HeatProbe: a Thermal-based Power Meter System for Tracking Per-user Power Consumption

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Abstract. This paper proposes HeatProbe, a per-user power meter system that uses thermal imaging to track the power consumption of individual users in a shared space. The per-user power consumption data produced by this system is helpful in designing personalized feedback to promote power-saving behavior.

Keywords: Power Consumption Monitoring, Per-user Power Meter.

1 Introduction

The United Kingdom Office for National Statistics [2] reported that domestic power consumption in the UK increased by 36 percent between 1971 and 2001. In an effort to provide energy-use feedback on this rapid increase in energy consumption, power metering systems such as ElectriSense [5] and Viridiscope [6] enable tracking of per-appliance power consumption by analyzing the electro-magnetic signals of appliances. However, appliances in a shared space are often not exclusively used by one user. Without a one-to-one mapping of appliances and users and per-appliance power consumption data, it is not possible to calculate per-user power consumption. Recognizing this difficulty, Hay *et al.* [3] proposed the Personal Power Meter, which apportions total power consumption to individual users by analyzing appliance usage data. However, this approach requires manual effort in labeling appliance usage information, and is therefore only semi-automated.

To track per-user power consumption, this study proposes HeatProbe, a per-user power meter system that automatically assigns total power usage to users in a shared space by tracking the heat patterns produced by their appliance usage. This approach is based on *indirect sensing* [4]. Rather than directly sensing the power line connecting to an appliance, HeatProbe uses a thermal camera and computer vision techniques to identify the heat patterns of running appliances. Figure 1 shows thermal images of appliances captured at two different times. The left thermal image (Fig. 1(a)) shows that appliances are near room temperature in the power off state. The right thermal

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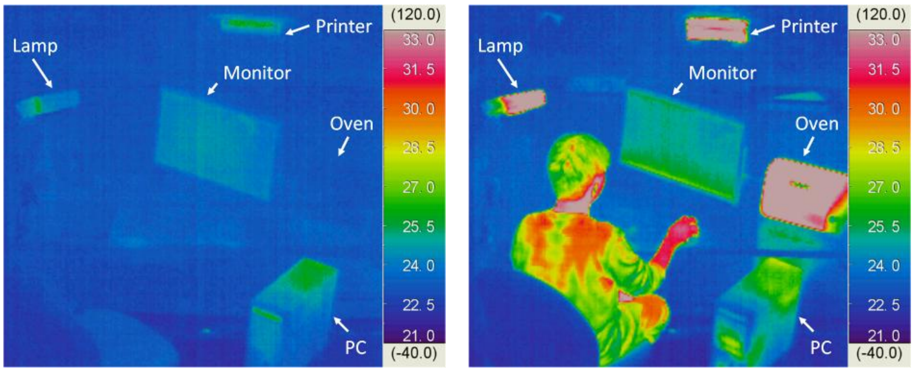
image (Fig. 1(b)) shows that a user has entered the space and turned on appliances (e.g., a lamp, a monitor, a printer, a PC, and an oven), whose temperatures now exceed room temperature. Since running appliances produce some heat as a byproduct of their operation, HeatProbe can determine the change in an appliance's power state by tracking its surface temperature. A rising surface temperature means that the appliance has been turned on, while a declining surface temperature means the appliance has been turned off. A steady surface temperature means no change in the appliance's power state.



(a) Before turning on appliances

(b) After turning on appliances

Fig. 1. Two thermal image frames captured (a) before and (b) after appliances are turned on.

2 HeatProbe Design

Figure 2 presents the HeatProbe system design. HeatProbe consists of two sensors: a thermal camera, which produces heatmap images (Fig. 1) of appliances in a shared space, and a power meter sensor installed at the main power switch, which produces continuous power readings (Fig. 3). HeatProbe operation includes the following steps. (1) A heatmap image segmentation algorithm takes each heatmap image and partitions it into multiple heat segments, where each segment corresponds to either a heated (running) appliance or a human body. For example, after segmenting each heatmap image (Fig. 1(b)), the system locates six heat segments corresponding to five appliances and one human body. The system the computes the surface temperature of each appliance heat segment. A rising (falling) surface temperature, based on analysis of subsequent heatmap images, indicates a *thermal event* that represents the on/off power state change of an appliance. Likewise, the system identifies *human events*, which represent changes in the user's locations, by analyzing subsequent heatmap images. (2) Using power readings from the power meter, power consumption detection then identifies *power events* correlated to a change in an appliance's on/off power state. For example, the system identifies PC and LCD monitor power-on events around the 2nd minute in Fig. 3. (3) The power-thermal join algorithm calculates an appliance's power consumption from matching power events (i.e., power-on/–off events detected from the power meter) to thermal events (i.e., thermal-rising/-falling events detected from the thermal camera) based on the events' time proximity. This calculation requires joining power and thermal events. This study uses two matching rules: (a) a power-on(-off) event must correspond to a thermal event with rising(falling) appliance surface temperature, and (b) if multiple event matches are possible, the system chooses an event occurring within the closest time proximity. (4) The power-thermal-user join algorithm calculates each user's power consumption by summing all power consumption from appliances whose locations are closest to that user. This calculation pairs power-thermal events (obtained from the previous step) with human events (obtained from the first step). Note that each power-thermal event includes the appliance's location and power consumption, while each human event records the user's location. The event matching rule pairs power-thermal and human events based on location proximity to attribute power consumption from power-thermal events to the appropriate user. The output of this step is per-user power consumption in the shared space.

