E-tree: Understanding an In-Home Energy Consumption Display

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ABSTRACT
E-tree is an in-home Energy Consumption Display (ECD), which the user can use as both stationary and portable device. We explored E-tree to help the user understand their energy consumption at the home. Project phase two included three goals. First, we implemented a wireless measurement device, which uses an Infrastructure Mediated Sensing (IMS) system attached to the home power breaker. E-tree received information about total current household electricity consumption and the consumption of appliances from the measurement device. The measurement device has both real-time and periodical monitoring. Second, we compared two algorithms for the measurement device. Third, we refined design and form factor, which included the ability to select an appliance to display the consumption at surface.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces. – User-centered design.

General terms: Design, Human Factors

Keywords: Ubiquitous Computing, Sustainability

INTRODUCTION AND MOTIVATION

Human-centered problem
Ever since the seminal 1970’s Twin Rivers empirical study of energy consumption, we have known that human behavior plays a critical role in energy conservation [6]. While there are ways to reduce energy use automatically through advanced technologies and public control, the Twin Rivers study showed that even in identical physical environments, variations in human behavior may increase consumption as much as twofold. An interest for the HCI community is to understand what role the technology plays in influencing the behaviors that impact domestic energy consumption. We investigated how a minimal in-home energy consumption display (ECD), either stationary or portable, affects energy awareness and use.

Providing direct, continuous consumption feedback reduces household energy use more effectively than providing generic information about energy conservation or periodic feedback in the form of a bill [5]. Chetty et al. found that consumers desire easily-accessible, real-time feedback to encourage sustainable behaviors [2]. Several commercial solutions for real-time domestic energy monitoring have become popular as diagnostic tools for appliances (e.g., Wattson – http://www.diykyoto.com/uk/wattson/about (Figure 1)) and for collaboratively managing power use with the electric company (e.g., Cellnet+Hunt – www.cellnethunt.com). However, few commercial systems have explicitly explored the relationship between the ECD and the user’s behavior.

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Empirical studies have focused on appliance-level feedback ECDs that provide real-time information about energy consumption [7]. While this approach has shown great promise, it assumes a world of distributed, intelligent appliances that may never be affordable to the masses. Fischer emphasizes that failure to meet technological preconditions has stunted the development of useful feedback systems [5]. Wood and Newborough suggested that a household-level display unit placed inside the home might offer the best value in terms of practicality and comprehensiveness [10]. They proposed two characteristics of such a device that may impact its success: a simple presentation and a portable form factor.
Other research results have focused on supporting the following statements regarding household energy conservation, 1) curtailing household energy conservation has become as important as cutting industrial energy conservation because, unlike industrial use, home use is increasing 2) changes in human behavior are needed because energy efficiency thorough technology is not enough to meet cutback requirements, and 3) energy use feedback can work to support household conservation behavior if certain conditions are met 8. One study concentrates on an interactive technology system installed in household appliances that provides advance feedback techniques. This system is developed by designing a meaningful display of energy feedback for the user using the interface of the household appliance and providing the method for the user to react to the feedback before deciding to continue with the action. This sort of system between the user and the device can support a foundation for the development of more elaborate feedback systems using smart agents that can learn about the pattern of individual behavior and guide the energy use behavior of each person in a household. This feedback allows the user to find out other actions and their resulting energy activities before making a final decision.

Technology-centered problem
Two approaches have recently emerged in the research community for studying human activity in the home setting. The first approach involves approximating the actual home environment with a "living laboratory" which is equipped with a rich set of sensors, network infrastructure, and computation resources. Because of their purpose-built nature, living laboratories such as the Aware Home [10] at Georgia Tech, and the PlaceLab [11] at MIT, allow the deployment of a virtually unlimited variety of sensors to capture human activity inside the home. Sensor infrastructure deployed in a living laboratory can be experimental in nature and does not need to meet the cost, stability, robustness, scalability, aesthetics, or maintenance constraints that would confront a sensor system suitable for deployment by an ordinary consumer in own home. This approach, while extremely valuable for developing applications in a controlled setting, does not provide high quality data about the real-world utility of the applications that are developed, because the DDS approach is generally too costly and/or too complex to permit widespread deployment.

