Rapid Prototyping of Energy Management Applications with FRESH

Brian Y. Lim, Kurt Roth, Sainath Nambiar, Haritha Rayakota, Fraunhofer Center for Sustainable Energy Systems

ABSTRACT

Home energy management systems (HEMS) can reduce energy consumption while maintaining comfort. However, HEMS suffer from slow adoption and unproven energy savings. As intelligent automation and persuasive design features are increasingly added to HEM products, many research questions remain regarding their efficacy. We present the FRESH research platform to facilitate (i) the development of innovative features in HEM applications, and (ii) their evaluation in field deployments. FRESH has extensible modules for (a) sensing to acquire data from wireless hardware sensor nodes and online sources, and actuation to control custom devices and commercial-off-the-shelf appliances, (b) adaptive and intelligent modeling to test various machine learning and control algorithms, (c) flexible user interface to explore the design of features based on behavioral research, and (d) field experimentation with tools for user interaction logging, automatic context-aware surveys and messaging, and data visualization. We have deployed FRESH in residential apartments and commercial offices used as test beds. We demonstrate the versatility of FRESH with four application use cases: environmental monitoring, non-intrusive load monitoring (NILM), an elevator energy display, and a smart thermostat. We have used FRESH to iterate on sensor nodes, develop and evaluate intelligent algorithms and models, and design mobile and web user interfaces to investigate HEM usability.

Introduction

Residential buildings account for 22% of the energy consumption in the U.S. (DOE 2011). This leaves much potential to save resources with home energy management systems (HEMS) as indicated by diverse HEMS products and companies (LaMarche et al. 2012, GTM Research 2013), including home energy displays, smart thermostats, plug load control, and non-intrusive load monitoring. However, the HEM market is "expanding at a slow but steady pace" (Navigant Research 2013). Roth and Sachs (2012) identified several barriers impeding their adoption, such as unclear energy savings and return of investment, lack of consumer awareness of products, and the complexity of use and deployment. This drives research for novel HEMS, including user-driven design (e.g., Stragier, Derboven, and Laporte 2012), development (e.g., Alahmad et al. 2012), and longitudinal field evaluation (e.g., Pereira et al. 2013).

We propose the FRESH hardware-software research platform for HEMS to accelerate more of such research by supporting (i) the development of innovative features in HEM applications, and (ii) their evaluation in field deployments. FRESH differs from related HEMS research platforms, such as Dehems (Liu et al. 2013), SINAIS (Pereira et al. 2012), and HomeOS (Dixon et al. 2012) by supporting a wide range of applications including environmental monitoring, non-intrusive load monitoring (NILM), an elevator energy display, and a smart thermostat, and by supporting participant engagement and field evaluations of novel HEMS concepts and products. Furthermore, unlike open source sensor platforms for smart homes which focus on applications for end-users and home occupants (e.g., Ninja Blocks, Domoticz), FRESH is also designed to facilitate field research experiments. To demonstrate the breadth of applications of FRESH, we have deployed FRESH in residential and commercial buildings, focusing on consumer-oriented applications which provide feedback and control to lay building occupants. However, this paper does not describe measurement and validation studies or user acceptance studies using FRESH.

Requirements for a HEMS Research Platform

We identified five qualities which distinguish innovative, intelligent HEMS (such as smart thermostats) from simple HEMS (e.g., basic thermostats):

i. **Internet-enabled** to allow HEM systems to communicate with servers online to post their data, and allow online clients/browsers or utilities to access or control them.
ii. **Mobile apps** to allow light-weight and more salient user interaction and engagement.
iii. **Sensor-driven** to capture and monitor more information about the built environment, occupancy, and activity to provide more context-appropriate information and services.
iv. **Adaptive algorithms** to better model activities in the home and provide more intelligent, inference-based services to users, such as pre-heating based on predicted occupancy (Lu et al. 2011; Scott et al. 2011) and target temperature preference (Nest Thermostat).
v. **High usability** to improve user understanding of HEM and facilitate the correct use of features in HEMS, particularly those for energy efficient behavior.