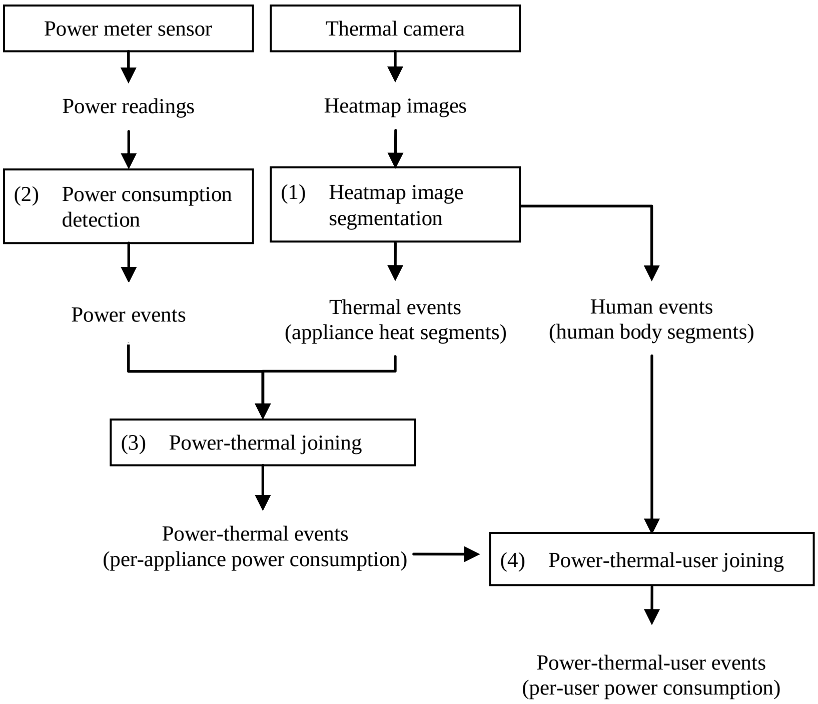


Fig. 2. HeatProbe system design

3 Preliminary prototype and experiment

A prototype was created to test the feasibility of the HeatProbe system. A NEC TH7102MX thermal camera was mounted to the ceiling of a shared space. Figure 1 shows thermal images of five appliances recorded by this camera. A Nonintrusive Load Monitoring power meter was then installed at the main power switch. The prototype used the Nonintrusive Load Monitoring (NILM) technique [1] to identify power events. A 2D median filter smoothed out the heatmap images based on temperature values of pixels prior to image segmentation. A human suppression algorithm removed human body from the foreground. A test subject performed scripted actions by turning on/off these appliances. Though the initial results are promising, we look forward to completing the HeatProbe prototype and conducting additional experiments to validate this thermal-based approach.

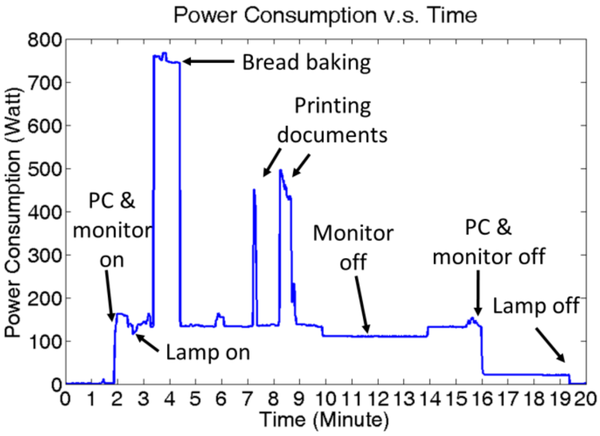


Fig. 3. Power readings

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