An Ontology-Based Reasoning Approach Towards Energy-Aware Smart Homes

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***Abstract*-We present an ontology-based reasoning approach for saving energy in a smart home setting where a mobile phone can serve as a generic sensor which can collect the inhabitant's contextual data. The paper details an ontology that describes the smart home domain and a prototype to test the system. Finally, we conclude with lessons learned from our work in developing an energy-aware smart home prototype and suggestions for future work.**

I. INTRODUCTION

Due to recent environmental problems such as global warming, sustainability has become the most important issue in this century. Therefore, the industries focus on green products that consume less, renewable energy. The IT technologies to solve energy and environmental problems are referred to green computing or green IT, and divided into two types: Green of IT and Green by IT. Green of IT attempts to reduce the energy consumed by IT equipments (e.g., PC, server, consumer products, network equipments), which accounts for 2% of the total energy consumption—equivalent to the energy consumed by the aerospace industry. Green by IT promotes the energy reduction in non-IT areas, constituting 98% of the total energy consumption. For instance, online education, tele-conferencing, e-commerce, and e-government would mitigate the CO_2 emissions since they eliminate the needs for travel and paper use. Furthermore, intelligent IT services that can assist the users with eco-friendly decision-making have been emerged; for example, the Horvitz' group at Microsoft Research [4] has built a prototype traffic service that predicts traffic conditions in the near future and reports congestion in the Greater Seattle area to the service subscribers.

As an effort to reduce the energy consumed by IT devices, we present a framework that can control electronic devices in a non-intrusive manner for saving home energy where the mobile phones can serve as generic sensors which can collect the inhabitant's contextual data (e.g., physical activities, locations, schedules). In designing the system, we consider the consumer's convenience as a critical factor that determines the success of this system.

A study involving 10,000 consumers in 10 European countries [5] has reported that 80% of the respondents have shown concerns in environmental problems (80% of the sample population) and yet they take little actions to reduce energy consumption at homes; on average they carried out 1.4 of their 6 key energy efficient behaviors (i.e., cut down on heating and air conditioning, cut down on lighting and use of home appliances, took initiatives to save energy at work, used their vehicles less; changed your car to another one that consumes less fuel, used public transport more) during a year. The report suggests that IT technology and visualization of energy consumption can bridge this attitude-behavior gap, as supported by several studies [1, 2, 7, 16, 17]. As such an effort, Google has offered the web-based energy monitoring service PowerMeter [14] which visualizes home energy consumption.

This paper presents an ontology-based reasoning approach to control the electronic devices to reduce energy when various contextual data are usable. The rest of this paper details the system, an ontology, and a prototype to verify the framework. We conclude with lessons learned from implementing the prototype and future work.

II. AN ENERGY-AWARE HOME FRAMEWORK

A. A Framework

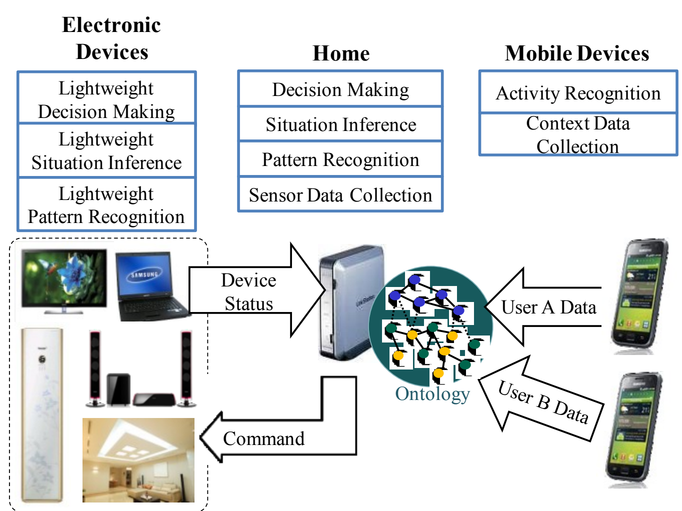

Figure 1.An Energy-Aware Home Framework

Figure 1 shows our system framework which consists of a home server (or a cloud server) and mobile phones. The server collects various data such as the resident's location and the electronic devices' power status (i.e., power-on, power-save, power-off, plugged-out), and determines their next status for the purpose of energy reduction. Electronic devices are presumed to be connected to a smart controller [13, 15], which can report the device's power status to the server and control the device as commanded from the server.

