Connected Tools in Digital Design

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EDITOR'S INTRO

The Internet of Things has become a mainstream topic. Many ideas and concepts discussed in pervasive and ubiquitous computing over the last two decades are now commonly accepted. Here, the authors give us a glimpse of the potential when we make tools part of the Internet of Things. Their prototypes aren't yet products. However, in looking at the potential for reducing errors and saving time, I expect many connected tools to hit the market in the next few years—not only in engineering but also in other domains such as medicine, cooking, and agriculture. The examples provided show impressively how tools, once connected, offer new opportunities.

The idea of bridging the digital and physical is intriguing, and many technologies get us closer to this vision. Some of the ideas, although they've been around for a while, are still inspiring. It might be a good time to read (or re-read) the book *Mirror Worlds: Or the Day Software Puts the Universe in a Shoebox—How It Will Happen and What It Will Mean*, by David Gelernter (Oxford, 1993). Also see this issue's related Spotlight department, "The Mirror World: Preparing for Mixed-Reality Living."

— Albrecht Schmidt

DIGITAL DESIGN AND FABRICATION

As digital fabrication and digital design become more and more pervasive, the physical tools we use in conjunction will have to catch up. With the Internet of Things, cyberphysical systems, and Industry 4.0 in our midst, connecting and integrating measurement tools into design processes is a logical step. Here, we describe the first steps in that direction, coming from a variety of communities: academics, makers, and industry alike. In particular, we present our spatio-tangible (SPATA) tools for fabrication-aware design.

DIGITAL DESIGN AND FABRICATION

Digital fabrication, such as 3D printing and laser-cutting, lets users quickly create physical artifacts from digital files. The interfaces and environments used for designing these artifacts are typically tied to a computer screen and are thus removed from the physical world. This separates the physical nature of the fabricated artifacts from the virtual environments in which they were designed. However, during the design of a fabricable artifact, physical features (such as size and angle) play an important role, because the artifact will be subject to that physicality once fabricated. Furthermore, fabricated artifacts often interact with previously existing objects—for example, holding, encasing or decorating them.

In digital fabrication, as well as in design and engineering, physical features play an important role. Many tools, such as calipers, rulers, and protractors, have been developed to measure those features so that they can inform a particular design. These tools, until now, have been analog tools, because users must manually read a value from them (for example, from a veneer scale or a display) to incorporate the value into a design. In particular, when using CAD software, or designing in any other virtual environment, users often employ these tools to get a sense of the size of what they're designing. How big is the box shown on the screen in the real world?

BRIDGING THE INPUT GAP

With digital design, these analog, disconnected tools create an inconvenient design experience. Every interaction with physical features requires us to shift our attention from the design environment to the physical world and back. The measured value must be manually transported from the measurement tool or vice versa. These context switches are time consuming and disruptive to the design workflow.

This disconnection has been recognized by measurement tool vendors and makers. Both communities are exploring and producing computer-connected tools—for example, calipers that can unidirectionally transfer measured value to a computer. An example is Mitutoyo; they sell data cables for their measurement tools that act as virtual keyboards. Measurements are directly entered into the computer, and these cables are advertised as a means

to make repetitive data-entry tasks more efficient.[1] Because the input is the same as from a keyboard, it works with any software. The maker community uses an Arduino to connect to a cheap traditional caliper, read its value, and integrate that into a 3D design environment.[2] This is just a starting point for connected tools and, in our research, we explore how to extend this concept.

SPATIAL-TANGIBLE TOOLS

SPATA is a system that introduces tangible tools for fabrication-aware design (SPATA tools),[3] a digital adaptation of two commonly used measurement tools: calipers for measuring length, and bevel protractors for measuring angle. The SPATA tools can measure their respective value (length or angle), but are also actuated so that they can actively present the value in the physical world: the calipers have a self-actuated lower jaw that can physically represent length; the protractor can move its blade to output an angle (see the red parts shown in Figure 1).

Both tools can bidirectionally transfer—input and output—their value between the physical and virtual world. Users can measure a physical object, and the measured value is automatically transferred to the design environment. Conversely, length, distance, and angle measured in the virtual environment are automatically transferred to the physical world and presented by the SPATA tools. For example, to get an impression of the size of an object a user is designing, you can measure the object in the design environment and have the SPATA calipers tangibly output the size in physical space.

