Saving Energy in Smart Homes with Minimal Comfort Level Reduction

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***Abstract*—In this paper, we propose an energy-saving device control method with the minimal reduction of user's comfort level. Given the past histories of device's states and the target energy-saving ratio, our method first assigns each device the weight proportional to the comfort level deterioration when reducing energy supply to the device by a unit of energy and reduces more energy supply from less weighted devices, in order to achieve the target-energy-saving ratio. Moreover, we propose a method for constructing power consumption models of devices based on measurements of actual power consumption of real devices and a method for constructing comfort level functions of users based on the questionnaires. Through simulations, we confirmed that the proposed method achieves the target energy saving ratio with small comfort level reduction.**

***Keywords*-energy saving, networked appliances, context-aware systems, smart home**

I. Introduction

Recently, people's interest to energy and environmental issues such as fossil fuels depletion and global warming has been increasing. However, the change ratio (of that in 1990) of the energy consumption in Japan is 102%, 135%, and 114% in industrial, people's livelihood, and transportation sections, respectively. We need some measures to stop increasing energy consumption in people's livelihood.

On the other hand, thanks to advance of device and sensor network technologies, it is becoming easier to design and develop context-aware systems. The context-aware systems realize *smart spaces* that are physical spaces embedding devices with sensors and actuators. Smart spaces provide users with useful services without conscious operations by acquiring *context* comprising user's position, physical quantity like temperature, humidity, etc., and device states. It is desirable to realize energy saving by context-aware device control.

So far, various methods on controlling devices depending on user's context have been proposed [1] [2] [3] [4] [5] [6]. However, these methods did not achieve sufficient energy saving without decreasing user's comfort level. According to the report in [7], showing information on power consumption can achieve relatively large energy saving. Ueno, et al developed a system called ECOIS that can monitor power consumption of each device [8]. However, these methods may largely decrease user's comfort level, since it only shows devices which consume relatively big power. Therefore, we need a system that supports energy saving activity while suppressing user's comfort level reduction.

In this paper, we propose a method for calculating an energy-saving plan keeping comfort level as high as possible and realizing a specified target energy-saving ratio (e.g., -20%) to the past amount of the energy consumption during a specified period like one month. We formulate the problem that decides the reduction amount of energy supply to each device so that the user's overall comfort level deterioration is minimized while achieving the target energy-saving ratio. To solve the problem, first we assign each device the weight proportional to the comfort level deterioration when reducing energy supply to the device by a unit of energy. Our method reduces more energy supply from less weighted devices. Our method also considers the relative importance among different situations.

Through simulations, we confirmed that the proposed method achieves 20% energy-saving with only 14.47% of user's comfort level reduction.

II. Energy Saving Problem

A. Target environment and assumption

We assume that the target indoor space consists of multiple sub-spaces called *rooms*. Let R denote the set of rooms in the target space. Let r_o denote the space outside the target space. Let U denote the set of users in the target space. We also denote the room in which a user $u \in U$ exists at time t by $u.loc(t) \in R$. Let V denote the set of physical quantities types that may affect user's comfort level. Temperature, humidity, and light intensity are examples of V. We denote the set of devices in room r by D_r. We denote the time period for energy-saving support by T. We suppose that T is a relatively long time like one month.

1) Situation: Each user $u \in U$ is in one of possible activity states called *situations* at any time t. Let SIT denote the set of possible situations. Examples of situations are watching TV, reading a book, dining, and so on.

2) Context: We refer to the condition of each room by *location context*. Room r's location context comprises the physical quantities of r and conditions of devices D_r. We define the location context $rc(r, t)$ of r at time t as follows.

$$rc(r, t) = (v_1(t), ..., v_n(t), d_1.s(t), ..., d_m.s(t)) \quad (1)$$

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Here, $v_i(t)$ denotes the value of each physical quantity of V at time t and $d_j.s(t)$ denotes the condition of device d_j of D_r. Similarly, we denote the location context of the space r_o outside the target space at time t by $rc(r_o, t) = (v_1(t), ..., v_n(t))$. Let $rc[p](r, t)$ denote the specific physical quantity p's value in room r's location context.