Figure 2.The Smart Home Emulator Interface. Four family members are represented as pink-colored circles.

Although not shown in this framework, we assume that other information such as weather and room temperatures can be collected through the Internet and wireless sensors if necessary. Each resident's mobile phone serves as a generic sensor which can report its owner's contextual data (e.g., locations, schedules, preference). Furthermore, we expect that sophisticated mobile devices can replace the home server.

As illustrated in the figure 1, each device in the framework can carry out lightweight pattern recognition, inference, and decisions with only the information available to it. For instance, a lighting device or a computer monitor can determine whether to maintain its power status or not depending on the detection of people in its close proximity. Since the device's computing performance may be limited, complicated decisions that take into account each inhabitant's preference and other device's status would not be made by the device alone.

III. AN ENERGY-AWARE HOME ONTOLOGY

In order to verify our framework, we defined a two-day scenario that involves a family of four members: a father, a mother, a sixteen-year-old daughter, and a two-year-old boy. Figure 2 shows the emulator screen where the emulator user manipulates the avatars to move and control the devices with mouse and keyboard. When such event occurs, the system can adjust the device status.

A. Energy-Aware Home Scenarios

To create a believable scenario, we asked 5 members of our research team to collect their daily energy usage patterns at home. Selected patterns are then modified and combined into six energy usage situations (Friday morning/afternoon/evening situations and Saturday morning/afternoon/evening situations). Each situation is divided into 1-8 scenes each of which describes the family members' activities and their corresponding control of electronic devices, as some of the scenes are presented in Figure 3 and Figure 4. Overall, 25 scenes were created for the prototype scenario.

Situation Case	Scene	Activity Descriptions
Friday Morning C1	S01	A1. When alarmed, the father and the mother woke up. A2. The father took a shower. A3. The father dried the hair and dressed up in the powder room.
Friday Afternoo n C2	S01	A1. A robot vacuum cleaned the house when all of the family members were out. A2. After cleaning, the robot returned to the docking system for charge.
Saturday Evening C5	S01	A1. The daughter turned on the television set and went to the kitchen to cook the dinner. A2. She went to the living room to watch a DVD title while having her dinner.

Figure 3.Scenario Scene Examples

Scenario	C1-S01	The father woke up	
Contexts	User	Father, Mother, Son	
	Activity	Wake up	
	Device	(Room1) humidifier, light (Bathroom) light, thermostat	
	Sensor	Location, luminous intensity, actions	
Control	A1	User Contexts	~location sensor: family members are in Room 1 ~activity sensor: sensed that the father and the mother got up ~luminous sensor: senses luminous intensity
		Device Context	~humidifier: ON ~lighting: PLUG-OUT
		Decision Making	~humidifier: plug-out when all the family members in Room1 are up (maintains ON in this case since the son is asleep) ~lighting: on when all the users in the room are up and the luminous intensity is low (maintains PLUG-OUT in this case since the son is asleep)

Figure 4. Device Control Specification for the case C1-S01

B. Ontology Engineering

We listed 174 keywords based on the smart home scenario and specifications. We then identified 345 classes during the conceptualization process. Our system employs an OWL-DL ontology to represent the various types of classes and their relationships [10]. Figure 5 shows parts of our ontology, which is engineered using the ontology editor Protégé (version 4.0) software package [11]. Everything in the GreenHome can be categorized either Material or Immaterial at the top level, where the Material class deals with physical concepts (i.e., device, goods, person, sensor) and the Immaterial class handles abstract concepts (i.e., measurement, policy, situation, intent).