To overcome the challenge of obtaining human activity data in a widely deployable fashion, a few researchers have recently begun working on a technique that we call "Infrastructure Mediated Sensing", or IMS. Infrastructure mediation refers to the use of existing home infrastructure to sense human activity through the detection and classification of human interaction with that infrastructure. We have identified the home electrical system, plumbing system, heating, ventilation, and air conditioning (HVAC) system, natural gas piping, and computer network (whether wired or WiFi) as widely deployed, existing infrastructure buses where initial experiments have shown that we can sense human generated events caused by interaction with those buses. We informally refer to IMS as "home bus snooping" by analogy to computer network snooping.

Informed by this work, we created the E-tree as ECD for in-home use that presents real-time energy consumption data as an ambient and numeric display and the wireless measurement device. We produced not only energy feedback but also games, one intended to be used as energy feedback system and another that could engage the user’s attention of energy consumption with IMS.

E-TREE OVERVIEW
We developed E-tree as the in-home ECD that looks like a tree and a fruit. Each fruit has an ambient and numeric display to display the real-time energy consumption information received wirelessly from the house power breaker. The fruits are plugged into a household outlet or are battery operated to allow it to be carried anywhere in the home.

The user can assemble tree with fruits to look at total energy consumption at home, room-level consumption, or appliance-level consumption. E-tree shows a simple representation of current energy use as a multi-color LED and a seven-segment LED. The system can display consumption between 0 and 4,096W, representing typical appliance power levels [4]. A multi-color LED has 256 levels of color change from green to blue, where one level of brightness represents 4W of power. Thus, pure green color represents 0W of power used; if consumption increases past that, blue color begins to light as well. If total usage exceeds the maximum range of the display (4,096W), the LED begins to blink in blue. The use can indentify quantitative usage by looking at the numeric LED as well.

MEASUREMENT SYSTEM OVERVIEW
The system consists of a measuring system and the E-tree. Two devices communicate with each other through Zigbee interface. The measuring system uses two neural networks: Adaline neural network for a preprocessing and MLP (Multi-Layer Perceptron) for identification of appliances. The MLP can be replaced by a BST (binary search tree.) Here’s the brief outline of how the system works.

Preparation
Before using the system, we need to train the MLP or construct the BST which we will use at the time of real use.
Measurement and preprocessing
Since we use harmonic values of load current as appliance signature, we need to measure the current and then obtain the harmonic values from the current. Here’s the procedure to obtain harmonic values.

For each appliance, we do the following.
• Measure a load current for certain period using a current sensor attached to main power source. (At this time, calculate the amount of power consumption of the appliance and save it.)
• Extract harmonic values by performing regression using the Adaline neural network.
• Save those harmonic values with the current state of the appliance. E.g., ( 3.5 0.02 1.0 -0.03 ... Microwave )

Composition
After finishing the above step with all appliances, we mathematically create training data for all possible combinations of appliances. All these values are used as training data for the MLP or data for BST.

Training (Construction)
1. MLP training
For the MLP approach, we train the network with the harmonics data as inputs and states of appliances as target values. After training the network as many epochs as needed, the network is saved.

2. BST construction
For the BST approach, based on the 1st harmonic value (the fundamental frequency component), we sort all collected data, and then construct a binary search tree.

Identification
Now we are ready to use the system. With certain interval, the system broadcasts the data, which consists of states of all appliances, amounts of energy consumed by each appliance and total consumption amount.

Real-time Identification
The user can detect currently used appliances and how much energy each of those appliances is consuming. For this task, the system needs to perform the measurement and preprocessing (in the same manner that we did at the preparation stage) and then run the MLP network or search through the BST to output the result. After figuring out states of all appliances, we retrieve power consumption information of each appliance saved at the preparation stage.

