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The Design Space of Personal Energy Conservation Assistants

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ABSTRACT

There are many routes to reduce one's energy footprint, ranging from picking the right means of transportation to switching off the heating when leaving a room to choosing seasonal local food. Many of these options, however, cannot be selected in an automated fashion, but require a deliberate decision. Pervasive computer systems may support this process, acting as personal energy conservation assistants. Such solutions can be characterized by a range of properties including the degree of obtrusiveness, data privacy, and coordination with utilities or domestic power generators. Along with discussing dimensions of the design space, this paper points out existing approaches and avenues for future research.

Keywords: energy efficiency, pervasive computing, persuasive computing.

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1. Introduction

Computers may support sustainable behavior through automated control or through suggesting appropriate choices to the human, based on the specific context. Currently, a large number of projects address the efficient use of energy, in particular concerning “Smart Grid” solutions (Ipakchi & Albuyeh, 2009) in which users or “intelligent” appliances are supposed to take into account which power generation capabilities are available at the given moment of time. This is particularly important due to the lack of storage for the highly intermittent power generated by wind turbines and photovoltaic systems.

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This paper is concerned with mapping out the space of design options to build computer-based systems that help individuals or households to reduce their energy footprint, here termed personal energy conservation assistants. These comprise solutions ranging from digital power meters to heating control systems to applications for mobile phones that suggest local produce (Li, Chen, Wang, & Baty, 2009). This paper looks at the overall concept of such solutions; it is not concerned with details of software design and system architecture. In the vocabulary for energy-conserving interactions introduced by Pierce, Schiano and Paulos (2010), all five options are addressed: cutting, trimming, switching, upgrading, and shifting. A computer-based system may cut or trim power consumption fully automatically; it may suggest switching, upgrading, or shifting to a human.

DiSalvo, Sengers and Brynjarsdóttir (2010) find five "genres" of research topics in a survey of literature on sustainability and human-computer interaction (HCI): persuasive technology, ambient awareness, sustainable interaction design, formative user studies, and pervasive and participatory sensing. In addition, they describe major "axes of difference" such as seeing sustainability as research focus versus seeing it as an application area. Finally, they point out emerging issues for sustainable HCI. All of this helps shaping future research, but is not directed toward facilitating the design of actual applications.

In an earlier literature survey, Goodman (2009) looks into three "discourses" concerning environmental issues in research on human-computer interfaces: sustainable interaction design, re-visioning consumption, and citizen sensing. This, too, is remote from the design of actual applications. However, in the first point, i.e. sustainable interaction design, Goodman (2009) mentions three main design directions: "systems that provide information relevant to the sustainability of goods and services […], visualizations of resource consumption […], persuasive applications, such as games." This indicates a design decision to be made. The current paper aims at focusing on such design decisions. HCI is only seen as means to an end. Most of the solutions comprise human-computer interfaces; some, however, may not possess any direct human-computer interface at all.

This paper puts forward the following three main usages of personal energy conservation assistants, as will be detailed in Section 2:

- Information
- Advice, persuasion
- Automation

A single system may address one or several of these three usages. For each of them, a given system can be characterized through several aspects, to be detailed in Section 3:

- Control targets
- Data sources
- Data processing
- User interface modalities
- Data and control sharing

Table 1 shows the resulting grid of design decisions. Section 4 gives examples of this grid in action. Section 5 concludes this paper.

Aspects / ***Usages***	**Control targets**	**Data sources**	**Data processing**	**User interface modalities**	**Data and control sharing**
Information					
Advice, Persuasion					
Automation					

Table 1. The usages on the vertical axis and the aspects on the horizontal axis form a grid of fundamental design decisions. Note that the distinction between “Information” and “Advice, Persuasion” may be gradual (see Section 2).

2. Three Usages

The most prominent of the usages—and typically also the one easiest to implement—is to provide data to the user, best in such a way that it constitutes not only bare data but builds **information** meaningful to humans (Rowley, 2007). This can refer to the current time such as a power meter reading, to history such as the neighborhood's power consumption in the past five years, or to future developments such as an estimate of the expenses a certain appliance will cause per year or the amount of locally available photovoltaic power based on a weather forecast.