Established software engineering and interaction design approaches can address the former two qualities, while there remains much opportunity for innovation in the latter three qualities, along with the need to validate them. We develop these three qualities into two broad requirements for facilitating innovation in HEM features and evaluating those features.

R1) Facilitate Innovation in HEMS features by supporting:

a) **A diverse range of sensors** to better capture and monitor the built environment, occupant preferences and behavior, and HEMS user interaction.
b) **The development and integration of intelligent models** to provide improved feedback and control for energy efficiency in the home. These models can be based on data science, machine learning, energy modeling, and behavioral modeling approaches.
c) **The design of high usability user interfaces** to more effectively communicate data about the building energy usage and to allow users to more easily engage in energy efficient behavior. The research platform should support providing a wide range of numeric, interpreted, aggregated, and historical data to be rendered in the prototype interfaces. It should support the currently popular display media of web and mobile.
d) **Lowering the barrier to developing HEMS** to allow developers to focus on innovative features rather than low-level microcontroller programming or network communication by using easy-to-program, popular, open microcontroller / embedded computing platforms, and open networking, web and mobile APIs.

R2) Facilitate Field Experiments and Evaluation of HEMS by supporting:

a) **Longitudinal data acquisition and data analysis** to collect ground truth information from buildings to support A/B testing and treatment/baseline testing. Furthermore, the system will need to have robust features to run continuously over long periods by anticipating and recovering from failures (e.g., dropped Wi-Fi connections).
b) **Participant engagement** to provide messaging and alerts, obtain user feedback and opinions through surveys, and log how they interact with the HEM prototype over time.

c) **Integration with third-party HEMS** by being able to communicate via application programming interfaces (APIs) to enable commercial HEMS to be tested in instrumented environments, other than just standalone research prototypes.

FRESH Research Platform

We present the **Fr**aunhofer **E**xperimental **S**mart **H**ome (FRESH) hardware-software research platform for the rapid prototyping of home and commercial energy management systems. It consists of customizable hardware components for the addition of sensors and nodes, and extensible software components. Figure 1 illustrates its software architecture which we describe later. We next describe several feature requirements FRESH supports for prototype development and evaluation, and detail the architecture that satisfies the requirements.

