

Context Aware Services using Multi-Environmental Sensors and Its application for Ubiquitous Home Networks

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ABSTRACT

As we go about our daily lives, people often collect surrounding information and adapt to the situation. Computer development trends show that one wants computers to work like human beings, i.e. computers can sense its context and adapt corresponding to context changes. To implement this expectation, a context aware service layer is needed. In this layer, sensors capture its environment and send this information to the service center. Considering received information as its context, the service center seeks the suitable operation according to the context. This paper presents a context aware service which is applied in controlling air-conditioner. The air-conditioner includes sensors which are installed at some special positions in a room. Each of these sensors gathers comfort-influenced information like temperature, humidity and sends them to air-conditioner. The air-conditioner adapts its operation to the environment according to the sensed information. To control the air-conditioner effectively, we use a genetic algorithm which is suitable in adaptation issues. The simulation shows that the room condition can be maintained at a comfortable level by using context-aware services in the operation of the air-conditioning system.

Keywords: Context Aware Services, Air-conditioner, Thermal comfort, Genetic algorithm

1. INTRODUCTION

Every operation cannot be separated from its context. Before making decisions, one always considers the current surrounding information. For example, a person who wants to buy a stock of

a company needs to know what the company produces, if the company prospers or loss, how many stocks other people want to sell/buy, etc. This kind of information forms the context for decision-making which influences his/her decisions.

There are a lot of researches which focus on how computing systems can work like human. This field of research needs to overcome a number of challenges. First, we need a framework which can capture and send context information to computing systems. Second and a more important challenge, computing systems need to understand context and adapt its operations to new context. It is required that computing systems are as intelligent as human beings.

Currently, sensor networks are widely applied in our life. This factor gives us a chance to solve the first challenge. Sensors are installed at some positions in environment to gather and send environmental information to a data center. Furthermore, this data center should understand the context information from sensors and control its operation

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Receipt date : Mar. 15, 2007, Approval date : Jun. 13, 2007

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* This work was supported by Korea Research Foundation Grant (KRF-2006-211-D00247).

with respect to received new context. This mission can be implemented as a context aware service layer. In this paper, we use this layer to control the air-conditioning system. In the control model, each air-conditioner is composed of an air handler which includes the blower, heating and cooling elements, filter racks or chamber, dampers, humidifier, and other central equipment in direct contact with the airflow and some sensors which are implemented at some positions in a room. Sensors measure temperature, humidity around its position and send them to the air handler. Based on received information, the air handler controls its operations corresponding to current context. The reaction of the air handler to the current context allows the air-conditioning system to maintain a certain comfort level for the whole room.

The remainder of the paper is organized as follows. In section II, we present a review of some previous works in context aware systems. Section III shows our context aware layer model which is used to control air-conditioner. The air-conditioning system is composed of sensors and a control center. Sensors measure temperature, humidity and send them to the control center. The control center collects data from sensors and implements control operations to meet comfortable requirements. In section IV, we use a genetic algorithm to provide control rules for the control center. We simulate our model and algorithm by using the ontology engine JESS in section V. The simulation results show that the algorithm is efficient in controlling the air-conditioning system. Section VI draws the conclusion and summarizes the results and future works.

2. LITERATURE WORKS

Nowadays, context-aware issues attract a lot of researchers' attention. There exist some context-aware applications which are applied in a lot of fields. In office applications, Active Badge sys-

tem[1] and ParcTab system[2] are two of the first context-aware applications. In Active Badge system, each person wears a badge which communicates with its center by IR-signals. A network of sensors is installed around the office building and picks up radio signals from the badges. Based on the received signals, the telephone receptionist can determine where a person is located. This allows the receptionist to direct the call to an appropriate telephone. ParcTab system is composed of some small wireless palm-sized computers (ParcTab). In each ParcTab, some context-aware applications are installed. For example, when one enters a room, information about the room is displayed in the ParcTab's monitor. ParcTab can help people to find the most convenient local resource, e. g. the nearest printer. Some context-aware applications are used in tourist guide applications[3-5]. Each tourist has a personal digital assistant (PDA) or a cell phone. When he/she enters a place, the PDA can help him/her to look for direction or other indications. Furthermore, some context aware systems are also applied in home appliances. The Future Computing Environments (FCE) group develops some projects such as Aware Home Research Initiative, eClass, Smart Floor, etc[6].