The system may not only passively provide data; it may also become active in the sense of **automation**. Instead of relying on the user to react to the data, the system may take action on its own, for instance turn off the heating when a window is open. Whereas automation may reach so far as to eliminate any standard human-computer interface, the designer will in most cases be wise to allow some degree of user intervention. Maybe, the heating is on while the window is open because there is a person lying sick in bed.

There is an interim stage between active (automation) and passive (information): **advice**. Here, the system interprets the data on its own and presents a recommendation, to which the user may or may not adhere. The output may be as basic as switching on a red traffic light (Strengers, 2008). Persuasive systems (Fogg, 2003) are related to systems that provide advice in that they urge the user to take a specific action—though by **persuasion** such as games (Gustafsson, Katzeff, & Bang, 2009) and hence less neutral and/or through a less direct means. Hence, this paper argues for placing persuasion and advice in the same category. A specific focus of persuasive approaches is to cause long-term effects on the user's actions such as preferring taking the bus to going by car. Nevertheless, long-term effects may also be present when the same suggestion is given in neutral terms, as an advice. For a survey of behavior models and motivation techniques concerning energy use see He, Greenberg and Huang (2010). Froehlich, Findlater and Landay (2010) look into how both HCI and environmental psychology address eco-feedback.

The decision whether a specific output of a system is to be considered information or advice or an attempt to persuade may become blurry at times. A more complete, but often too sophisticated representation would involve a continuous scale that measures the subjectivity or the amount of interpretation present in the feedback given to the user.

Systems may support one or several of the three usages. This may happen in parallel: for instance, a less critical appliance such as a freezer may be controlled fully automatically, whereas the same system only suggests starting the washing machine at a certain point of time because there are enough photovoltaic power and solar-heated water available. The three usages may, however, also occur in an escalating sequence that starts with a message about an open window and ends with the system shutting down the heating in that room.

3. Five Aspects

Each of the three usages (information; advice, persuasion; automation) can be characterized further. As it turns out, one can employ the same four groups of properties for every usage. In this paper, these groups of properties are termed aspects, sticking to the terminology of aspect-based programming (Filman, Elrad, Clarke, & Aksit, 2004): there as well as in this paper, aspects crosscut the core concerns, which in this paper are the three usages.

3.1 Control Targets

This basic aspect concerns what can be controlled either automatically or by a human operator informed by the computer: the setting of the air conditioning, which means of transportation to choose, which kind of food to buy, etc. The control targets are often determined through the basic task, such as optimizing a heating system, and seem not to be open to design. On close inspection, however, surprising design options may become visible. For instance, the optimization of a heating system could include advising the resident to go to work an hour earlier than usual.

3.2 Data Sources

The most vital aspect to be designed describes the data sources on which the information output, the generation of advice, or the actions of the automation are based. Abstractly speaking, these data may stem from three different realms: power generation, power use, and context. Data pertaining to power generation may comprise the current capacity of a domestic photovoltaic generator as well as a forecast concerning wind power from off-shore sites. Power use data comprise the now-classic electronic power meter reading (Fischer, 2008) and the current miles per gallon (MPG) rate of a car. Whether or not a resident is at home or whether or not this day is a holiday are examples for data describing the context. These data include statistics collected in the past, measurements that reflect the current state, and forecasts of the future.

There is a plethora of ways to collect such data. The basic solution is input from the user via keyboard and screen, be it on a dedicated device, a standard computer, a mobile phone, or an extended TV set. This includes the manual input to receive suggestions from Microsoft Hohm (www.microsoft-hohm.com). Data from humans, however, may also consist in advice or persuasive feedback from Web-based social networks such as the one described by Qiao, Liu and Guy (2006).

Data collected automatically may stem from smart power meters, possibly distributed throughout the home such as with digitalSTROM (www.digitalstrom.org) or other low-cost solutions (Quintal, Nunes, Ocneanu, & Berges, 2010). Sensors mounted in the home do not only target the consumption of electrical power. They include temperature sensors, motion sensors, cameras, microphones (De Silva, 2009), and even a presence detector in the TV set (Ariizumi, Kaneda, & Haga, 2008). Likewise, in a mobile setting, one may look into engine performance data (Won & Langari, 2003) of a car and leverage the accelerometer circuits in mobile phones and notebook computers.

