Sustainability in (Inter)Action provides a forum for innovative thought, design, and research in the area of interaction design and environmental sustainability. The column explores how HCI can contribute to the complex and interdisciplinary efforts to address sustainability challenges.

Elaine M. Huang, Editor

Physical Prototyping of an On-Outlet Power-Consumption Display

Florian Heller
RWTH Aachen University | flo@cs.rwth-aachen.de

Jan Borchers
RWTH Aachen University | borchers@cs.rwth-aachen.de

Less than a year ago, the tsunami in Japan reminded us what we like to forget: how dangerous producing electricity can be. In the Western world, electricity has become such an omnipresent source of power that most of us think of it only when the monthly bill needs to be paid or our cellphone battery dies. But this is changing. During the past few years, a series of commercial products and research projects have addressed the visibility problem of power consumption through various types of displays and artifacts. Power suppliers equip more of their clients' households with smart meters, which on the one hand allows better management of the smart-grid, and on the other hand enables all sorts of visualizations. Clients can see their current consumption, a history over the past few months, and maybe even a comparison to similar households in their neighborhood, either through a Web interface or a dedicated display.

But what about integrating a display right where power is consumed? As reported in Pierce et al., having a personal energy meter at hand does not necessarily mean it will be used [1]. Instead of introducing new artifacts and devices or deploying new apps and websites, we could create a display that is just there, every day, device-independent, and part of the electrical installation. Over the past year, a series of touchscreen displays and phone apps has been shown to be effective in enhancing energy awareness. However, if we want to understand how a prototype is integrated into the user's home and everyday life, we need to provide devices that have the right physicality to be used as such. Many interesting usage patterns will occur only if the prototype becomes an integral artifact, as is the case with the Energy Aware Clock [2] or the WaterBot [3].

We encourage you, the sustainable HCI community, to focus on design and integration while you build your prototypes, as the quality and finish of prototypes greatly influence the adoption and integration of technology into our homes. The FabLab community provides us with the required technology, such as 3-D printers and laser cutters, to build beautiful, polished physical prototypes. Here we present an iterative design approach to building such integrated prototypes using the example of an on-outlet power-consumption display.

Iterative Design: From Software to Hardware

Iterative design is well established in the areas of both software and hardware design. The only difference is that hardware prototyping is reserved mostly for professionals. The software designer can rely on well-established techniques like paper or screenshot prototypes that can be realized at low cost, but this becomes much more complicated if you enter the field of embedded devices. Toolkits like Arduino (http://www.arduino.cc) or Mbed (http://www.mbed.org) open the path to the embedded world for many software designers, but they allow them to create only low-fidelity prototypes. So how do you design a high-fidelity ambient physical display in an iterative manner but keep the costs low? We began by referring back to the known and making use of the physicality of existing devices.

Making Power Consumption Visible

The problem with power consumption is that it is neither tangible nor visible. Everybody knows what a liter of water is, but what about a kWh? A leaking faucet is easily discoverable, but where does stray electricity go? During the past few years, the HCI community has focused intensely on how to visualize power consumption. Known to reduce power consumption by up to 20 percent [4], enhanced feedback is an essential step toward environmentally friendly and sustainable behavior. The presented solutions range from simple personal energy meters (PEM) like the Kill-A-Watt (http://www.p3international.com/products/special/P4400/P4400-CE.html), to more complex displays showing a consumption history [5], to very ambient artifacts like the Power Aware Cord [6] or the Wattson (http://www.diykyoto.com). However, the physical units of *W* and *Wh* are problematic and not easily quantifiable [7], which is why a lot of systems translate the consumption information into something more graspable, such as cost, caused amount of CO_2, or color.

But how much energy does my hair dryer consume? The level of granularity greatly differs among devices. PEMs are flexible, as one can easily vary the number of attached devices and thereby isolate the consumption of a specific appliance. The Wattson, on the other hand, displays consumption only at the level of a household, as it is attached to the main fuse box. The visualization of accumulated consumption on a household level also complicates the discovery of the consumption of single appliances, as some other consumers could be automatically turned on or off.

Next-Generation Power Outlet

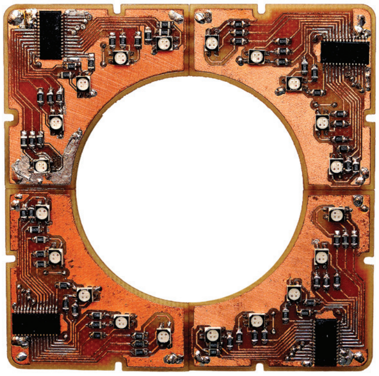
The design of the PowerSocket is focused on a simple and ambient visualization of consumed power at the level of a single outlet. We envision the socket to be installed in future homes, helping the inhabitants increase their awareness of power consumption without the need for additional hardware. But how do you visualize power consumption in a way that is easily understandable for everyone? And how do you prototype an ambient display to test different visualizations?

We had a physical device in mind, but its physicality was a serious problem for our prototyping procedures. Building a single prototype is easy with the popular embedded hardware toolkits, but making it flexible enough to evaluate different visualizations would require building several of them. At the same time, building a simple software prototype on a PC or laptop would not allow us to take the typical location of an outlet into account; nor would it result in an experience that resembled the designated use case.