SPATA integrates closely into virtual environments used to design fabricable artifacts—namely, mechanical computer aided design (mCAD), mesh-based modeling, and 2D design. When designing new objects in these environments, users create shapes (such as primitives like boxes, cylinders, or rectangles), manipulate them, and combine them into new forms. Those tasks, in a fabrication-aware context, often
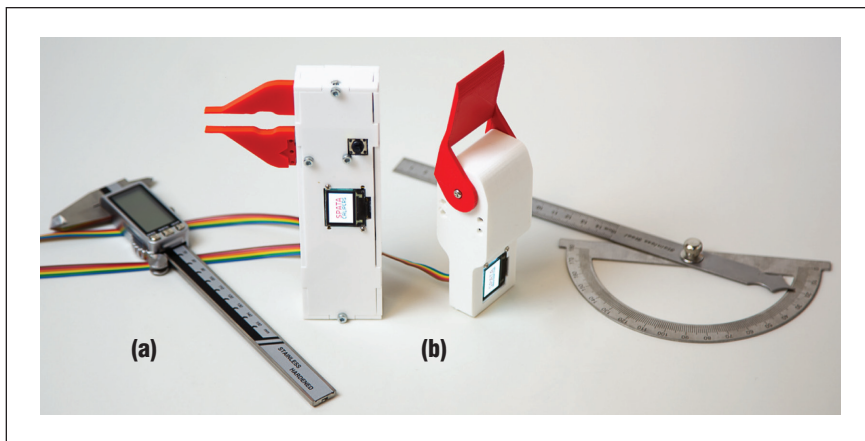

Figure 1. The two spatial-tangible (SPATA) tools next to their original counterparts. (a) calipers for size in-/output and (b) the protractor for angle in-/output.

require physical measurements taken from existing objects.

To reduce the need to switch between the virtual and physical world, the integrated tools support those tasks in the respective design environments. By partially offloading control to the measurement tools, task execution becomes more fluid and convenient. For example, to model a box-shaped object (such as an enclosure) using SPATA, users can measure all three dimensions (width, height, and depth) in sequence without having to put down the SPATA calipers or manually type in measurements.

To further support design tasks, SPATA tools can sense their orientation, display additional information (such as estimated fabrication time or the amount of required material), and have a button built in. We combine these capabilities to provide a more integrated and convenient design experience when designing for the physical world.

INTEGRATION WITH DESIGN ENVIRONMENTS

Modern mCAD systems, such as Autodesk Inventor or SolidWorks, are based on 2D sketches that are extruded or revolved into solid 3D objects. When drawing sketches or creating these objects, users need to constrain different dimensions, often using physical values, such as length and angle.

SPATA supports the creation of boxes from a prescribed series of real-world measurements (width, height, depth, and so on). The measurements can be performed in rapid succession using the button on the SPATA tool, so users can create a new cube with no context switch (see Figure 2). A similar sequence exists for cylinders: first measuring the diameter, then height. After a primitive has been created, SPATA stays in this mode, enabling a series of primitives to be built on top of each other. Elsewhere, we describe a use case in which this workflow integration reduced the number of context switches by 74 percent.[3]

Another common design environment type is mesh-based 3D modeling, which is a general-purpose modeling paradigm. It's often used to create organic and artistic models in tools, such as Autodesk Mudbox, Blender, or ZBrush. The smallest unit of manipulation is a vertex or an edge of the 3D model. Among other things, SPATA can be used to scale models in these environments, bringing, for example, the model to a certain size based on a single dimension. The application scenario in the related sidebar demonstrates more of the integration available.

GENERALIZING BEYOND FABRICATION

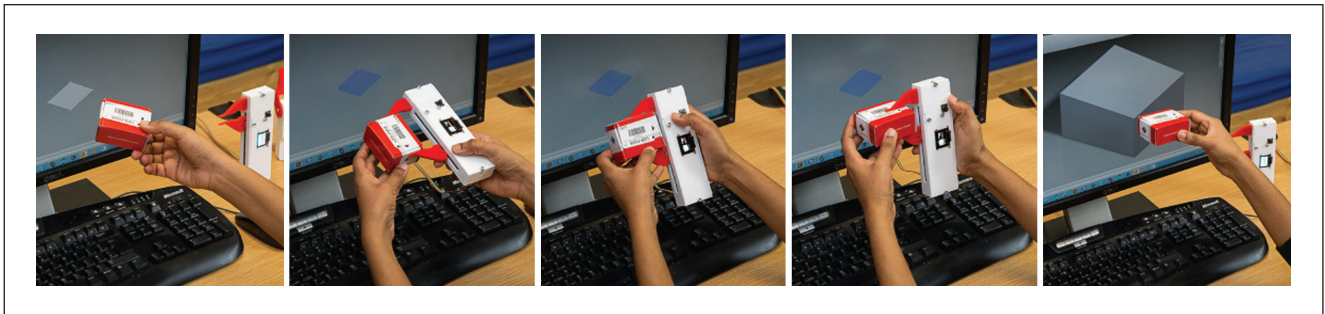The SPATA concept—automated measurement transfer and integration into

Figure 2. Creating a box (from left to right): select the ground plane, measure width, height, and depth.

APPLICATION SCENARIO

In this scenario, we want to create a flower vase that will be 3D printed. To model the vase, we use a mesh-based design environment that supports vertex-based modeling, sculpting, and constructive solid geometry. For artistic modeling, open input is often used instead of a mouse; we follow this practice.