Other data can be collected automatically from outside networks. Weather forecasts and power market data are available on the Web. The local utility company may offer on online service with real-time data for time-of-use pricing. Outside data may concern the immediate neighborhood as well as larger regions; they may for instance be provided by a local utility company, by large-scale services such as Google Power Meter (www.google.org/powermeter/). This does not only concern data on power; schedules and real-time data for public transport (Ferris, Watkins, & Borning, 2010) belong to the same group.

3.3 Data Processing

This aspect refers mostly to the amount of "intelligence" present in the system. A basic system will operate entirely on strict rules, such as switching off all lights in the home one minute after the user has picked up his or her key from its hook. A smarter system may have learned that if this happens at 7 a.m., the user will return after two minutes (because he or she has just fetched the newspaper from the mailbox). Learning, adaptation, and forecasting may happen through a huge variety of methods, with (Qiao et al., 2006) or without feedback and/or supervision by the user.

There is a catch, however: A system with shallow intelligence may be easy to understand and to handle; a sophisticated system may vex the user if it requires micromanagement of dozens of parameters or if it acts in an unpredictable fashion. One option to deal with this issue is to let the system be rule-based, but let it guess new rules and present them to the user for inspection, such as in the "Smart Home Energy Assistant" developed at TU Berlin (http://energy.dai-labor.de). This signifies a shift from instance control to pattern control (Koskela & Väänänen-Vainio-Mattila, 2004). In a similar vein, a recommender system can suggest algorithms for building automation (LeMay, Haas, & Gunter, 2009).

The level of abstraction afforded by the system becomes clear when one looks into questions such as these: Are data given in their native units such as watts or are they—reliably?—converted to more meaningful quantities such as a price or an amount of greenhouse gases? Are rules to be formulated in terms of signals (e.g., the sunshine is strong enough for the domestic photovoltaic system to generate 2 kW of power) and controls (e.g., turn on the washing machine) or can rules be given on a level closer to the human understanding? (E.g., "Run the washing machine on renewable energy!") Is it possible to define high-level goals (e.g., "Save as much money as possible!" or "Do the washing within 24 hours as much environmentally friendly as possible!") instead of defining the rules that underlie them?

3.4 User Interface Modalities

The aspect of which type(s) of user interfaces are being employed encompasses a huge range of subordinate design choices. Looking at the specific case of energy displays in the home, Fitzpatrick and Smith (2009) discuss design choices concerning the four domains of metrics, frequency, granularity, usage comparison.

In a broader view, one may start by asking if there needs to be any interface at all and, if so, which senses (vision, hearing, haptics, etc.) are to be supported. A broad variety of vision-based interfaces have been suggested to display power consumption, reaching as far as painting the electrical devices with a corresponding color in augmented reality (Lapides, Sharlin, & Greenberg, 2009). The use of auditory interfaces seems to be underdeveloped in this domain. Tangible robotic objects such as a cartoon cat that frowns about a poor setting of the washing machine (Midden & Ham, 2009) may form a mixed category. Interfaces may support mobility (Weiss, Mattern, Graml, Staake, & Fleisch, 2009) or may be accessed only from a specific location. This location—such as that of a control screen for a building management system represents yet another design choice.

Interfaces can be sober and factual such as an MPG display in a car or they can be similar to pieces of art, like most ambient data displays are (for an exploration into this topic see Pierce, Odom, & Blevis, 2008). Kim, Hong and Magerko (2010) compare a factual display to an ambient display aiming at reducing the idle time of computers.

Ambient interfaces often are "slow interfaces"—such as a lamp that starts to open like a flower to indicate environment-friendly behavior (Mazè, 2010). In addition, ambient interfaces tend to be subliminal and unobtrusive—unlike the notorious Office Assistant "Clippit" of Microsoft Word 97 and unlike room illumination that turns itself off when nobody is moving for a minute. An escalating response of the system may start with a faint signal and then become obtrusive over time.