- Thing
  - GreenHome
    - Immaterial
      - Measurement ▶
      - Policy ▶
      - Situation
        - Activity ▶
        - Behavior ▶
        - Schedule ▶
        - Space
          - SpaceByStatus
            - AllSleepingSpace
            - DarkSpace
            - EmptySpace
            - NotEmptySpace
          - SpaceByFunction
        - Time ▶
      - Intent ▶
    - Material
      - Device
        - DeviceByFunction
          - BeautyDevice ▶
          - CleaningDevice ▶
          - CommunicationDevice ▶
          - ControlDevice ▶
          - CookingDevice ▶
          - HeatingDevice ▶
          - ITDevice ▶
          - LightingDevice ▶
          - MediaDevice ▶
          - SanitationDevice ▶
          - SecurityDevice ▶
        - DeviceByLocation
          - LivingRoomDevice
          - MultipurposeRoomDevice
          - RoomDevice ▶
          - VerandaDevice
          - KitchenDevice
          - PowderRoomDevice
          - FrontDoorDevice
          - BathRoomDevice ▶
        - DeviceByStatus
          - DeviceVolumeStatus
            - CurrentVolumeStatusDevice ▶
            - GoalVolumeStatusDevice ▶
          - DevicePowerStatus
            - CurrentPowerStatusDevice
              - CurrentOffDev
              - CurrentOnDev
              - CurrentOutDev
              - CurrentSaveDev
            - GoalPowerStatusDevice ▶
          - DeviceIlluminationStatus
            - CurrentIlluminationStatusDevice ▶
            - GoalIlluminationStatusDevice ▶
        - DeviceByPowerMode
          - BatteryPowerModeDevice
          - MechanicPowerModeDevice
          - NonSavingModeDevice
          - SavingModeDevice
        - DeviceOperationMethod ▶
      - Goods ▶
      - Person
        - User ▶
        - PersonByStatus ▶
          - AwakenPerson
          - SleepingPerson
        - PersonByRole ▶
        - PersonByBehavior ▶
      - Sensor ▶

Figure 5. A Smart Home Ontology. An arrow symbol denotes that it contains sub-classes.

C. *Rules*

SWRL (Semantic Web Rule Language) [12] is a submitted language standard for representing Horn-like rules. When a set of SWRL rules and the current primitive contextual information are given, the system activates the rule-based situation inference engine to infer abstract contexts and relevant controls for energy reduction. A SWRL rule consists of an antecedent and a consequent; it is interpreted that the conditions in the consequent hold whenever the conditions in the antecedent are true (see Figure 6 and 7). We defined 25 concept rules to infer abstract concepts and 11 application rules to control the devices for saving energy. A concept rule defines an abstract concept by combining multiple concepts and attributes, of which values are determined by sensors. For example, the CR-P01 rule in Figure 6 (a) denotes that a person (i.e., *?person*) who is in a sleeping state (i.e., *hasState(?person, "sleep")*) is as a *SleepingPerson*. Likewise, the CR-S01 rule in the Figure 6 (b) states that a space without any person inside corresponds to the *EmptySpace* concept. The rule CR-S04 states the *DarkSpace* concept as a space of which illumination level is less then a predefined threshold, *optimalMinIllumi*. As listed in Figure 6 (c), Concept rules also define the power status of a device from its electricity level is given. When the level is given as numerical value, the inference engine applies these rules to determine if the device is plugged-out, power-off, power-save, or power-on. For example, the CR-D01 rule infers that a device is off if its power level is between 0 and 1. Most devices maintain non-zero values unless they are plugged-out.

CR-P01	Person(?person), hasState(?person, "sleep") → SleepingPerson(?person)
CR-P02	Person(?person), hasState(?person, "awake") → AwakenPerson(?person)

(a) Concept Rules regarding Person

CR-S01	Space(?space), hasPerson(?space, 0) →EmptySpace(?space)
CR-S02	Space(?space), hasPerson(?space, ?countPerson), greaterThan(?countPerson, 0) → NotEmptySpace(?space)
CR-S03	Space(?space), allSleep(?space, true) → AllSleepingSpace(?space)
CR-S04	Space(?space), IlluminationSensor (?illumiSensor), hasSensor (?space, ?illumiSensor) senseIllumi(?illumiSensor, ?currentIllumi), lessThan(?currentIllumi, ?optimalMinIllumi) → DarkSpace(?space)

(b) Concept rules regarding Space

CR-D01	Device(?device), sensedPower(?device, ?power), lessThanOrEqual(?power, 1), greaterThan(?power, 0) → CurrentOffDev(?device)
CR-D02	Device(?device), sensedPower(?device, ?power), equal(?power, 0) → CurrentOutDev(?device)

(c) Concept rules regarding Device

Figure 6. A set of SWRL concept rules that composite multiple predicates defined in the ontology. These rules are used to infer abstract concepts categorized in three different types (Person, Space, Device) from primitive contexts.