Many context-aware applications are widely applied and they significantly improve our life. Currently, most applications operate as follows. Each application has an information store. When it enters a new context, the information, which is related to context, is accessed from the store and displayed to user. There is still lack of applications that can adapt themselves to the context. This kind of application is required to be intelligent. This paper presents another home appliance which can be considered as an intelligent air-conditioning system. This air-conditionings system can understand surrounding environment conditions and keep it in comfortable state without explicit control.

3. DESIGN OF CONTEXT AWARE SERVICE

In this section, we describe our context aware service layer which is used in controlling our air-conditioning system.

3.1 Multi-Environment Sensors

In practice, traditional air-conditioning controls air condition using sensor readings on temperature. However, other factors affect the comfort level of a person. Studies show that air humidity can also affect a person's comfort level particularly on the ease of respiratory processes. Also, air humidity is affected by the change in temperature and some trade-offs are observed between these factors. The following sections discuss important factors that affect a person's comfort level. Fanger studied six factors which affect a human being's comfort level[7]. These factors should be accurately measured and maintained so as to achieve an optimal comfort level. This paper attempts to design an intelligent air-conditioning system therefore the system must react to changes in the mentioned factors. Multi-environmental sensors are needed to measure accurately the changes in the comfort level factors. In the same way that the human body has nerve endings in the skin to sense the environment, our systems also needs sensors to determine surrounding conditions. The important characteristics of these sensors are accuracy and reliability. The sensors should have good accuracy and must be able to detect small changes in environmental conditions. These sensors should also output the correct data measurements throughout its lifetime without intermittent failure. In this paper, three comfort level factors are measured to evaluate environmental condition: air temperature, humidity, and CO₂ concentration. These measured factors are then sent to the coordinator for future processing. Fig. 4 shows one of the sensor nodes designed. The

hardware and sensor specification will be further discussed in the implementation and simulation section.

3.2 Logical Design Components.

The layer is composed of autonomous software programs called Agents. These agents play real-world objects such as devices (sensors, coordinator, air-conditioner) and services like air-conditioning. These agents communicate with each other, deduce goals from context information and automatically launch behaviors to achieve the goals. For example, sensor agents contain information which sensors measure like humidity and temperature. This information is sent to the air-conditioner agent, and the air-conditioner will decide which action is performed to keep air comfortable. Each agent is not a simple program, instead it is self-aware; i.e., it knows that it represents a semantic object and its relation with rest of the agents and real-world objects, and it is capable of taking productive actions proactively.

An agent should contain three main logical components[8]:

- Interface: These are communication ports between agents and real world, between agents.
- Context: This is the language that the agents converse in.
- Intelligence: Intelligence puts the awareness in context aware system. While the context is just an information store, the intelligence component is what makes sense of the information and uses this knowledge to take productive actions proactively, depending upon the context or environment.

We will discuss interfaces and intelligence in more detail in next section. For now, we consider the context component. The objective of the air-conditioning system is to keep indoor air in comfortable state. Therefore, context here is de-

defined as the air condition in every position in the room. However, it is very difficult to measure all positions; hence, we just use some important positions as representatives and air conditions at representatives are context.

One question is which factors influence thermal comfort. Of course, most people say “air temperature”. But air temperature is not sufficient to indicate of thermal comfort. Fanger shows that there are six factors which influence people’s comfort. These are air temperature, mean radiant temperature, relative humidity, air velocity, activity level, and clo-value (comfort-influenced factors). These factors may be independent of each other, but together contribute to a person’s thermal comfort level. Fanger’s research is standardized in ISO 7730 standard[9]. Therefore, the context which is composed by six above factors should be collected by agents. These six factors are combined in thermal comfort equations to compute the thermal comfort index PMV (Predicted Mean Vote). The *PMV* index determines whether a given indoor climate is satisfactory or not using a seven-point thermal sensation scale [-3,3]. They recommend that *PMV* should be kept in the range [-0.5,0.5]. This range is recommended for optimal comfort level.