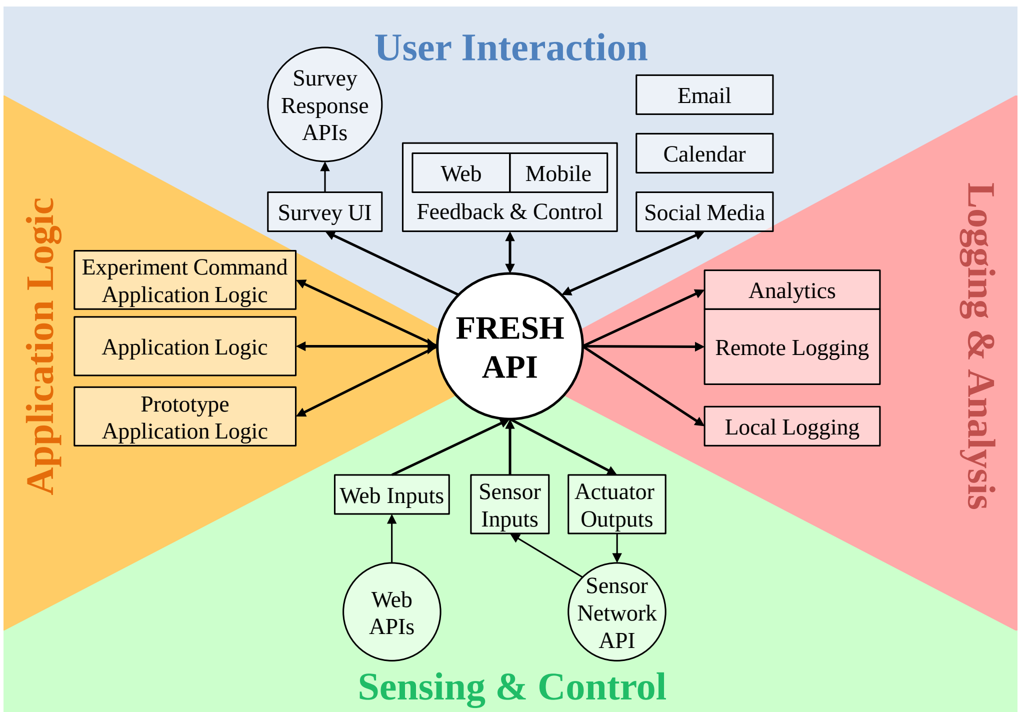

Figure 1. Software architecture showing the main functional sets of software components in the FRESH platform communicating through the FRESH API.

Hardware Sensor Nodes and Network

To support field experiments and building modeling projects, each FRESH sensor node is *expandable* to connect different sensors. Some base sensors (temperature, relative humidity, ambient light, and motion) are currently hardwired through the printed circuit board (PCB) design, while additional unused pins from the microcontroller allow new sensors to be added.

We leverage popular and easy-to-program hardware prototyping platforms to simplify the development of applications using the hardware. In particular, the FRESH sensor nodes implement a custom Arduino[1] PCB, allowing software to be implemented with the Arduino IDE and accompanying libraries. Version 1 nodes use cheaper ATmega328P microprocessors to

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[1] An open source hardware prototyping platform. http://www.arduino.cc/.

reduce cost. Version 2 nodes use ATmega2560 microprocessors which have more memory and pins to support more sensors per node, and more simultaneous capabilities (Wi-Fi connectivity, SD card storage, more sophisticated algorithms).

It may be difficult to access wall sockets to power the sensor node due to placing them in remote sections or due to the lack of available sockets (Hnat, et al. 2011). Therefore, we provide different node models powered from a battery, wall outlet, or 24VAC HVAC wires (see Figure 2a, b, c). To increase the appeal to residential users, we refined the enclosure design to reduce the size of the FRESH nodes and improve their aesthetics (from version 1 to 2).

The FRESH hardware can be operated as individual sensor nodes for quick deployments to test concepts or to monitor isolated locations, or as a sensor network to collect environmental data of a building from dispersed nodes for high fidelity monitoring. For the sensor network gateway hub, we use an embedded computer, currently the low-cost, easy-to-learn Raspberry Pi with a vibrant open source community (see Figure 2d).

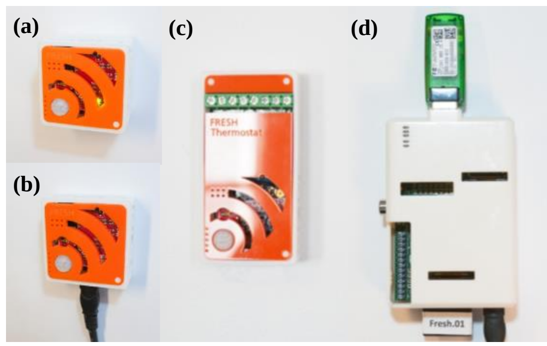

Figure 2. FRESH hardware components: (a) lithium-polymer battery-powered node, (b) slimmer wall-powered node, (c) node with relay control capabilities, and (d) gateway hub for wireless sensor network.

Software Architecture

FRESH supports the development of new features through a modular software architecture that is *event-driven* and *message-based*, using a *publish/subscribe* mechanism. Developers can build individual functionality in atomic *software components* which trigger based on subscribed input conditions and which subsequently publish an output for other components to respond to. For example, a thermostat application can be made smarter by adding an occupancy prediction component that subscribes to motion events and publishes temperature events to help inform a relay component to call for heat/cool early. FRESH specifies modular components for different functions as illustrated in Figure 1. Components communicate via a common application programming interface (API), hereafter called FRESH API.