3.5 Data and Control Sharing

Given the history of computer viruses, shady Internet-based businesses, and large-scale privacy breaches, any design of a personal energy efficiency assistant has to make and enforce transparent decisions which data and which controls are shared with whom.

It has been known at least for a decade that detailed power consumption data lend themselves well to the discovery of usage patterns (Drenker & Kader, 1999) and life styles. For instance, the data easily indicate when somebody is at home and with little more processing allow to determine if a resident is self-employed. Even more privacy concerns exist with more advanced data. Social Web sites such www.wattzon.com and www.stepgreen.org, however, pose the usual threats known from the Internet in general—as long as they only deal with coarse-grained consumption data.

Systems that provide data to the user may be prone to spoofed data. Systems, however, that can directly control electrical or mechanical devices pose an essentially new security threat. Many smart grid scenarios incorporate the notion of a utility company controlling appliances remotely. It is conceivable that an attacker may exploit such pathways for instance for extortion or stalking.

4. Application Examples

This section looks into specific examples to demonstrate the proposed grid of design choices in action. The first example is very lean: the Power-Aware Cord (Gustafsson & Gyllenswärd, 2005). Here, glowing threads in a power cord are used to indicate power usage, see Table 2. The second example is a full-fledged home energy management system, as demonstrated in Simon Fraser University's North House and West House (Bartam, Rodgers, & Woodbury, 2010), see Table 3. To show that the range of possibilities is not quite exhausted today, Table 4 contains the choices for a hypothetical integrated kitchen system, which not only shaves energy through smart-grid technology, but also helps the resident to choose and buy (or even grow?) food that both is healthy and has little environmental impact.

Aspects / ***Usages***	**Control targets**	**Data sources**	**Data processing**	**User interface modalities**	**Data and control sharing**
Information / **Advice, Persuasion**	Power consumption	Real-time power consumption measurement	Conversion of the current power consumption to a light intensity or a flow pattern	Visual, ambient, located at the device to be controlled	None
Automation	None	None	None	None	None

Table 2. Choices made in the Power-Aware Cord.

Aspects / *Usages*	Control targets	Data sources	Data processing	User interface modalities	Data and control sharing
Information	Heating, lighting, use of applicanc-es and enter-tainment systems	Smart meter, so-lar energy pro-duction, diverse sensors	Report genera-tion	touch panels, mobile devices, PC	Comparisons
Advice, Persuasion			Conversion of data to light ef-fects	Ambient display	Challenges and competitions
Automation			Hierarchical con-trol model	Physical controls, PC, touch pan-els, mobile de-vices	None

Table 3. Choices made in North House and West House.

Aspects / *Usages*	Control targets	Data sources	Data processing	User interface modalities	Data and control sharing
Information	Food preparation procedures	Scales etc., dura-tion and tempera-ture data from the stove	Stepping through finite state ma-chines	Kitchen back-splash screen, ambient auditory signals	None
Advice, Persuasion	Choice of dishes and ingredients	Web services, inventory of food stored in the home	Recommender system	Web page for mobile devices	Social Web site
Automation	Scheduling of oven and fridge	Diverse sensors, e.g. for the fridge's content	Optimization	Touch panels on appliances	Smart Grid

Table 4. Choices made in a hypothetical integrated kitchen system.

5. Conclusion and Outlook

This paper has described salient design dimensions for personal energy efficiency assistants. To engineer such a system, one may start by collecting requirements and then decide which of the usages are to be supported and how each aspect of each usage is to be implemented. The set of requirements will include the affinity of the prospective users to computer systems, the general state of health of the users in the spirit of ambient assisted living, and the motives of the users such as wanting to feel comfortable, to save money, or to be friendly to the environment (Dillahunt, Mankoff, Paulos, & Fussell, 2009; Chetty, Tran, & Grinter, 2008).

Further research can aim at deepening and validating the design dimensions. Investigations into novel options in a given design dimension may bear particularly surprising results. For instance, personal finance data is an underrated data source to estimate one's impact on the environment (Schwarz, Mankoff, & Matthews, 2009).

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