3.3 Context Aware Architecture.

Fig. 1 shows our context aware layer model where there are three parts: physical layer, virtual layer and inference engine. In this model, real sensors and air-conditioner is mapped with corresponding virtual objects.

In the context aware services layer, there two main interfaces:

- Interface between agents and real world: We use some multi-platform sensors to measure environment parameters like temperature, humidity, and CO₂.
- Interface between sensors and coordinator: All sensors and the coordinator form a sensor network where the coordinator plays as a sink

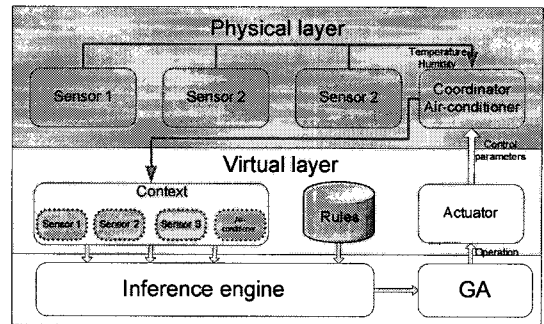


Fig. 1 Logical model.

and the other sensors play as endpoints. The network protocol operates in the network is ZigBee. The endpoints collect environment parameters and send them to the sink.

In the air-conditioner, we need to make decisions where information gathered from the sensors are the input signals. Because the input signals are variable and diverse, and each particular input signal require a different response, we implement a context aware layer and this layer works as a rule-based system. Information collected by sensors, is stored in the virtual objects and plays the fact role in rule-based system. When this information is updated, an event is raised, and the inference engine maps between the new fact and the corresponding rule. By installing rules, the inference engine can understand context. With a six receipt *PMV*-influenced factors, the engine knows the current state of the context, i.e. is it too hot or too cold. Based on the current context, the engine adapts by carrying out appropriate operations. Operation parameters are computed by Genetic Algorithm (GA) which is presented in the next section.

4. CONTROL SCHEMS USING GENETIC ALGORITHM

4.1 Algorithm flowchart

Now, we consider the algorithm to compute the parameters of the reply operations. Many re-

searches propose effective control algorithms for controlling air-conditioning systems[10-15]. Most authors use genetic algorithms, but some use neural network algorithms. But until now all solutions just consider how to adjust valve aperture and intensity of fresh air, steam, heating and cooling processes. They are acceptable in small rooms where transfer process of fresh air and thermal is fast. But in a big room, the direction of fresh air should be changed according to thermal condition at every position in the room. Hotter position should receive cooler air flow if the air-conditioner plays a cooling role and colder room positions should receive warmer air flow in the case of the air-conditioner playing a warming role. We consider the issue in this paper. The air-conditioner model is presented in Appendix I.

The inference engine use genetic algorithm (GA) (section IV) to compute control parameters and air-conditioner perform its operations with control parameters received from inference engine. We chose genetic algorithm because of following reasons:

- First, and also the most important, our problem is to minimize PMV in whole room, and since PMV depends completely on six above-mentioned factors, direct solutions such that iterative methods for convex problem do not exist. Therefore, GA is suitable solution for this problem.
- Second, we need to minimize PMV at three corners of the room at the same time. Furthermore, to control PMV, all six PMV-influenced factors should be controlled simultaneously. This is a multiple objective problem. This multiple optimization should be solved by GA.
- Finally, GA is an easily understood approach that can be applied to a wide range of problems with little or no modification.

As we say in the previous section, we need to take account six PMV-influenced factors to keep

indoor air comfortable. Three of them, air velocity, activity level, and clo-value, are difficult to measure by sensors. When one starts the air-conditioner, it should configure air velocity, activity level, and clo-value. In practice, these factors are configured using default values and only changed if necessary. For example, air velocity should be 1m/s in tight room, activity level should be from 0.8 to 4 met depending what occupants do in the room, clo-value value should be 0.6 for summer and 1.3 for winter. Our air-conditioner does not control three above parameters but it needs them to compute *PMV* and fitness in genetic algorithms.