We first did a classification of existing visualizations and adapted a series of visualizations to our on-outlet display [8]. From these five visualizations, we wanted to find the one that was easiest to understand for the end user, without having to build a hardware prototype for each of them, as they are quite different in shape. We thus reverted back to the known, which in this case meant a software prototype. To simulate the “ambientness” and physical location of the outlet, we used an iPad as platform. Over a WiFi connection, we could easily switch the visualization types and modify their parameters. To provide the right physicality, we went out to our FabLab (http://fablab.rwth-aachen.de) and quickly modified a power cord to fit the display. For our studies, we mounted the iPad on a wall at the usual height of a power outlet and “plugged in”

▸ Figure 1. The software prototype of the PowerSocket. It combines the flexibility of a software prototype with simple hardware to simulate the physicality and “ambientness“ of the envisioned product.

▸ Figure 2. The PowerSocket showing low, medium, and high consumption levels.



▸ Figure 3. The custom-designed PCB for the visualization unit.

▸ Figure 4. The final high-fidelity prototype of the PowerSocket.

the special power cord (Figure 1). We simulated the visualization for a series of home appliances, including a cellphone charger, a hair dryer, a vacuum cleaner, and a laptop.

With the results of our first evaluation, we went back to the FabLab, this time to build the device for real. We decided to implement a visualization that communicates the amount of consumed power over two channels. The first one is movement: A colored stripe circles the outlet (as shown in Figure 2) with rotational speed that varies according to increasing power consumption. With a very low load, the movement is barely visible instantly (0.15 rpm), but still perceivable over time. The other end of the scale is a very fast rotation (300 rpm) that indicates consumption beyond 1600W. The second channel involves the color of the stripe, which fades from green to orange to red with increasing consumption. The combination of these two components allows a quick estimate of consumed power at a glance, both for an outlet that is directly visible or, through the colored glow, for one that is obscured by furniture, for example. When the consumption is still measurable, but below 1W, the visualization changes to a gentle pulse, which was reported as an incentive to unplug a device—for example, an unused cellphone charger.

A High-Fidelity Hardware Prototype

To get the consumption data for our prototype, we used a PEM with a dedicated metering chip of known type and attached an Arduino to sniff on the data lines. We thereby avoided a lot of high-voltage electrical engineering, which constitutes a serious risk of injury (at least for computer scientists). Having obtained the current wattage, we turned to the less dangerous task of building the visualization unit.

We designed a PCB that holds 20 RGB-LEDs and their controller ICs (see Figure 3) to seamlessly fade between the different colors and brightness levels. The visualization program runs on a second Arduino board. This PCB fits nicely in our custom-made casing, which we built using a 3-D printer and a laser cutter. With this setup we could evaluate and improve the visualization. Things that were easily achieved with the iPad prototype, for example, a smooth rotation or soft edges of the stripe, needed to be implemented carefully in the hardware. After several iterations and improvements, we now had a very realistic prototype that we could use to evaluate our design.

DIY Hardware Design

From an industry perspective, the creation of such a piece of hardware is nothing new, as laser cutters and 3-D printers have long been part of the tool set designers use to build their prototypes. What is new in this kind of project is that this technology has become available to other groups of people outside industry. The perfect and polished finish of our prototype is a result of the easy access we had to these tools. It allowed us to experiment with different materials and form factors, and iterate through different designs with a speed and degree of quality not possible with standard tools. This *sketching in hardware* is an essential contribution of the rapidly growing FabLab community, which opens high-tech prototyping facilities to the public. The same community also promotes 3-D printing technology for the home by developing low-cost construction kits that allow you to build your own printer (http://www.makerbot.com). This, like the Arduino toolkit for embedded electronics or the LilyPad for wearable computing (http://web.media.mit.edu/~leah/LilyPad/), will revolutionize the way we think about prototypes. In a ubiquitous computing environment, more and more tasks are transferred from one central computer to smaller mobile devices. The prototyping of these devices mostly focuses on functionality, not so much on casing and form factor. As Arroyo et al. state in their paper on WaterBot, "The concern for appearance in this design goes beyond marketing and has direct consequences on the success of the persuasive interface" [3]. With these freshly acquired possibilities, we can now push this further and create high-fidelity prototypes that better reflect how they might be adopted for their designated use. We thus add another flavor to prototyping, going beyond the evaluation of plain functionality by creating artifacts that people can enjoy in their homes and surroundings.

Into the Wild

To collect feedback and insights, we handed out the prototype (shown in Figure 4) to different users to use for a week each. Besides the playful discovery aspect that arises when an interested user is confronted with a consumption display, the PowerSocket was used in creative ways that we did not imagine in the lab. One user reported that he used the pulse visualization to check from a distance if his cellphone was fully charged. Despite their high value in discovering such use cases, the deployment of power-consumption visualization prototypes is difficult. In most countries, the manufacturing and installation of anything that is connected to the electric network is strictly regulated and restricted to certified companies and engineers. Testbeds like the E.On 2016 House (http://www.eon-uk.com/about/2016house.aspx), a replica of an 1930s English semi-detached house, are rare and available to only a small number of researchers. Fortunately, chip manufacturers like NXP have realized this problem and provide easy-to-use wireless solutions (http://ics.nxp.com/support/design/microcontrollers/smart.metering/) that integrate well into prototypes and do not require any handling of high-voltage equipment.