Let $RC_{all}(0, T)$ denote the set of all past location contexts appeared in the target space during time period $[0, T]$ where time 0 is a reference point of time in the past. Let $RC_{ext}(0, T)$ denote the set of all past location contexts in outside space r_o appeared during $[0, T]$.

We refer to the user's condition by *user context*. We define u's user context at time t, $uc(u, t)$, as a pair of u's situation $u.sit$ and the location context of the room $u.loc(t)$ as follows.

$$uc(u, t) = (u.sit(t), rc(u.loc(t), t)) \quad (2)$$

Let $UC_{all}(0, T)$ denote the set of user contexts of all users appeared in the target space during $[0, T]$.

3) Comfort Level Function: We denote a function that returns a comfort level of a user u for a user context uc by $sat_u(uc)$, where $0 \le sat_u(uc) \le 1$ and a higher value means higher comfort level. Let $SAT_{all}(0, T)$ denote the set of comfort levels for all contexts of $UC_{all}(0, T)$.

4) Devices: Each device can control at most one physical quantity type of V. Let v_d denote the physical quantity type that device d can control. Each device d has basically two states: ON and OFF, where the device has a *target value* for its controllable physical quantity type such as the target temperature when d is at ON state. Let $d.set(t)$ denote the target value at time t. The room's physical quantity value always reaches the target value when the device is at ON state. The power consumption of each device d is 0 when d is at OFF state, and is decided depending on the target value $d.set(t)$, the physical quantity v_d for control, and the current values of location context of outside space r_o when d is at ON state. Let $pow_{d,p}(v_{set}, v_{cur}, v_{ext})$ is the power when the current physical quantities of room r and outside space r_o are v_{cur} and v_{ext}, respectively, and the target value of device d is v_{set}. Each physical quantity of room r gets equal to that of outside space r_o when all devices in r are at OFF states.

From $RC_{all}(0, T)$ and $RC_{ext}(0, T)$, we can calculate the power consumption during $[0, T]$ as follows.

$$E(0, T) = \int_{t=0}^{T} \left(\sum_{r \in R} \sum_{d \in D_r} pow_{d,v_d}(d.set(t), rc[v_d](r, t), rc[v_d](r_o, t)) \right) dt \quad (3)$$

B. Problem definition

We assume that $RC_{all}(0, T)$, $RC_{ext}(0, T)$, $UC_{all}(0, T)$, and $SAT_{all}(0, T)$ are given. Let t_0 denote the start time of energy-saving support. We assume the following. The location context of outside space r_o at each time of a period $[t_0, t_0 + T]$ is similar to that of the measured period $[0, T]$. The comfort level functions $SAT_{all}(0, T)$ or $SAT_{all}(t_0, t_0 + T)$ of both periods $[0, T]$ and $[t_0, t_0 + T]$ are the same. Moreover, each user u's behavior pattern, that is, the room and situation at which u is at time $t \in [t_0, t_0 + T]$ is similar to that in period $[0, T]$. Thus, the following equations hold.

$$RC_{ext}(t_0, t_0 + T) = RC_{ext}(0, T) \quad (4)$$

$$SAT_{all}(t_0, t_0 + T) = SAT_{all}(0, T) \quad (5)$$

$$\forall u \in U, \forall t \in \{t | uc(u.sit(t), ...) \in UC_{all}(t_0, t_0 + T)\}, \forall t' \in \{t' | (uc(u.sit(t'), ...) \in UC_{all}(0, T)\}, u.sit(t) = u.sit(t') \wedge u.loc(t) = u.loc(t') \quad (6)$$

Let $E(t_1, t_2)$ denote the energy consumed during time period $[t_1, t_2]$. We assume that the *target energy-saving ratio* is specified as the ratio α to the energy consumption in the past period $E(0, T)$, where $0 < \alpha < 1$. In this case, $E(t_0, t_0 + T)$, that is, the energy consumed during a new period $[t_0, t_0 + T]$ must satisfy the following equation.

