circuits are a good example here. Fortunately, the fabrication and simulation design data for most electronic circuits are arranged in two sources:

- schematics, which describe the different components' connectivity; and
- layouts, which is the physical mapping of components and their conductive traces.

Having access to schematic design data is quite helpful while testing, assembling, or debugging a printed circuit board (PCB), because it reveals exactly how the components are connected. The BoardLab system[31] (see Figure 5e) consists of a handheld probe that permits direct interaction with the board and its components for just-in-time information on board schematics, component datasheets, reference waveforms and voltages, and source code. This system also lets users annotate schematics with measurements made on the physical PCB.

As a growing research community continues exploring new domains and developing new devices that rapidly evolve into consumer products, smart tools have moved out of the fictional realm. Arising as part of the digital fabrication and DIY movement, smart devices merge subjectivity, personal engagement, computational control, and accuracy to achieve a new type of hybrid tool for creativity. To conclude our survey of this trend toward smart fabrication technology, we offer a vision of smart tools for fabrication and creative expression using our own insights gained both while developing devices and reflecting on the work of others.

Smart devices merge subjectivity, personal engagement, computational control, and accuracy to achieve a new type of hybrid tool for creativity.

Our first insight relates to the importance of the hybrid territory, where a cognitive design process, computational control, and an intuitive engagement in the making process merge into a single creative unit. Hybrid technologies reach widely across the range of human creative expression, from manual skills to knowledge of design. In addition, due to their scale, these devices can be cheaper and more accessible than fully automatic CNC machines.

Second, while performing a user study with the FreeD and through interactions with commercial manufacturers, we learned of a specific fabrication need: the imitation of style. Digital fabrication technologies focus on materializing a predesigned model with varying accuracy levels, but no significant work was recorded outside the computer graphics communities on capturing and imitating the fabricator's working style. For example, one user in the FreeD study, a professional violin maker, said he "would like to have a digital assistant in the form of a suit with tracking devices, trackable tools, and a scanner to determine the condition of the work… [he] would use this robot to save time, guiding it during the process and checking the quality of the work at important stages."

This interest in capturing style and manual skills has vast implications for smart tools' collaborative and pedagogic potential. Instead of defining a final product, master users can employ smart devices that capture and record their style and tool-path characteristics to train students learning to use the devices. Whether a Chinese calligraphy brush, kitchen knife, or carving chisel, many tools require a great deal of skill to master, and a computational agent embedded in the device itself could assist in practice and collaboration.

Third, most projects discussed here augment power tools by digitally controlling some aspect of the device's analog mechanism. A more complicated task is to augment tools with no degree of freedom, such as hammers, knives, and axes. Unlike the smart utensils presented earlier, here we envision smart tools that will prevent their default function in instances of danger. For example, similar to Kornbluth's smart fictional surgeon kit, we propose a concept design for a kitchen knife that prevents the user's fingers from being cut. If the user operates it properly, the knife performs like any other. However, when an IR sensor detects that the blade's cutting plane might hit the user's finger, a gyroscopic mechanism would force the knife to tilt in another direction (Figure 5e) or the blade would be otherwise shielded.

Ultimately, we envision a future line of work that includes tools with seamless operation and subtle guidance, relinquishing complex tracking systems and supporting users with tactile, innate feedback: smart tools that refuse to function if used improperly but that otherwise augment human judgment with mechanistic perfection, enhancing human capabilities while preserving manual touch.

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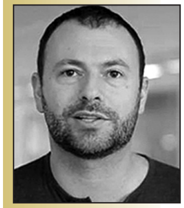

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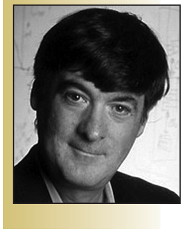

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