The air-conditioner parameters are presented in Appendix I. The air-conditioner only control the three remain factors air temperature, humidity, and radiant temperature. These parameters are adjusted

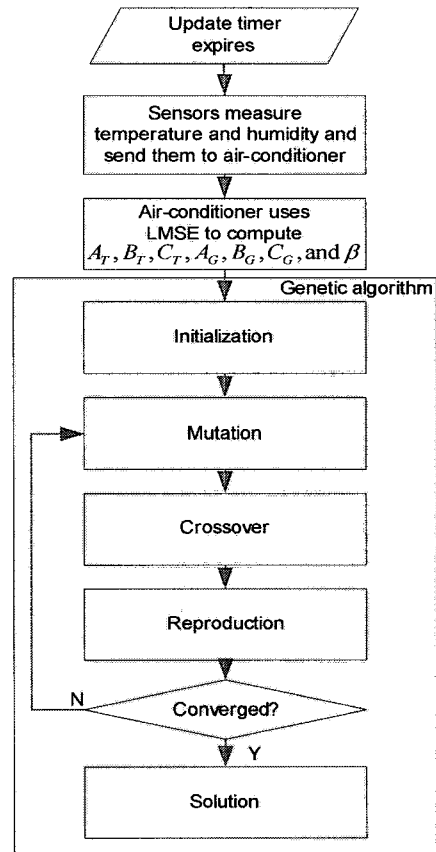


Fig. 2. Control algorithm flowchart.

by control variables $(t_{ind(1)}, t_{ind(2)}, t_{ind(3)}, Q_T, Q_G, t_{ac}, g_{ac})$ where $t_{ind(1)}, t_{ind(2)},$ and $t_{ind(3)}$ are percentages of time the air-conditioner points to the positions of sensor 1, 2, and 3 respectively. Q_T and Q_G are power ratings that the air-conditioner uses for cooling and dehumidification. t_{ac} and g_{ac} are temperature and humidity at the air-conditioner. In this algorithm, time is divided into time slots, each time slot is called duty cycle. At the beginning of a duty cycle, sensors measure and send temperature and humidity measurements to the air-conditioner. Because air-conditioner knows $t_{ia}, t_{ac}, Q_T, g_{ia}, g_{ac}, Q_G,$ and t_{ind} at current time and in the past, it can estimate $A_T, B_T, C_T, A_G, B_G, C_G,$ and β parameters in (10) and (12) by using LMSE (Appendix I). When $A_T, B_T, C_T, A_G, B_G, C_G,$ and β are defined, i.e., the relationship between control variables and the PMV-influenced factors is defined Fanger's equations, air-conditioner uses the genetic algorithm to calculate control variables. Next we will show more detail how the genetic algorithm works.

4.2 Genetic algorithm

4.2.1 Initialization

The air-conditioner generates N feasible solutions for control variables. A $(t_{ind(1)}, t_{ind(2)}, t_{ind(3)}, t_{ind(3)}, Q_T, Q_G, t_{ac}, g_{ac})$ variable set is feasible if the following constraints are satisfied.

$$\begin{aligned}
 t_{ind(1)} &\geq 0 \\
 t_{ind(2)} &\geq 0 \\
 t_{ind(3)} &\geq 0 \\
 t_{ind(1)} + t_{ind(2)} + t_{ind(3)} &= 1 \\
 -Q_{T \max} &\leq Q_T \leq Q_{T \max} \\
 -Q_{G \max} &\leq Q_G \leq Q_{G \max} \\
 t_{ac \min} &\leq t_{ac} \leq t_{ac \max} \\
 g_{ac \min} &\leq g_{ac} \leq g_{ac \max}
 \end{aligned} \tag{1}$$

4.2.2 Mutation

Mutation is the random changing of individual in the new population. The probability of mutation

is P_m , i.e., about $N \times P_m$ individuals are selected for mutating. As we mentioned in previous section, our problem is constraint, thus, each step in optimization process should guarantee that new individual does not violate the constraints. To overcome this problem, we use mutation and crossover mechanisms for constraint problems[16].

First, each individual is selected for mutation with the probability P_m . The position of mutation is from 1-7. If it is from 4-7, the value of $Q_T, Q_G, t_{ac},$ or g_{ac} are chosen randomly in $[-Q_{T \max}, Q_{T \max}], [-Q_{G \max}, Q_{G \max}], [t_{ac \min}, t_{ac \max}], [g_{ac \min}, g_{ac \max}]$ respectively.