We start the design process by creating a new cylinder. The vase needs to be correctly sized so that flowers fit in it and it can be placed on a desk. Using the SPATA calipers and their ability to globally scale, we scale the cylinder until it is 8 centimeters high. Using local scaling, we scale the diameter of the vase to 4 centimeters (see Figure A1).

Next, we add the decorative features by drawing on the cylinder using the pen. We use the SPATA calipers, which we now hold in our nondominant hand, to rotate the model so that we can draw on all sides (see Figure A2). This way, we don't have to change the mode from drawing to rotating; use the pen to draw and the SPATA tool to rotate.

Sculpting the shape has changed its size as well. Using Blender's built-in measurement tool, we measure the vase model. This causes the SPATA calipers to output that size in the physical world (see Figure A3). This way we can compare the size against the flower, or get a feel for the dimensions of the vase we're creating.

To make the vase more interesting, we want it to stand slightly angled. To explore different angles, we use the SPATA protractor. During this exploration, our focus is on the SPATA tool, which gives us additional, fabrication-specific feedback. When we use a too steep angle, we'll be warned when the current angle will make the fabrication take longer and be more expensive (see Figure A4).
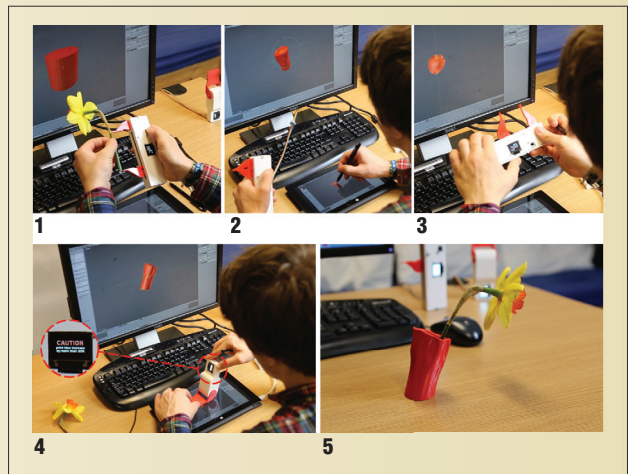

Figure A. Creating a vase. (1) We start with a cylinder, scaled to 8 centimeters using the SPATA calipers. (2) We sculpt decorative features, using the SPATA tools for orientation. (3) We check the size of the model and (4) explore different flower-hole angles.

Lastly, we cut off the bottom to create a flat surface for the vase to stand on and add the flower hole. We then send it to a 3D printer. The resulting vase fits the flower as designed and doesn't need support structures to print (see Figure A5).

design environments—generalizes to tools other than calipers and protractors. On different scales, different tools are used. HandSCAPE,[4] the digital measurement tape, for example, could also output its value using an additional motor. Alternatively, a folding ruler could be augmented to support input and output of not only length but also the angle along its joints.

Physical features besides length and angle could also be considered. For example, an integrated measurement tool for material stiffness could be used to design multimaterial 3D printed objects. Adobe sells tangible, integrated tools (a pen and a ruler) for Desktop Publishing and sketching (www.adobe.com/uk/products/ink-and-slide.html). The pen can pick up colors from the environment and display the current ink color on its back.

The need for integrating spatial features extends beyond design for fabrication. In computer supported collaborative work, or whenever there is a spatial/temporal division between users, SPATA could be used to transfer spatial features. For example, two spatially disconnected users could exchange the screen-size of the new

tablet they've bought. In a temporally disconnected scenario, users could get an impression of the size of an object offered in an online store, or measure parts of their body to order a custom-made product.

Connected and integrated design tools have the potential to make digital design not only more convenient but also easier to use. Through close integration into design environments, we can lower the barriers for new users. Future work will need to explore this potential and go beyond traditional tools. Connecting new tangible interaction technologies (such as shape-changing displays) with digital design environments will likely have a profound impact on how we design things. 🄿

REFERENCES

1. Mitutoyo America Corp., "New Mitu-toyo USB Input Tool," 3 Aug. 2011; www.mitutoyo.com/press_releases/new-mitutoyo-usb-input-tool.

2. M. Thalheimer, 2013, "Arduino Reads Digital Caliper," blog, 2013; https://sites.google.com/site/marthalprojects/home/arduino/arduino-reads-digital-caliper.

3. C. Weichel et al., "SPATA: Spatio-Tangible Tools for Fabrication-Aware Design," *Proc. Ninth Int'l Conf. Tangible, Embedded, and Embodied Interaction* (TEI), 2015, pp. 189–196; http://doi.acm.org/10.1145/2677199.2680576.

4. J. Lee et al., "HandSCAPE: A Vectorizing Tape Measure for On-Site Measuring Applications," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI), 2000, pp. 137–144; http://doi.acm.org/10.1145/332040.332417.

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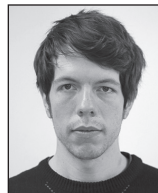
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