With a network of outlet-based metering systems, we can also envision all sorts of interesting applications. An integration to social networks could encourage people to challenge their friends to consume less. Smart homes could also challenge their inhabitants to undercut their own consumption or that of their neighbors. Families could discuss who consumes most and if the consumption was necessary. As reported in Laschke et al. [9], this can be a strong motivation for behavioral change.

Another factor that should be considered is the power consumption of the display itself. With no load attached, our prototype consumes about 0.7W, which can be reduced drastically when using dedicated hardware. Nevertheless, the comparison between consumed and saved power is a crucial factor for the credibility of such projects. Indeed, one minute of hair-dryer usage is approximately equivalent to a cellphone charger plugged in without load for a whole week. This is something most people will never have thought about. From the literature and the feedback we received during this project, most people start this kind of reflection when they are given a tool that helps them understand power consumption. Once at the maintenance stage [10], the visualization could be turned off and reenabled only if some sensory systems detected that the average consumption had increased. We should clearly address the problem of consumption in our displays, but in the end, what we want to achieve is a change in lifestyle. Our displays may add some minimal consumption, but this is offset by increased awareness and reflection. Once this process has begun, we strongly believe it should not be limited to power consumption, but should also apply to water or gas consumption and other areas of everyday life, resulting in reduced overall energy consumption and a more environmentally sustainable lifestyle.

Acknowledgements

We would like to thank our student Wolfgang Kluth for the creation of this wonderful prototype. This work was funded in part by the German B-IT Foundation.

ENDNOTES:

1. Pierce, J., Schiano, D.J., and Paulos, E. Home, habits, and energy: Examining domestic interactions and energy consumption. *CHI '10: Proc.of the 28th International Conference on Human Factors in Computing Systems.* ACM, New York, 2010, 1985-1994.

2. Broms, L., Katzeff, C., Bång, M., Nyblom, A., Hjelm, S.I., and Ehrnberger, K. Coffee maker patterns and the design of energy feedback artefacts. *Proc. of the 8th ACM Conference on Designing Interactive Systems.* ACM, New York, 2010, 93-102.

3. Arroyo, E., Bonanni, L., and Selker, T. Waterbot: Exploring feedback and persuasive techniques at the sink. *CHI '05: Proc. of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, 2005, 631-639.

4. Froehlich, J., Findlater, L., and Landay, J. The design of eco-feedback technology. *CHI '10: Proc. of the 28th International Conference on Human Factors in Computing Systems.* ACM, New York, 2010, 1999.

5. Petersen, D., Steele, J., and Wilkerson, J. WattBot: A residential electricity monitoring and feedback system. *CHI '09: Proc. of the 27th International Conference Extended Abstracts on Human Factors in Computing Systems.* ACM, New York, 2009.

6. Gustafsson, A. and Gyllenswärd, M. The power-aware cord: Energy awareness through ambient information display. *CHI '05 Extended Abstracts on Human Factors in Computing Systems.* ACM, New York, 2005, 1423-1426.

7. Chetty, M., Tran, D., and Grinter, R.E. Getting to green: Understanding resource consumption in the home. *Ubicomp '08: Proc. of the 10th International Conference on Ubiquitous Computing.* ACM, New York, 2008, 242-251.

8. Heller, F. and Borchers, J. PowerSocket: Towards on-outlet power consumption visualization. *CHI EA '11: Proc. of the 2011 Annual Conference Extended Abstracts on Human Factors in Computing Systems.* ACM, New York, 2010.

9. Laschke, M., Hassenzahl, M., Diefenbach, S., and Tippkämper, M. With a little help from a friend: A shower calendar to save water. *CHI '11: Proc. of the 2011 Annual Conference Extended Abstracts on Human Factors in Computing Systems.* ACM, New York, 2010, 633-646.

10. He, H.A., Greenberg, S., and Huang, E.M. One size does not fit all: Applying the transtheoretical model to energy feedback technology design. *CHI '10: Proc.of the 28th International Conference on Human Factors in Computing Systems.* ACM, New York, 2010, 927-936.

ABOUT THE AUTHORS

Florian Heller is a Ph.D. student in the Media Computing Group at RWTH Aachen University and just completed a scholarship at the B-IT Research School. His research focuses on physical interaction modalities and embedded devices. For more information and an overview of other projects, please visit http://hci.rwth-aachen.de/heller.

Jan Borchers is full professor of computer science and head of the Media Computing Group at RWTH Aachen University. His research group explores the field of human-computer interaction, with a particular focus on new post-desktop user interfaces for smart environments; ubiquitous, wearable, and physical computing; interactive exhibits; and time-based media such as audio and video. He can be found online at http://hci.rwth-aachen.de/borchers.

DOI: 10.1145/2065327.2065332