Periodical monitoring
The system provides feedback of how much time each device has been used for and how much money has been spent for each device per hour, day or week. The user can set an interval to repeat real-time identification task (E.g., 5 minutes or 10 minutes)

Comparison between MLP and BST
MLP has shorter processing time while BST showed better accuracy (Table 1). With 16 input nodes (each harmonic value for each node respectively), 12 hidden nodes and 5 output nodes (each appliance for each node, respectively), it takes about 0.05 milliseconds for the MLP to perform the identification task. In case of the BST, it took about 0.07 milliseconds on average. Although it is not a big difference currently, it is likely that, as the number of appliances increases, the processing time for the BST will increase more rapidly than the processing time for the MLP does. Test environment was that we used a Lenovo laptop with Intel core 2 duo 1.66 GHz and 1GHz RAM

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Identification accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave</td>
<td>100%</td>
</tr>
<tr>
<td>Toaster</td>
<td>100%</td>
</tr>
<tr>
<td>Hair dryer</td>
<td>100%</td>
</tr>
<tr>
<td>Lamp stand</td>
<td>93%</td>
</tr>
<tr>
<td>Halogen lamp</td>
<td>78%</td>
</tr>
<tr>
<td>Microwave</td>
<td>100%</td>
</tr>
<tr>
<td>Toaster</td>
<td>100%</td>
</tr>
<tr>
<td>Hair dryer</td>
<td>100%</td>
</tr>
<tr>
<td>Lamp stand</td>
<td>94%</td>
</tr>
<tr>
<td>Halogen lamp</td>
<td>86%</td>
</tr>
</tbody>
</table>

Test result with BST

Table 1: Comparison of accuracy between two algorithms

USAGE SCENARIO

Ambient Display
Julie places E-tree in the living room. She glances occasionally at the device to check the status of energy consumption of her house. E-tree displays total energy consumption of the house using an ambient light. When E-tree turns into blue, Julie is able to comprehend as to which appliance or room lead to that state.

Game
Tom a 12-year-old kid is interested to know more about the things that make his home a better place to live in. His games include E-tree. E-tree is an innovative gaming gadget that helps kids like Tom to know more about the devices in the home. The fruits are discovery devices. When removed from stems, each fruit is a gaming bulb. The server randomly assigns each of these fruits to some appliance’s energy consumption. The fruit changes the color to depict current levels of the associated device. The goal of the game is to find the associated device in the home within 10 chances. The game is played between 2 or more players. Tom places his fruit next to an energy-consuming device. This fruit then starts blinking. If the color of the blink is blue then that means the device is not the one with which is currently assigned to the face. Otherwise, if it’s green then that means the correct device is
identified. These and many other games can be played or constructed using this infrastructure.

DISCUSSION
During the project phase two, we implemented a new design ECD and the associated measurement infrastructure. Another previous work, which individually measured and displayed the consumption of many devices in the home tried to achieve the same goal. We propose that low-granularity feedback provided by our ECD will have a substantial impact on household consumption when combined with goal-setting strategies on the part of the user.

In previous study, the users who were successful in reducing energy consumption viewed the process as a game. This provides us with opportunities for playful goal setting that can be used to bridge the gap between providing feedback and achieving a reduction in energy consumption. However, Low and moderate awareness individuals represented 76% of the 149 participants asked to respond to the same measure in a previous investigation [3]. The ECD should provide options to request feedback of a higher granularity, as well as historical and social points of comparison.

Ambient information displays like the E-tree are intended to fit in a part of the interface design space that are designed to convey background or context information which in our case is the energy consumption of the entire house or individual rooms that the user may or may not wish to attend to at any given time [9]. These Ambient Displays are designed to work primarily in the periphery of a user's awareness, moving to the center of attention only when appropriate and desirable. In our case such scenarios may be sudden turning of fruits from green to blue or vice versa, or may be consistent blue color. These scenarios are effective in making the house dweller aware about the current energy consumption while under taking the day-to-day tasks in the home environment.

FUTURE WORK
We are exploring energy feedback system to help the user more quickly and easily understand their energy consumption at the home. Additionally, E-tree can receive information about total current household electricity consumption and the consumption of each appliance from a wireless measuring device we created. This measuring system broadcast an encrypted signal to E-tree every second via the Zigbee™ wireless protocol. We will enhance accuracy of the measuring system. Social networking websites will have applications to depict the result achieved by ECD for an individual house. This could promote awareness in the community about sustainability and energy conservation. Thus the validation and publication of the results of the goal setting game and introduction of applications based on created infrastructure in the social networking systems are our future coarse of action.