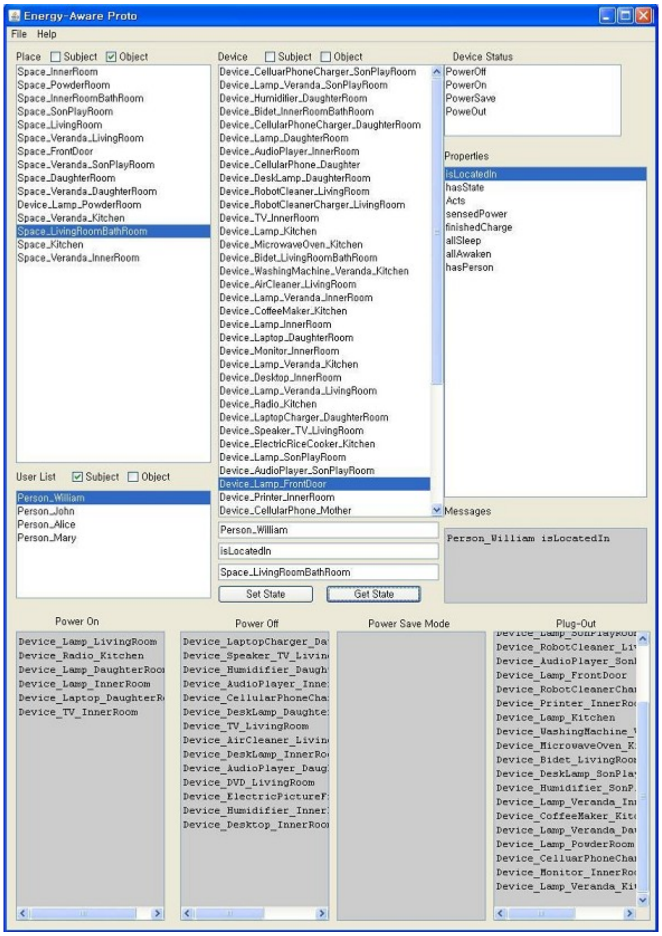

Figure 7. The User Interface for Ontology Verification

While the primary task of concept rules is to describe a set of concepts in terms of an abstract concept (e.g., sleeping person, dark space, empty space), application rules can have a direct impact on each device's status. The AR-01 rule in Figure 7 states that the lightings in a space where persons are sleeping shall be turned off. Likewise, according to the AR-02 rule, currently power-on devices in an empty space shall be set to power save status if the device has a power-save mode.

AR-01	AllSleepingSpace(?space), Lightings(?lightings), CurrentOnDev(?lightings), deviceLocatedIn(?lightings, ?space) → TargetOutDev(?lightings)
AR-02	EmptySpace(?space), SaveModeDev(?device), CurrentOnDevice (?device), deviceLocatedIn(?device, ?space) → TargetSaveDev(?device)

Figure 7. A set of SWRL application rules that composite multiple predicates defined in the ontology to infer appropriate services or power control for energy reduction.

D. SWRL Limitations

We have noted that SWRL requires additional efforts to engineer the smart home knowledge, since SWRL has no explicit syntaxes for negation and quantification. As an illustration, the CR-S02 defines the concept *NotEmptySpace* corresponding to the negation of the term *EmptySpace*, which already appears in the CR-S01 rule. If negation is allowed we could have used *~EmptySpace* instead. The CR-S03 defines *AllSleepingSpace* to represent that all the people in a specified room are sleeping, and it is up to the system to understand what the term *allSleep(?space, true)* means. As pointed out in [9], additional reasoning layer for interpreting can be considered as a solution.

IV. An Energy-Aware Home Prototype

We implemented a prototype to test the inference and decision-making functionalities of the server in our system, as the first step towards energy-aware smart homes. We implemented a virtual simulation environment (Figure 2) and a user interface on a desktop PC (Figure 7). We used the Pellet (version 2.0) reasoning engine on the Jena Platform to infer high-level concepts and appropriate controls for a given situation. The user's location and activities along with the devices' status can be specified using the user interface in Figure 7 or the visual simulator in Figure 2. When a collection of primitive contexts (e.g., power level, user location) is given as input, the server applies concept rules to infer a high-level situation. Then, the application rules are used to determine the devices' energy-saving status.