If the position of mutation is from 1 to 3, because of the constraints, $t_{ind(1)}, t_{ind(2)},$ and $t_{ind(3)}$ should be changed simultaneously. $(t_{ind(1)}, t_{ind(2)}, t_{ind(3)})$ is a point in the flat:

$$t_{ind(1)} + t_{ind(2)} + t_{ind(3)} = 1 \tag{2}$$

Assume that vector $u=(t_{ind(1)}, t_{ind(2)}, t_{ind(3)})$ is selected for mutation, draw any line through u . This line crosses the bound of the flat at a and b . The new individual is selected randomly in the line from a to b (Fig. 3). Using this kind of mutation, a new individual created by mutation till satisfies the constraints (1).

4.2.3 Crossover

Each individual is selected for crossover randomly with probability P_c , i.e., about $N \times P_c$ individuals are selected for crossover. These individuals are grouped in pairs. Assume that s_1 and s_2 are in a pair. Two new individuals who are created from s_1 and s_2 are

$$\begin{aligned}
 as_1 + (1-a)s_2 \\
 (1-a)s_1 + as_2
 \end{aligned} \tag{3}$$

Where a is selected in $[0,1]$. Because s_1 and s_2 are feasible solutions, therefore, two new individuals, who are defined in above equations, are also feasible solutions.

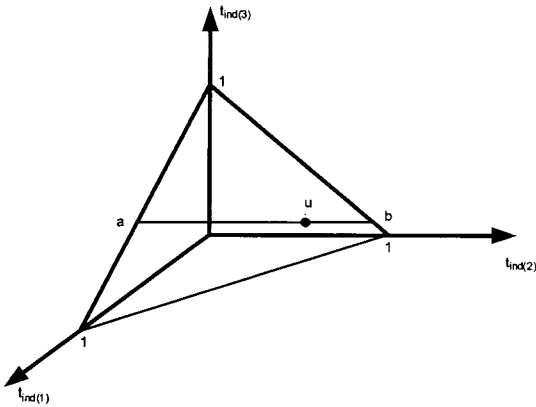


Fig. 3. Random choice of indication time.

4.2.4 Reproduction

Reproduction is an operator where an individual is selected from the initial population, population created from mutation, population created from crossover, and copied into the new population. As in nature, the probability of an individual being selected to pass its genetic material to the next generation depends on its fitness.

Our objective is that the indoor air is kept in the most comfortable state. Therefore, we chose the following function as fitness function

$$f = \frac{1}{PMV_1^2 + PMV_2^2 + PMV_3^2} \tag{4}$$

Where PMV_1 , PMV_2 , and PMV_3 are predicted mean values at the position of the three sensors. To compute PMV , we need to compute the six PMV -influenced factors. Air velocity, activity level, and clo-value are configured by users, radiant temperature is air-conditioner temperature, one of control variables, and air temperature and humidity are defined in (9) and (11). PMV can be obtained from Fanger's tables of PMV for different combination of six factors, or using fuzzy logic, but here we solve Fanger's equations directly by using iterative solution to get PMV .

The reproduction operator employed here determines the probability of selection for individual

i as:

$$P_{select} = \frac{f_i}{\sum f} \tag{5}$$

Where f_i is the fitness of individual i , and $\sum f$ is the summation of all the fitness values for the entire population. In this way the new population will contain more copies of the fit individuals, and fewer copies of the less fit individuals. After reproduction, we have a new generation of N individuals which are better previous generation in term of comfort.

4.1.5 Solution

The genetic loop terminates when there exists an individual in the population which has desired fitness. We chose the individual of the population which has the largest fitness value as control parameter for air-conditioner.