Sensing components contain hardware and software to acquire data from physical sensors (e.g., passive infrared (PIR) sensors for motion), sensor networks (e.g., ZigBee Home Automation), or from online "virtual" sources (e.g., weather APIs, commercial HEMS product APIs). Software wrappers are provided to publish input and sensor data to the FRESH API where other components can use them for further processing. **Control** components are the counterpart to sensors and subscribe to command messages to perform actuations, e.g., turning a light on.

Application Logic components apply various application logics. For example, a basic thermostat application could have components for `TemperatureComparator`, `RelayControl`, and

`RelayActuator`. A smart thermostat application could add *prototype* application logic components such as the `OccupancyPreHeat` component to predict occupancy and determine when to start heating the building before occupants arrive. FRESH also includes *experiment command* logic components which perform administrative and participant engagement tasks for field experiments. For example, experimenters can use the `SendSurvey` component to manually send a survey popup to participants' mobile phones or even automatically trigger them given an event (e.g., send a comfort survey when temperature exceeds 80°F).

Note that each application logic component may reside on a single device or be distributed across multiple devices to deliver an end-to-end service function (e.g., compare temperature, set relay state). For example, an occupancy prediction component could be implemented in a hub computer at a deployment site or on a server in the cloud. It would just need to communicate through the FRESH API.

User Interaction (UI) components subscribe to sensor and application states, and provide feedback and control functions to end-users and home occupants through Web or mobile interfaces. For example, when the motion sensor triggers, it sends out a motion detection event to the FRESH API and a mobile device subscribing to such events can display a notification to the end-user. When the user wants to change the temperature set point, she can tap a button on a mobile device which can send a message to the FRESH API. A `Thermostat` application logic component subscribing to such messages could then determine whether to change the relay state. FRESH supports other channels for user interaction and engagement which are useful for field experiments. See the Field Experimentation Features section for more details.

Logging and Analysis components subscribe to some or all messages and store them locally (i.e., in devices deployed in the field) or remotely (e.g., on a server accessible via the Internet). The data storage format is not specified and data can be stored in databases (e.g., MySQL, Apache Cassandra, KairosDB), in cloud storage (e.g., ThingSpeak.com, Xively.com), flat files (e.g., CSV, XML JSON), etc. FRESH includes *data visualization* tools to allow experimenters to monitor real-time sensor data and to investigate historical data of deployed HEMS.

Communications API

To support event-driven messaging between components of the FRESH platform, we developed the FRESH API over the Message Queuing Telemetry Transport (MQTT), a machine-to-machine/"Internet of Things" connectivity protocol. Its lightweight design makes it ideal for embedded microcontrollers and mobile devices. It has been used for highly scalable mobile instant messaging (Zhang 2011), context-aware apps on Android phones (Ferreira 2013), and smart grid applications (St. John 2013). Therefore, MQTT is suitable for FRESH which uses sensor nodes and mobile displays. *Publisher* clients send messages to *subscriber* clients based on subscribed *topics*. Clients do not need to be aware of one another; a *broker* server mediates between the receipt and broadcasting of messages between clients.

MQTT Messages consist of a topic and payload body. The payload contains the main information of messages, which we implement as string data to improve human readability. Topics in MQTT are specified in hierarchical levels (e.g., SENSOR/1/HUMIDITY). We define the topic hierarchy in the format:

```
fraunhofer/cse/fresh/<Fresh.ID>/<Node.ID>/<action>/<metric>
```

- **Fresh.ID** denoting the gateway hub installed at a house or building
- **Node.ID** of a specific sensor node in a deployed system of multiple nodes
- **Actions** for command-based messaging so that metrics can have their values requested (`get`), reported (`measured`), modified (`set`), and commands acknowledged (`reply`).
- **Metrics** relate to *sensor* data types (e.g., temperature, humidity, motion, ambient light), *application* variables (e.g., setpoint, relays), *usage* and *experiment* events (e.g., usage, note, survey), and *administration* (e.g., boot, firmware, commandline, ipaddress).