For ontology verification, the upper part of the interface in Figure 7 allows the user to specify the contexts in the domain by clicking the "Set State" button. When all the contexts are set, clicking the "Get State" button lets the system determine all the devices' status and list them on the list boxes located in the lower part of the interface, under the labels of PowerOn, PowerOff, PowerSaveMode, and Plugged-out. To evaluate the ontology, we listed 34 competency questions, each of which consists of a pair of one query and one answer. The ontology is tuned to give the expected answer whenever its paired query is given. In our prototype, each device is presumed to perform its basic function—to report its status and electricity level to the server. Therefore, devices with low computing power can be usable in this prototype as long as they are connected to the server.

V. Related Work

The research on energy reduction has been actively researched [3, 6, 7, 8, 17]. Previous research has shown that the future usage of energy in a certain environment has been successfully predicted using AI techniques and probabilistic approaches [3, 7]. Dong et al. [3] use a machine learning algorithm, support vector machine (SVM), to predict monthly energy consumption of four commercial buildings in Singapore when the weather data (monthly temperature, humidity, and global solar radiation) are given as input. In the location-based predictive framework developed by Roy et al [7], the experimental study has shown significant daily energy reduction in a single inhabitant environment. These energy prediction techniques can give benefits to consumers by helping them plan to use energy wisely in smart-grid environments where the prices of electricity can vary depending on time and demands.

While these methods are effective in energy reduction, they mainly depend on a single algorithm that takes into account a single context such as the distance between the user and the device. However, we believe that such simplified approaches may harm the consumer's convenience. For example, if a resident cooking in a kitchen temporarily leaves the place to answer the door, the lightings and cooking devices in the kitchen shall maintain their status until she returns. To address this issue, we have employed a general reasoning approach that manage the data (ontology and rules) and the reasoning engine separately. This allows the system operator to modify contextual knowledge when necessary. Moreover, it is possible to replace and integrate a part of the ontology with another ontological model that is engineered by other engineers.

VI. Conclusion and Future Work

This paper describes a framework that can automatically control the electronic devices in a smart home environment for energy reduction. To this end, we employ an ontology-based reasoning approach to infer relevant device controls for a given situation. Our system considers the residents' and the devices' contextual data, which can be input from devices, sensors, and mobile phones. We built an ontology and a set of rules based on a two-day scenario assuming a family of four members. We also implemented a prototype to test the server that employs the ontology to reason energy-aware decisions.

A. Challenges

Although the ontology-based reasoning approach has shown promising results in making context-aware decisions for saving energy, a couple of issues still remain. First, the effort to engineer an ontology is not trivial. For one month, two professional ontology engineers at Saltlux [18] and two members of our research group had co-worked on the ontology design. Therefore, it is expected that significant efforts and costs will be required for ontology engineering when building practical systems.

Second, personalization issue can be a major concern in building the ontology. During the discussions to create the prototype scenario, we have noticed discrepancies in the participants' preferences in using electronic and lighting devices. For example, one resident may want to turn off the TV in the living room when she's in another room, whereas another resident want to maintain the TV on in the same situation only to entertain himself by listening to the TV. This means that the system shall be able to learn the application rules that can control the device's status according to each user's device usage pattern. We believe that machine learning techniques can be incorporated into our system to solve this issue as suggested as future work below. In this case, a method to secure the user's privacy shall be accompanied.

B. Future Work

Our future work includes conducting empirical experiments on the system's efficiency in energy reduction in the virtual simulation environment we built. We also plan to employ a machine leaning technique such as Bayesian networks to solve the personalization problem described above. The system can be extended to contain a learning component which observes the contextual data reported by the devices and sensors (including the consumer's mobile phone) to generate personalized application rules. For example, if a certain resident keeps turning on the TV in the living room whenever the system turns it off while he is in another space, a new application rule that keeps a main TV on can be extracted. And such rules can be prioritized according to their frequency and importance. When these rules are found to be conflicting with some of existing rules (i.e., infer different devices' status in an identical situation), the system can determine whether to maintain these rules or not, based on their priorities.

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