論文内容の要旨

論文題目

A Machine Learning Approach for User-centric Context-aware Computing

（機械学習に基づくユーザ中心のコンテキスト適応型コンピューティングに関する研究）

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Research in Ubiquitous Computing has arrived at a crossroad: A point of convergence where a technology proliferated environment meets with the ability of people to interact with, and make use of, the possibilities that this technology creates. Advances in the various fields of technology allow us to create artifacts and environments that provide computing and communication resources. The understanding of how humans will interact and make use of such systems is however largely unresolved and often not addressed in current research. A key to understanding such systems and their use can derive from the observation that humans usually interact with others or their environments implicitly considering the "situational" or "context" information. Therefore, context-aware computing, or more specifically how to create applications that are context-aware, is a central issue for Ubiquitous Computing research.

The idea of "context-aware computing" is to have computers understand the real world so that humans can interact with the technology augmented environments at a much higher abstraction level, hence to make the interactions much more pleasant or invisible to human users. A simple example of a context-aware computing system is a smart home, which can automatically adjust the air-conditioner and light switches based on the time of a day, the current temperature and brightness of the room, and the residents' activities and preferences. However, based on our research, we believe four challenges must be solved to build such a system:

- **What does context mean and how to acquire them?**
  What does context mean and how is it connected to situations in the real world? There is still a fundamental lack of understanding in terms how contexts relate to situations and how general context information can be used to help enhance applications. In addition,

acquiring context is a prerequisite for any context-aware system. Generally context acquisition can be seen as the process where the real situation in the world is captured, the significant features are assessed, and an abstract representation is created, which is then provided to components in the system for further use.

- **How to use context?**
  Assuming that context is available in a system, then we must ask the questions what context is useful for, or what type of applications can be enhanced? Since different applications may need different types of context, these questions also relate to the previous challenge.
- **How to connect context acquisition and context usage?**
  It is easy to understand in a location-aware system, where a close relationship exists between context acquisition and context use, most often the location sensor is attached to the device using position as context. In more general environments context use and context acquisition is distributed. This makes it obvious that mechanism to connect context acquisition and context use become essential. Furthermore, since a context-aware computing system usually reflects how a user will act in certain situations, it is crucial for the system to understand what is the user's normal action in such situations, or what is his action in a rarely abnormal situation.
- **How the users react to context-aware systems?**
  When systems are context-aware their behavior is dependent on the context of use or the general situation of use. The ultimate goal is to make systems in such a way that they react as anticipated by the user. In real life however this creates complex problems, in particular if the system reacts differently from the users expectations. Two critical issues are how can the user understand the system and its behavior? And how to give the user control over the system?

The research presented in this thesis will discuss all the four challenges, among which we specifically emphasis on the third one, because it is the core to interconnect others, and reflect users' behaviors in certain situations. Some of these behaviors can be described as simple rules. For instance, in the previous example, the smart home can mimic user's behavior as "if a user enters a dark room, turn on the light." However, the real world is too complex to be fully represented by rules. As asserted by former United States Secretary of Defense Mr. Rumsfeld, "There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. These are things we do not know we don't know." Based on rigorous logic, we can find four possibilities of our knowledge about human behavior: known knowns, known unknowns, unknown knowns, and unknown unknowns.

The first possibility, known knowns, means we know user's certain behavior in a situation, such as the "turn on light" example. Although we can explicitly describe these "knowns" as rules, as the number of rules in- creases, it may become difficult to coordinate rules in different situations. The second possibility, known unknowns, means we know we do not know user's certain behavior in a situation. For instance, although we know different users may have different preferences of TV programs, we do not know whose preference is what unless we observe or learn from their fore- passed behaviors. The third possibility, unknown knowns, means we do not know that we know user's certain behavior in a situation. For instance, although people usually have some habits of saying, they are not aware of them until others point them out. These behaviors can also be "discovered" by observing or learning from their fore-passed behaviors. The forth possibility, unknown unknowns, are the "true" unknowns, which likes a whole new universe parallel with our current one. As a result, in order to explore the known unknowns and unknown knowns of user behaviors, we use machine learning approach to build the relationship between context acquisition and context usage. This approach also helps us to coordinate the complicated known knowns, and reduce the unknown unknowns.

The objective of this thesis is to answer the four challenges faced when building the user-centric context-aware computing system. In particular the focus is on using low-end, low-price computing and communication technology in order to identify solutions that could be economically deployed in everyday artifacts and environments in the near future.

The methods used in this thesis include systematically surveying literatures and available information, designing and implementing prototypes to prove the feasibility of the proposed ideas, creating models and concepts that generalize what was learned from the prototypes, and evaluation of the proposed solutions.

By reviewing the previous works, we first clarify the definition of context and context awareness. Then we provide a general architecture of user-centric context-aware computing system, which has four components: 1) context acquisition, 2) context-aware applications, 3) context adaptation, and 4) user interaction.

We first review literatures of context acquisition, and survey the nine requirements of context acquisition, and then we briefly introduce the twelve different sensing technologies for context acquisition. We select a group of sensors from these twelve technologies to build a multi-modal sensing system in an indoor environment. By evaluating their relevance with our context-aware applications, we narrow them down to particularly useful ones.

As to the applications of our context-aware computing, we focus on context-aware applications to facilitate users operation of home appliances to meet their goals of comfort and energy efficiency. We design and implement two systems called Synapse and Gynapse respectively. Synapse aims at providing the user with dynamic services that adapt to changing environment based on their habits, so as to make the user's life more comfortable. It is a hybrid context-aware service platform, which uses learning and rule-based engines to represent users preferences of services, and facilitates users operation of home appliances based on their preferences. Gynapse aims at reducing the energy waste of home appliances, by switching them according to user's usage. It is a context-aware power management system, which uses multi-modal sensors to predict the exact usage of each device, and then switches their power modes based on predicted usage to maximize the total energy saving under the constraint of required response time.

Several approaches are available for connecting context acquisition and context usage. We mainly use the machine learning approach, because of its capability and flexibility. By comparing the literatures of decision trees, reinforcement learning, genetic algorithms, neural networks, and dynamic bayesian networks, we find dynamic bayesian networks, including Hidden Markov Model, and Hierarchical Hidden Markov Model, is a appropriate method for user-centric context-aware computing. We implement and evaluate dynamic bayesian networks in our Synapse and Gynapse applications. However, an inevitable problem of machine learning approach is it cannot achieve 100% accuracy. Therefore, we also use rule-based approach to complement the system.

Based on our research, we find the users are most annoyed by two problems of context-aware computing system: 1) they are afraid of losing final control to computers, and 2) they are disturbed by wrong assistance. To solve the first problem, we use both automation and recommendation methods to provide service to users, so they can make the final decision. To solve the second problem, we collect user's feedback to improve the accuracy, and also use rule-based system for complementary.