CONCLUSION
E-Tree hopes to generate awareness among home dwellers about sustainability and conservation of energy. The main agenda through which it will achieve is by making invisible energy consumption of home appliances, visible by modes of auditing, games or ambient displays. The emphasis of the application is to provide accurate feedback to the user. This is done by implementing a learning measurement infrastructure, which provides real time accurate energy consumption of different levels of granularity (device, room, home) as defined by the user. This immediate feedback and the goal setting based gaming environment helps in behavior modifications of families and promote just usage of appliances in the daily life. These implications lead to less electricity bills and a greener environment for a sustainable future.

REFERENCES
Appendix

Project 1. E-cube Design Solution

Concept Ideation

We initiated from 3 basic concepts, which are based on fun and eco-friendly. Because our goal is the development of applications that reduce energy consumption while maintaining occupant comfort, all design ideas are representing “Silent Design” and “Eco-design”.

- Electronical PET
- Energy Dice
- Pixelized Wearable Design

Main Context: Raising an electronical PET. FEED your pet by Saving Energy. (Growth) Be warned if you waste energy. (Get Sick)

Figure 1. Idea #1 Electronical PET

Figure 2. Idea #2 Energy Dice
**Concept Refinement**

We decided to refine the second idea, Energy Dice. Based on the basic concept of the second idea, we generated the assembly type of device which is an ambient light display in normal situation and transfer its status to the game mode when it is detached from the cube.

![Figure 3. Idea #3 Pixelized Wearable Design](image)

**Project 1. E-cube Final Solution Details**

1. **Logo**

Representing our basic concept, we name this energy monitoring system ‘Energy Cube’, and ‘E-cube’ was selected as the name of product. For logo design, I used a cube for representing our product feature and put "E" on one surface. Moreover, to reveal our main concept, sustainability and eco-friendly. Green tone of color was exploited.
2. Mechanical Drawing
For the project 1, we made a simplified prototype. E-cube ver. 1 is consisted of 2 pieces, one is semi-transparent panel and the other is a hard case for technological devices. The dimension of E-cube assembly is 102*102*102(mm), and that of one piece is 102*102*25.5(mm).

![Figure 5. Orthographic 3 view Drawing of E-cube](image)

3. Application Feature

![Figure 6. Assembly Feature of E-cube](image)

4. Further Work
   - Test the connection between E-cube and specific electronic devices at home. Examples: Each piece of E-cube would have a selection dial on the face. We will test whether it could be delivered in game mode.
Develop more design variation, which can satisfy the needs and wants of real users.

Project 2. E-tree Design Solution

Concept Ideation

Regarding the second project, I initiated from 3 basic concepts, which are based on sustainability and eco-friendly. Because our goal is the development of applications that reduce energy consumption while maintaining occupant comfort, all design ideas are representing “Silent Design” and “Eco-design”.

- E-cube ver2
- Energy Plant
- Energy Flower & Vase

Figure 1. Idea #1 E-cube ver2
**Concept Refinement**

Deciding to merge the first and the second idea, we designed the new concept which we named E-tree, the abbreviation for “Energy Tree”. The form factor of E-tree is derived from the second idea, Energy Plant. We changed the form of E-tree to more decorative ornament shape made of eco-friendly paper. Moreover, we applied the context of stationary system, which contains eco-friendly and decorative functions in the refined design.
Project2. E-tree Final Solution Details

1. A module

The shape of a module, which represents each device, is similar to ornaments. Instead of selecting plastic for the material of a module, we decided to apply the semi-transparent paper, which can be recycled easily and eco-friendly. The structure made of wire holds the mechanical part of a module. Moreover, paper coverage shows ambient color of display beautifully.
2. Full Feature

In the second phase of the project, we explored the way to show the connection and relationship between each module display and the entire home. The reason we selected the tree to the main context was not only the sustainability concept, but also the possibility to mapping the home shape to each space of tree, branches. According the initial idea proposal of E-tree, we considered each module which represents the energy consumption of device in the certain space of house would be placed at certain branch. We anticipated observing certain pattern of energy consumption through the combination of ambient displays.

Figure 6. Full Feature Mapping