To support a more "human friendly" topic naming, such as `fraunhofer/cse/fresh/Fresh.01/home/bedroom/get/light`, we can implement *interpreter* application logic components to translate the raw topic to the more readable topic and republish the message. To support the security of user and home data, we can leverage the user name and password mechanism in MQTT.

Field Experimentation Features

FRESH facilitates field experiments of novel energy management technologies through several software components. The `Survey` UI component supports the *experience sampling method* (Csikszentmihalyi and Larson 1987) by displaying a survey when the experimenter manually sends one or when an event automatically triggers one (see Figure 3). This can be used to collect subjective opinion data and diary/journal reports for ground truth verification.

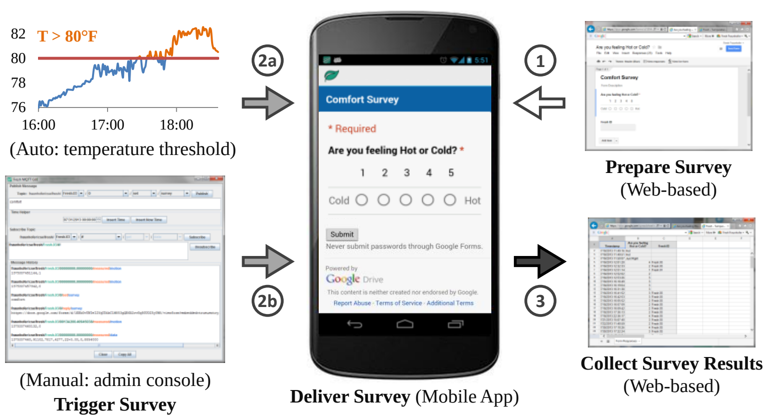

Figure 3. Triggering a web-prepared survey on the mobile app automatically or manually with the FRESH API.

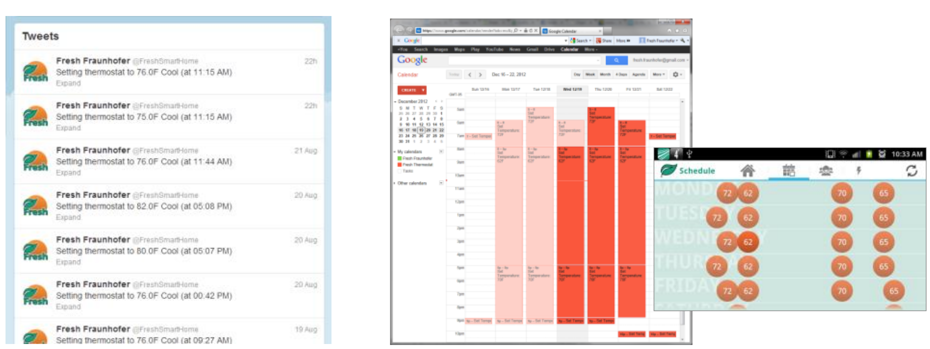

Figure 4. Integration of FRESH with online APIs for sharing via social media with Twitter (Left) and schedule management with Google Calendar (Right).

Additionally, `Email` and `Social Media` UI components provide additional means for FRESH to communicate with users by providing *notifications* and *reminders* through email and social media (e.g., Twitter, see Figure 4, Left), respectively. Finally, much functionality of HEMS is schedule-driven, so FRESH provides the `Calendar` UI component which leverages a calendar API service (e.g., Google Calendar, see Figure 4, Right). This allows non-technical experimenters to view and edit the system schedule through a familiar calendar interface.

Application Use Cases

We demonstrate the versatility of the FRESH platform to support research in energy management systems with four types of applications. Although FRESH was originally developed for homes, it has been extended and deployed in both residential and commercial buildings.