$$E(t_0, t_0 + T) \le E(0, T) \times \alpha \quad (7)$$

In order to make $E(t_0, t_0 + T)$ smaller than $E[0, T]$, each device's state and the target value during $[t_0, t_0 + T]$ must be changed so that the power consumption of device d is smaller during $[t_0, t_0 + T]$ than during $[0, T]$. For each $sit \in SIT$, let min_{sit} denote the marginal comfort level in situation sit. Then, the following equation must hold.

$$\forall u \in U, \forall t \in [t_0, t_0 + T], sat_u(u.sit(t), rc(u.loc(t), t))) \ge min_{sit(t)} \quad (8)$$

The objective of our target problem is to derive the state and the target values of each device during time period $[t_0, t_0 + T]$ that satisfy the constraints (4)–(8) and maximize the overall user's comfort level. Thus, we define the objective function as follows.

$$\text{maximize} \int_{t=t_0}^{t_0+T} \left(\sum_{u \in U} sat_u(uc(u, t)) \right) dt \quad (9)$$
$$\text{subject to constraints } (4) - (8)$$

The above problem is NP-hard since it implies the Knapsack problem as a special case.

III. Energy-Saving Plan Decision Algorithm

We aim to achieve the target energy-saving ratio by reducing the total energy supply to each device with the minimal user's comfort level reduction. For this purpose, we give each situation and each device a priority or weight so as to keep as high user's comfort level as possible even after energy supply to some devices is reduced.

Algorithm 1 Energy-Saving Plan Decision Algorithm

1: **for each** $sit \in SIT$ **do**
2: compute $weight(sit)$ from $RC_{all}, RC_{ext}, SAT_{all}$
3: **end for**
4: **for each** $sit \in SIT$ **do**
5: $E^-_{sit} = (1-\alpha) \times E \times \frac{\frac{1}{weight(sit)}}{\sum_{sit' \in SIT} \frac{1}{weight(sit')}}$
6: **for each** $d \in D_{sit}$ **do**
7: compute $weight(sit, d)$
8: $E^-_{sit,d} = 0$
9: **end for**
10: **while** $E^-_{sit} > \sum_{d \in D_{sit}} E^-_{sit,d}$ **do**
11: **for each** $d \in D_{sit}$ **do**
12: $E^-_{sit,d} = E^-_{sit,d} + e \times \frac{\frac{1}{weight(sit,d)}}{\sum_{d' \in D_{sit}} \frac{1}{weight(sit,d')}}$
13: update $weight(sit, d)$ to reflect $E^-_{sit,d}$
14: **end for**
15: **end while**
16: compute $d.set(sit)$ from $E^-_{sit,d}$
17: **end for**

1) Prioritizing situations: We should avoid uniformly reducing energy supply to all devices in the whole service period, since user's situation changes in the period. To determine the reduction ratio of the energy supply to durations of each situation, we assign a weight to each situation, called the *situation weight*. The larger value of the weight means that the situation is more important and the user's comfort level is more deteriorated when reducing power supply to the situation. We keep user's comfort level as high as possible in the whole service period, by reducing larger energy supply at situations with smaller weights.

2) Prioritizing Devices in a Situation: If we uniformly reduce the energy supply to all devices in a situation, user's comfort level may be greatly deteriorated. This is because each device or actuator affects some of physical quantity types in different ways and important physical quantity type is different among situations. Therefore, we take into account to what extent each device affects the user's comfort level per unit of energy supply. Then, we give each device a weight proportional to the deterioration of the comfort level when reducing a unit of energy supply to the device. We call this weight the *device weight*.

The proposed algorithm determines an energy-saving plan specifying how to control each device during the service period so as to achieve the target energy-saving ratio with the minimal user's comfort level reduction. We show the pseudo code of the algorithm in Algorithm1. The algorithm first calculates the weight $weight(sit)$ for each situation sit in the target service period based on the location context history RC_{all}, that in the outside space RC_{ext}, and the comfort level function calculated from SAT_{all} (lines 1–3).

Second, it calculates the reduction amount of energy supply to each situation, E^-_{sit} (line 5). Here, E is the total energy consumption in the past service period. Then, the weight $weight(sit, d)$ of each device d of D_{sit} (D_{sit} is the set of devices used in situation sit) is calculated, and the reduction amount of energy supply to the device $E^-_{sit,d}$ is initialized (lines 6–9).