5. IMPLEMENTATION AND SIMULATION

5.1 Hardware implementation.

We do not have enough air-conditioning devices such as chillers, pumps and fans which play process role in the control model; therefore, we cannot implement our model physically. Here, we only simulate the model by programming in Java. In this simulation, we use three sensors which are installed at three corners of a room $6 \times 4 \times 3m'$, and a coordinator which is installed at the remainder corner. The sensors and coordinator are implemented as ZigBee sensor modules based on IEEE 802.15.4 (Fig. 4). The network devices operate on the 2.4Ghz ISM band. A UART/RS-232 interface is implemented in the coordinator to facilitate communication between the network and the PC-based algorithm and simulation. In the real world, the information gathered by the coordinator would be transferred for processing to the air-conditioner control system. For simulation purposes,

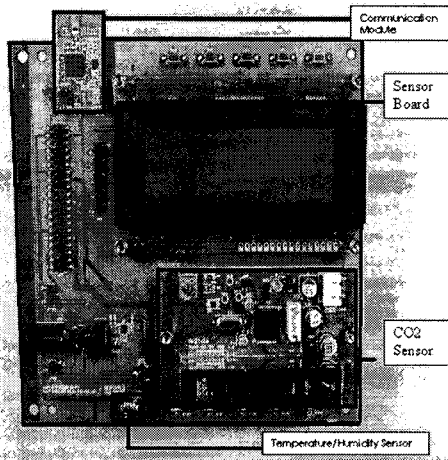


Fig. 4. Coordinator node/Sensor Modules.

the PC would represent the air-conditioner control system. Each module is equipped with temperature, humidity and CO₂ concentration sensors. Data is sent to the coordinator which is considered to be the data center. In real world implementation, the coordinator would be embedded to the air-conditioning unit. The coordinator then transfers the data to the PC using UART interface. Below, Table 1, is a table that summarizes the properties of the temperature and humidity sensors embedded in the devices.

5.2 Context aware service implementation.

For inference engine in the context aware layer, we choose Jess engine[17]. Jess is a rule engine and scripting environment written entirely in Sun’s Java language by Ernest Friedman-Hill at Sandia National Laboratories in Livermore, CA. Jess is small, light, and one of the fastest rule engines available.

In Java application, we simulate three sensors and a coordinator as objects which store information from hardware. Each sensor and coordinator is a JavaBean. They are stored in inference engine in the form of shadow facts which are virtual object as we mention in logical model. A shadow fact is an unordered fact whose slots

Table 1. Sensors Specifications

Accuracy:	Humidity CO ₂ Temperature	±2.0% RH ±50+3% PPM ±0.3 @ 25°C
Range:	Humidity CO ₂ Temperature	0 to 100% RH 0-10000 PPM -40 °C to 123.8 °C
Resolution:	Humidity CO ₂ Temperature	0.03% RH 2 PPM 0.01°C

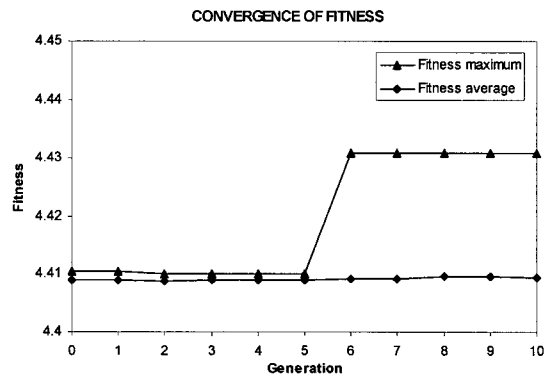


Fig. 5. Convergence of fitness.

correspond to the properties of a JavaBean. JavaBeans are a kind of normal Java object; therefore, shadow facts serve as a connection between the working memory and the Java application inside which Jess is running. When information is updated from hardware, it is automatically updated in inference engine. Then the inference engine links to GA to find optimal operations for air-conditioner.

5.3 Parameter setup and results

We implement an experiment with the following parameters:

- Air-conditioner parameters:
 - $[T_{min}, T_{max}] : [10^{\circ}C, 30^{\circ}C]$.
 - $[H_{min}, H_{max}] : [30\%, 70\%]$.
- Initial air-conditioner parameters (Table 2)

Table 2. Initial parameters

Parameters	Sensor 1	Sensor 2	Sensor 3
Initial temperature (°C)	15	27	35
Outside temperature (°C)	30	30	30
Initial humidity (%)	40	40	40
Outside humidity (%)	50	50	50
Air speed (m/s)	0.1	0.1	0.1
Clothing (clo)	1.1	1.1	1.1
Activity (met)	1	1	1

- Genetic algorithm parameters:

- Population size $N=100$.
- Mutation probability $P_m = 0.01$.
- Crossover probability $P_c = 0.5$.