Environmental Monitoring

A basic deployment of the FRESH platform is to instrument buildings with sensor nodes to monitor environmental variables such as temperature and ambient light, and occupancy data derived from motion sensors. We have deployed FRESH in three residences and two offices over 2-5 months (e.g., see Figure 5). This is particularly useful when commissioning new buildings to collect data about potential issues. For example, Figure 6 (Right) shows the overheating of a pre-commissioned office building from Friday evening to Monday morning due to a misconfigured HVAC system. The environmental and human behavior data collected by FRESH can also be used for other analytical and intervention applications, which we describe next.

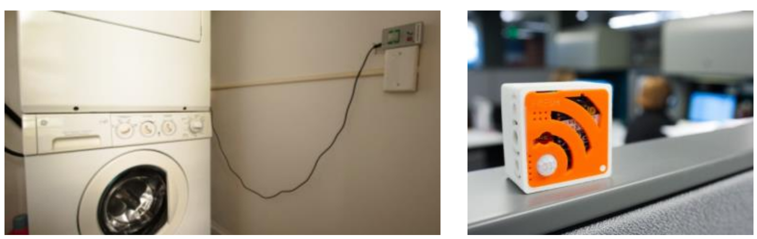

Figure 5. FRESH nodes with environmental sensors in a residential home (Left, ver.1) and an office (Right, ver.2).

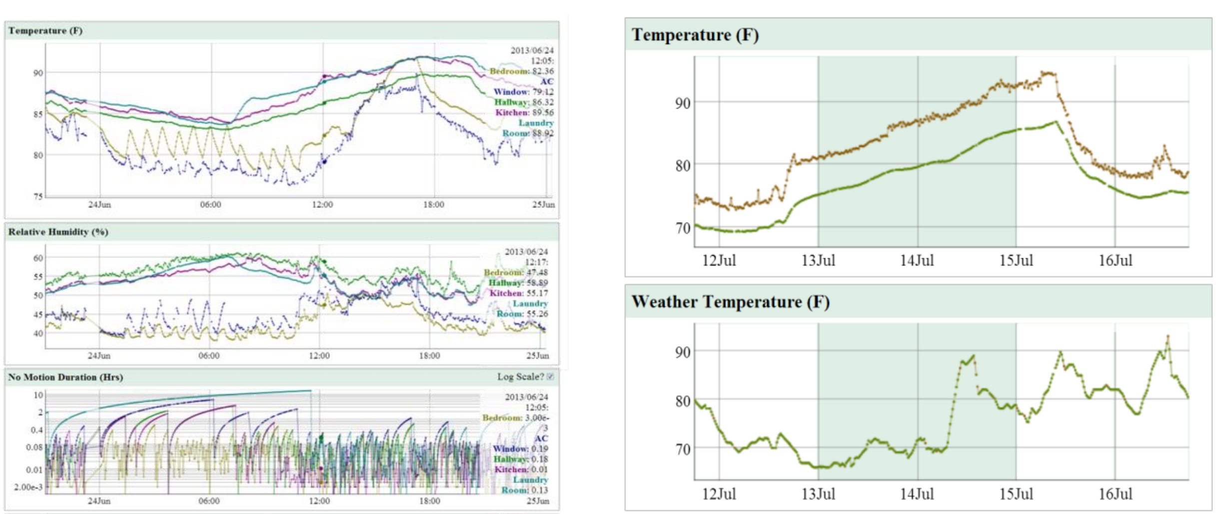

Figure 6. Environmental and occupancy data collected in a residential apartment unit (Left) and office (Right).

Non-Intrusive Load Monitoring and Plug Load Control

Energy is consumed in households by a range of appliances. Building analytics to informing occupants of individual appliance loads can help provide salient recommendations on how to reduce energy consumption of these loads. We are developing non-intrusive load monitoring (NILM) algorithms that can help provide this richer information without the need for installing sensors at individual loads (e.g., Zeifman, Roth, and Stefan 2013; Zeifman 2012). Ultimately, this would require installing a sensor only at one point, such as the circuit breaker or smart meter. As we refine our NILM algorithms, FRESH sensors can be deployed to acquire real-world and real-time data at plug loads to help train the statistical models.