Third, the algorithm increases the reduction amount of energy supply to each device by a fraction of a unit of energy e according to the ratio of the reciprocal number of the weight $weight(sit, d')$ (line 12). The final reduction amount of energy supply to each device is determined by repeating this calculation until the sum of the reduction amounts to all devices of D_{sit} reach E^-_{sit}, the reduction amount for situation sit (line 10–15). Here, note that the device weight of each device is updated whenever a unit of energy e is added since the device weight changes depending on what amounts of energy supply are reduced for the device (line 13). Finally, the algorithm calculates the target value of each device (line 16).

IV. Evaluation

We conducted computer simulations for a typical home scenario, where we constructed a realistic comfort level function about the temperature based on questionnaires and realistic device's power consumption models based on the consumed power actually measured for real devices.

A. Construction of comfort level function

We used the method to estimate user's comfort level from the questionnaire [4]. In this method, a user's comfort level for arbitrary context can be estimated by knowing the actual comfort level for some situations through the questionnaire. The questionnaire includes the following items, "Feeling to Temperature", "Feeling to Humidity", "User's Situation", "Devices in Use", "Date", "Actual Temperature", and "Actual Humidity". The questionnaires were collected for about 4 months from June 4 to October 3, 2010, and the number of the valid ones was 307. We constructed the user's comfort level function about the temperature based on the collected questionnaires as shown in Fig.1. In Fig.1, we see that the ratio of the users who felt comfortable is concave down where the ratio is the highest at around 27° C and it gradually decreases as the temperature goes far from this point. Since this trend is similar to PMV (Predicted Mean Vote) [9] which is a popular index to handle human's comfort level, we think that the constructed function adequately approximates the user's comfort level.

JIS (Japanese Industrial Standards Committee) provides the illuminance standard which shows the appropriate illuminance to each situation. In this paper, we make a comfort level function for illuminance based on this standard. In the function, if the illuminance is under appropriate level, the comfort level quickly goes down.

B. Construction of power consumption models

We also constructed the realistic power consumption models for devices. We measured actual power consumption of

