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A framework of energy efficient mobile sensing for automatic user state recognition

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A Framework of Energy Efficient Mobile Sensing for Automatic User State Recognition*

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ABSTRACT

Urban sensing, participatory sensing, and user activity recognition can provide rich contextual information for mobile applications such as social networking and location-based services. However, continuously capturing this contextual information on mobile devices consumes huge amount of energy. In this paper, we present a novel design framework for an Energy Efficient Mobile Sensing System (EEMSS). EEMSS uses hierarchical sensor management strategy to recognize user states as well as to detect state transitions. By powering only a minimum set of sensors and using appropriate sensor duty cycles EEMSS significantly improves device battery life. We present the design, implementation, and evaluation of EEMSS that automatically recognizes a set of users' daily activities in real time using sensors on an off-the-shelf high-end smart phone. Evaluation of EEMSS with 10 users over one week shows that our approach increases the device battery life by more than 75% while maintaining both high accuracy and low latency in identifying transitions between end-user activities.

Categories and Subject Descriptors

C.3.3 [**Special Purpose and Application Based Systems**]: Real-time and embedded systems

General Terms

Design, Experimentation, Measurement, Performance

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Keywords

Energy efficiency, Mobile sensing, EEMSS, Human state recognition

1. INTRODUCTION

As the number of transistors in unit area doubles every 18 months following Moore's law, mobile phones are packing more features to utilize the transistor budget. Increasing the feature set is mostly achieved by integrating complex sensing capabilities on mobile devices. Today's high-end mobile device features will become tomorrow's mid-range mobile device features. Current sensing capabilities on mobile phones include WiFi, Bluetooth, GPS, audio, video, light sensors, accelerometers and so on. As such the mobile phone is no longer only a communication device, but also a powerful environmental sensing unit that can monitor a user's ambient context, both unobtrusively and in real time.

On the mobile application development front, ambient sensing and context information [1] have become primary inputs for a new class of mobile cooperative services such as real time traffic monitoring [2], and social networking applications such as Facebook [3] and MySpace [4]. Due to the synergistic combination of technology push and demand pull, context aware applications are increasingly utilizing various data sensed by existing embedded sensors. By extracting more meaningful characteristics of users and surroundings in real time, applications can be more adaptive to the changing environment and user preferences. For instance, it would be much more convenient if our phones can automatically adjust the ring tone profile to appropriate volume and mode according to the surroundings and the events in which the users are participating. Thus we believe user's contextual information brings application personalization to new levels of sophistication. While user's context information can be represented in multiple ways, in this paper we focus on using user state as an important way to represent the context. User state may contain a combination of features such as motion, location and background condition that together describe user's current context.

A big hurdle for context detection, however, is the limited battery capacity of mobile devices. The embedded sensors in the mobile devices are major sources of power consumption.

For instance, a fully charged battery on Nokia N95 mobile phone can support telephone conversation for longer than ten hours, but our empirical results show that the battery would be completely drained within six hours if the GPS receiver is turned on, whether it can obtain GPS readings or not. Hence, excessive energy consumption may become a major obstacle to broader acceptance of context-aware mobile applications or services, no matter how useful the service may be. In mobile sensing applications, energy savings can be achieved by shutting down unnecessary sensors as well as carefully selecting *sensor duty cycles* (i.e., sensors will adopt periodic sensing and sleeping instead of being sampled continuously). In this paper, we define *sensor sampling duration* as the length of the time a sensor is turned ON for active data collection. We define *sensor sleeping duration* as the time a sensor stays idle. The sensing and sleeping durations, or sensor duty cycles, are generally referred to as *sensor parameters*.

To address the problem of energy efficiency in mobile sensing, we present the design, implementation, and evaluation of EEMSS, an energy efficient mobile sensing system that incorporates a hierarchical sensor management scheme for power management. EEMSS uses a combination of sensor readings to automatically recognize user state as described by three real-time conditions; namely motion (such as running and walking), location (such as staying at home or on a freeway) and background environment (such as loud or quiet). The core component of EEMSS is a sensor management scheme which defines user states and state transition rules by an XML styled state descriptor. This state descriptor is taken as an input and is used by our sensor assignment functional block to turn sensors on and off based on a user's current condition.