While FRESH hardware is not specifically engineered to interface with circuit breakers due to safety certification requirements, there are many commercial off-the-shelf solutions which FRESH can communicate with to acquire data. In particular, we have written software wrappers to interface with the APIs of the TED 5000 and eGauge energy meters (e.g., see Figure 7, Left).

At the plug level, FRESH nodes can be installed with current transformer (CT) clamps to monitor the use of individual appliances and collect ground truth data. The data can be collated into a common database for subsequent analysis or communicated in real-time to drive applications for home energy displays (HED) or plug control. To help manage energy consumption at the appliance level, FRESH nodes can be interfaced with plug load controls to automatically turn devices on or off. FRESH has been integrated with the PowerSwitch Tail II for simple on/off control. FRESH can also be interfaced with Underwriters Laboratories (UL) certified plug load meters which have software APIs, such as the Modlet by ThinkEco.

Figure 7. FRESH installed to support research in non-intrusive load monitoring (NILM): acquiring data from eGauge metering units in university housing via an API (Left), and metering a mini-fridge at the plug level (Right).

Elevator Energy Display

We have deployed FRESH to monitor the energy consumption of a novel energy-efficient elevator with a regenerative drive. Therefore, we are also able to measure the energy that the elevator regenerates (see Figure 8). The elevator also has other energy efficient features, such as LED lighting which turns off after a period with no passengers. We have used FRESH to evaluate this and other energy efficiency features in the elevator (see Figure 9).

We demonstrate the usefulness to lay users of instrumenting the elevator by introducing the concept of an Elevator Energy Display (EED) that displays the energy consumption of the elevator to inform the passenger of its energy efficiency features. Metering data is sent over Modbus from a Dent Power Scout 3 energy meter to the Obvius AcquiSuite A8110 DAQ server and then over Ethernet to the LAN. FRESH leverages the Obvius HTTP API to acquire energy consumption/regeneration data at a 1/sec sampling rate. Unlike typical home or commercial building energy meters and displays, the high sampling rate is crucial to capture instances of energy regeneration because of the short travel times. Leveraging the UI capabilities of FRESH, we installed an Android tablet in the elevator cab for the energy display. Other environmental data are collected by a FRESH sensor node and from other sensors on the tablet (e.g., occupancy, ambient light level, barometer to estimate floor level, acceleration to detect changes in motion). Together with sensed data and inferred actions, FRESH can be used to provide context-aware messaging, e.g., to support building sustainability campaigns by showing that energy is regenerated when a fully loaded cab descends.

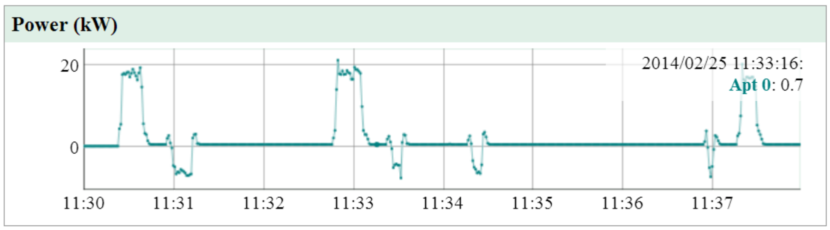

Figure 8. Data from FRESH showing energy consumption and regeneration of an energy-efficient elevator.

Figure 9. Elevator instrumented in the machine room with an electric meter and DAQ server (Left) and in the cab with a FRESH node and Android tablet (Right) to implement an Elevator Energy Display (EED).

Smart Thermostat

Heating and cooling in buildings contribute to the highest portion of energy consumption in residential buildings (45%, DOE 2011). Recently, smart thermostats have introduced many innovative features to help drive further energy savings (e.g., Nest Learning Thermostat, EcoBee, Radio Thermostat). Similarly, research labs are increasingly developing novel machine learning algorithms to capture energy saving opportunities via occupancy prediction (e.g., Lu et al. 2010, Scott et al. 2011). Furthermore, Sachs and colleagues (2012) emphasize the need to improve thermostat effectiveness. FRESH is well positioned to support the rapid prototyping of smart thermostats features based on actual user behaviors.