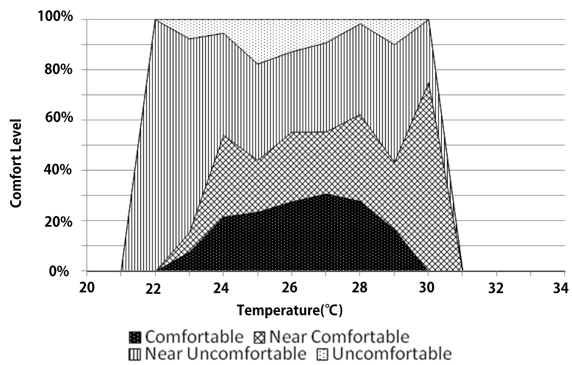

Figure 1. User's Comfort Level Function on Temperature

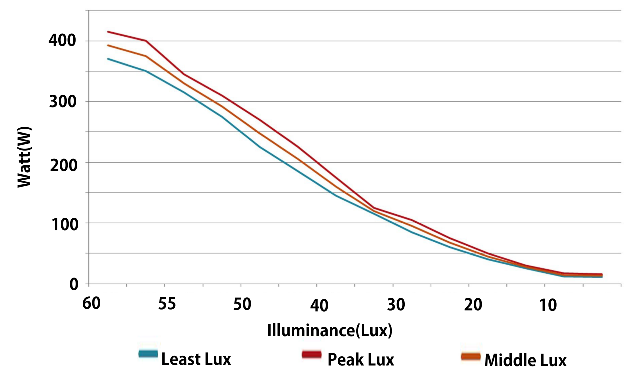

Figure 3. The Relationship Between Illuminance and Power Consumption

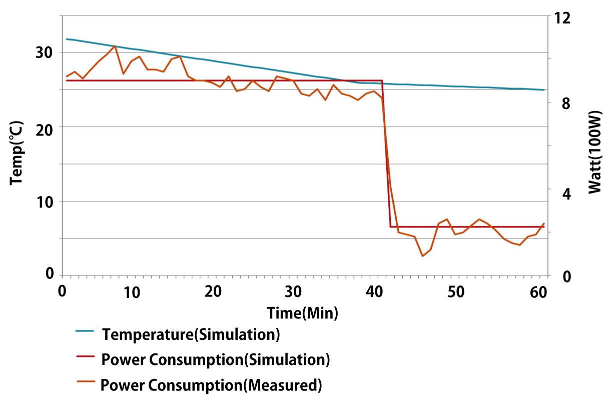

Figure 2. The Model and Measured Data of Air Conditioner

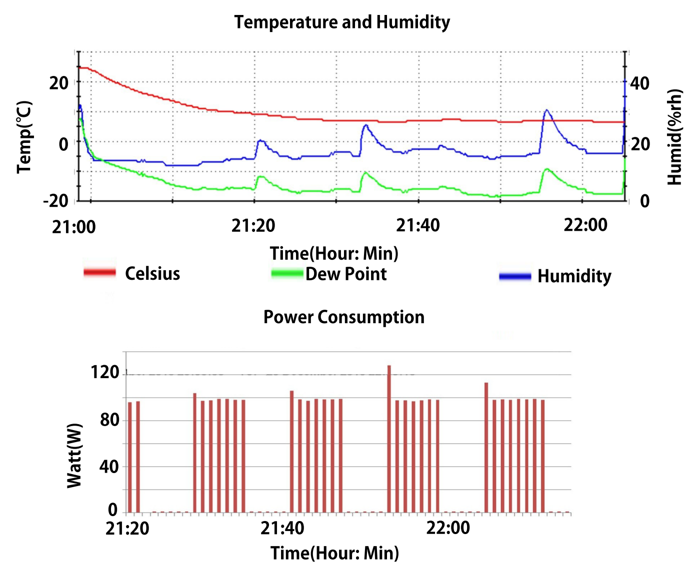

Figure 4. The Relationship Between Temperature in Refrigerator and Power Consumption

real devices: an air-conditioner, a lamp, and a refrigerator in various conditions (e.g., for different pairs of the initial and target temperatures) with a watt electricity usage monitor [10] and temperature and illuminance sensors [11].

First, we explain about the construction of air conditioner power consumption model. We found that the air conditioner repeats a cycle with high and low power consumption. The air conditioner consumes a high power when the room temperature is different from the target. It is because a compressor works. When the room temperature is the same as the target, the air conditioner consumes low power. It is because the compressor does not work and only fan works. Fig.2 shows the measured and simulated power consumption of air conditioner and simulated temperature in the room. The degree of room temperature change can be calculated from heat loss coefficient (Q value), room temperature, outside temperature, air conditioning, floor area of building, and heat capacity. Based on this, we constructed the air conditioner power consumption model.

Second, we measured the relationship between power consumption and illuminance of a dimming light as shown in Fig.3. Based on this, we constructed a light power consumption model.

Finally, we found that the refrigerator has the same cycle of power consumption as air conditioner. Unlike the air conditioner, it has a heat insulator. Thus, the compressor does not work if users do not open the door frequently. We measured the open period as well as power consumption and room temperature as shown in Fig.4 . We opened the door 5 seconds at 21:20, 10 seconds at 21:32, and 20 seconds at 21:55. This shows that the door open period under 20 seconds does not affect the temperature, while the compressor works frequently when opening the door more than 20 seconds. Based on this, we constructed a refrigerator power consumption model.

C. Experimental settings

In the experiment, we assumed a room (5.0m $\times$ 5.0m $\times$ 2.0m) with a user. The experiment supposes a hot summer day where the outside space temperature and the initial room temperature are 35° C and 32° C, respectively. We also assumed that the user's most comfortable temperature is 28° C. An air-conditioner (400W), a lamp (80W), and a refrigerator (120W) were placed in the room and their initial settings (target values) were 24°C, 100 (of 100 levels), and 10 (of 10 levels), respectively. We considered three situations: exercise, reading a book, and cooking, where each of them occurs for 60 minutes in a round-robin manner. We empirically determined that the situation weights of exercise, reading a book, and cooking are 6, 4, and 5, respectively. We used the comfort level function on the room temperature constructed in Sect. IV-A. The comfort level functions on the light intensity and the temperature in the refrigerator were manually defined based on the controllable target values of the lamp and the number of opening refrigerator door, respectively.