The benefits of our sensor management scheme are threefold. First, the state description mechanism proposed in this paper is a flexible way to add/update user states and their relationship to the sensors. For instance, to account for emerging application needs new states and sensors may be incrementally added to the state description. Second, to achieve energy efficiency, the sensor management scheme assigns the minimum set of sensors and heuristically determines sampling lengths and intervals for these set of sensors to detect user's state as well as transitions to new states. Lastly, our sensor management scheme can be easily extended as a middleware that manages sensor operations and provides contextual information to higher layer applications with multiple types of devices and sensors involved.

EEMSS is currently implemented and evaluated on Nokia N95 devices. In our EEMSS implementation, the state description subsystem currently defines the following states: "Walking", "Vehicle", "Resting", "Home_talking", "Home_entertaining", "Working", "Meeting", "Office_loud", "Place_quiet", "Place_speech" and "Place_loud". All these states are specified as a combination of built-in Nokia N95 sensor readings. The sensors used to recognize these states are accelerometer, WiFi detector, GPS, and microphone. EEMSS incorporates novel and efficient classification algorithms for real-time user motion and background sound recognition, which form the foundation of detecting user states. We have also conducted a field study with 10 users at two different university campuses to evaluate the performance of EEMSS. Our results show that EEMSS is able to detect states with 92.56% accuracy and improves the battery lifetime by over 75%, compared to existing results. Note that although in this paper we focus only on states that can be detected by integrated sensors on mobile devices, our sensor management scheme is general enough that one can apply our infrastructure to mobile sensing systems that involves more sensors and devices.

The remainder of this paper is organized as follows. In Section 2, we present relevant prior works and their relations to our study. In Section 3, we describe the sensor management scheme which is the core component of EEMSS. In Section 4, we introduce a case study of EEMSS on Nokia N95 devices and present the system architecture and implementation. In Section 5, we list the empirical results of different sensor power consumptions as one of the motivations of our system design and discuss the sensor duty cycling impact on system performance. In Section 6, we propose novel real-time activity and background sound classification mechanisms that result in good classification performance. The user study is presented in Section 7, where we evaluate our system in terms of state recognition accuracy, state transition discovery latency and device lifetime. Finally, we present the conclusion and our future work direction in Section 8.

2. RELATED WORK

There has been a fair amount of work investigating multi-sensor mobile applications and services in recent years. The concept of sensor fusion is well-known in pervasive computing. For example, Gellersen *et al.* [5] pointed out the idea that combining a diverse set of sensors that individually captures just a small aspect of an environment may result in a total picture that better characterizes a situation than location or vision based context.

Motion sensors have been widely used in monitoring and recognizing human activities to provide guidance to specific tasks [6, 7, 8]. For example, in car manufacturing, a context-aware wearable computing system designed by Stiefmeier *et al.* [6] could support a production or maintenance worker by recognizing the worker's actions and delivering just-in-time information about activities to be performed. A common low cost sensor used for detecting motion is the accelerometer. With accelerometer as the main sensing source, activity recognition is usually formulated as a classification problem where the training data is collected with experimenters wearing one or more accelerometer sensors in a certain period. Different kinds of classifiers can be trained and compared in terms of the accuracy of classification [9, 10, 11, 12]. For example, more than 20 human activities including walking, watching TV, running, stretching, etc. can be recognized with fairly high accuracy [12].

Most existing works to accurately detect user state require accelerometer sensor(s) to be installed on pre-identified position(s) near human body. Our aim is to avoid the use of obtrusive and cumbersome external sensors in detecting user state. As such, we remove the need to strap sensors to human body. EEMSS is able to accurately detect human states, such as walking, running and riding a vehicle by just placing the mobile phone anywhere on the user's body without any placement restrictions. In this context it is worth noting that Schmidt *et al.* [13] first proposed incorporating low level sensors to mobile PDAs/phones to demonstrate situational awareness. Several works have been conducted thereafter by using the commodity cell phones as sensing.

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