We have built a FRESH thermostat to control central HVAC systems in residential homes and plug-controlled window AC units. For central HVAC control, the FRESH thermostat can interface with the relay wires (see Figure 10, Middle), or through the software API of smart thermostats (e.g., Radio Thermostat's HTTP API). The FRESH thermostat can also be set up as an "interceptor" data logger by reading the relay states of control and test thermostats (e.g., see

Figure 10, Left). For local temperature control, FRESH can be used for plug load control of window AC units and fans (see Figure 10, Right).

Leveraging the FRESH communication API, we have built two user interfaces (UIs) for the FRESH thermostat as a mobile app and as a web interface using Android and open web technologies, respectively (see Figure 11). The UI can be easily extended to evaluate different behavioral interaction concepts (e.g., Gamification, social comparison via social media).

The FRESH thermostat can also be used to evaluate intelligent algorithms for smart thermostats. Figure 12 demonstrates evaluating the PreHeat algorithm (Scott et al. 2011) for predicting occupancy on motion data collected with a FRESH deployment. The algorithm can also be implemented to run in the FRESH hardware to evaluate its active performance.

Figure 10. Different setups for the FRESH Thermostat: interfaced with an analog and smart thermostat to monitor their relay states for controlled experiments (Left), interfaced directly to control the central HVAC (Middle), and interfaced with a plug-controlled fan (Right).

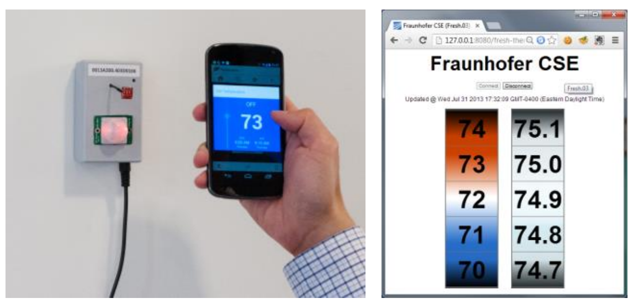

Figure 11. Flexible FRESH thermostat user interface with a mobile app (Left) and web interface (Right).

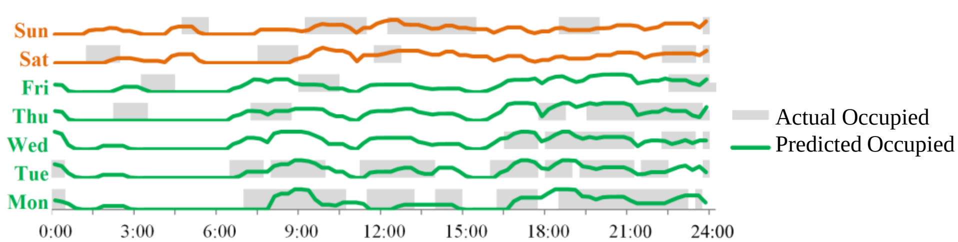

Figure 12. Occupancy data of a home kitchen collected with FRESH compared against our implementation of the PreHeat occupancy prediction algorithm (Scott et al. 2011).

Conclusions and Future Work

We have presented the FRESH research platform to accelerate the innovation of residential and commercial building energy management systems and facilitate their validation.

FRESH includes several features to support developing novel software and hardware features and to support the integrated evaluation of prototype and early commercial products along the spectrum of energy management systems and services. We have demonstrated its flexibility with four applications in environmental modeling, non-intrusive monitoring and plug load control, elevator energy displays, and smart thermostats.

We will use FRESH as a research tool to validate novel energy management solutions and behavioral intervention techniques, and evaluate their effectiveness in field experiments. We also intend to expand the technical capabilities of FRESH to support research in auto-demand response (ADR) through Open ADR and smart home integration, e.g., with ZigBee Home Automation to support research driven by utilities and broadband service providers.

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