We measured the comfort level deterioration for achieving the specified target energy-saving ratio, for the proposed method and the following two conventional methods for comparison: (1) method that considers only situation weights (since device weights are not considered, equal amounts of energy supply are reduced from all devices), and (2) method without considering weights (equal amounts of energy supply are reduced from all situations).

D. Results

The experimental results for target energy-saving ratios 10% and 20% are shown in Table I. In the table, "no saving" represents the case without any energy supply reduction and "average comfort level" does the comfort level (the maximum value is 1) averaged over the service period. Since "no weight" method did not consider the weights and simply reduced energy supply from all devices equally, the average comfort level is the smallest and its reduction ratio to "no saving" is 34.64% and 44.84% for 10% and 20% target energy-saving ratios, respectively. "Situation weight" method considered only the situation weight and achieved larger average comfort level than "no weight" method, but the comfort level reduction ratio is still big (23.01% for 10% target and 34.28% for 20% target). This suggests that the device weight suppresses the rapid reduction of the average comfort level. Our method kept the average comfort level higher than other methods, and achieved the smallest comfort level reduction ratios, 6.88% and 14.47% for 10% and 20% energy-saving ratios, respectively.

Table I
EXPERIMENTAL RESULTS

	Target Ratio=10%		Target Ratio=20%	
	Average Comfort Level	Comfort Level Reduction	Average Comfort Level	Comfort Level Reduction
No Saving	0.843	0%	0.843	0%
Proposed Method	0.785	6.88%	0.721	14.47%
Situation Weight	0.649	23.01%	0.554	34.28%
No Weight	0.551	34.64%	0.465	44.84%

V. CONCLUSION

We proposed a method for determining an energy-saving plan for devices to achieve the specified energy-saving ratio with the minimal user's comfort level reduction. The main characteristics of the proposed method are prioritization among situations and among devices. We showed that the proposed method can achieve the specified energy-saving ratio with small user's comfort level reduction through simulations where we constructed the realistic user comfort level function by questionnaires and the realistic device's power consumption models by actual power consumption measurements for real devices.

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REFERENCES

[1] H. Si, S. Saruwatari, M. Minami, H. Morikawa: "A Ubiquitous Power Management System to Balance Energy Savings and Response Time Based on Device-level Usage Prediction", Journal of Information Processing, Vol.18, pp.147–163 (2010).

[2] J.Scott, J.Krumm, B.Meyers, A.J.Brush, and A.Kapoor: "Home Heating Using GPS-Based Arrival Prediction", in Proceedings of Pervasive 2010 Workshop on Energy Awareness and Conservation through Pervasive Applications, Microsoft Research, May 2010.

[3] K. Ito, D. Tomita, T. Imaki, T. Hongo and H. Yoshikawa: "Development of an Affective Interface for Supporting Energy-saving Activities and its Evaluation", Proc. of CSEPC2004, pp.87-93 (2004).

[4] S. Yamamoto, N. Kouyama, K. Yasumoto, M. Ito: Maximizing Users Comfort Levels through User Preference Estimation in Public Smartspaces, *Proc. of the 7th IEEE Int'l. Workshop on PervasivE Learning, Life, and Leisure (PerEL 2011)*, pp. 187-192 (2011).

[5] S. Darby: "The effectiveness of feedback on energy consumption," Environmental Change Institute, University of Oxford (2006).

[6] M. Chetty, D. Tran and R.E. Grinter: "Getting to green: understanding resource consumption in the home," *Proc. of UbiComp 2008*, pp.242–251 (2008).

[7] NEDO: New Energy and Industrial Technology Development Organization, http://nedo.go.jp/.

[8] T. Ueno, F. Sano, O. Saeki and K. Tsuji: "Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data," *Energy and Resources*, Vol.25, No.5, pp.347–353 (2004).

[9] P.O.Fanger, "Thermal Comfort", Danish Technical Press (1970).

[10] Sanwa Supply Inc., http://www.sanwa.co.jp/index.html.

[11] Lascar Electronics, http://www.lascarelectronics.com/