First, we evaluate the convergence of the genetic algorithm. In fact, when sensors update information, the genetic algorithm is called. Therefore, we can evaluate the algorithm at anytime. In this paper, we choose a random time to test the algorithm. Fig. 5 shows the values of fitness maximum and fitness average for each generation. We can see that after 7 generations, fitness maximum reaches its optimal value. The value of fitness is not important in practice, but we need to search the individual which maximizes fitness. The result also shows that latter generation is better previous one because it has larger fitness value.

By using our algorithm, we can control air-conditioner so that PMV at the positions of the sensors converges to 0 where condition is completely comfortable. The convergence of PMV is as Fig. 6. We can see that, at the beginning, air conditions are much different at three corners. It is hot at sensor 3, cool at sensor 1, and comfortable at sensor 2. After units of times, it is comfortable in whole room (PMV at any position is in the range [-0.5, 0.5]). This result shows that algorithm work effectively in controlling air-conditioner.

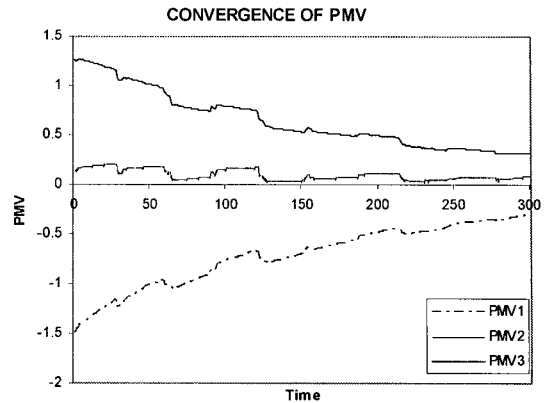


Fig. 6. Convergence of PMV.

6. CONCLUSION

In this paper, we present a context aware layer in air-conditioner. Air-conditioner control problem is considered as decision making issue; therefore, this layer is implemented as a rule-based system. The objective of control is to keep comfortable at whole room and one's comfort depends complexly on six factors which are air-temperature, radiant temperature, humidity, clo-value, air speed, and activity level. This multi-objective optimization is solved by genetic algorithm. The simulation shows that the algorithm operates efficiently; indoor environment is reached and kept in comfortable state. For future work, energy efficiency should be focused.

7. APPENDIX I

7.1 Physical model

Our air-conditioner is a local HVAC system. It is composed by 3 sensors which are installed at 3 corners of the room and control center at the remaining corner (Fig. 7). We also call control center as air-conditioner.

As we presented in section III, six factors which contribute to thermal comfort are air temperature, relative humidity, relative air velocity, radiant

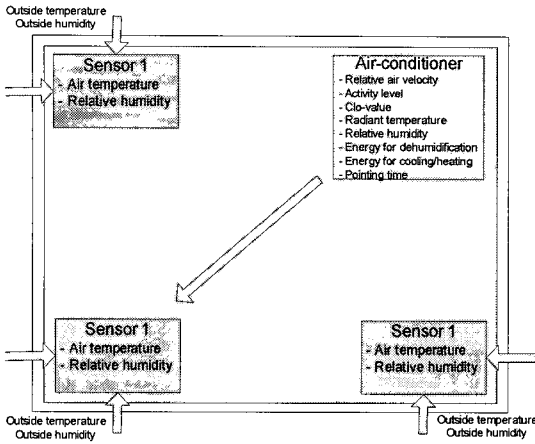


Fig. 7. Physical model.

temperature, activity level, and clo-value. All information should be collected by the air-conditioner. Because temperature and humidity vary frequently, each sensor measures them and sends updated information to air-conditioner. Three parameters air velocity, activity level, and clo-value rarely vary. Therefore, they should be configured by users at air-conditioner. The air temperature from air-conditioner plays the radiant temperature role to compute *PMV*. Based on receipt information from users and sensors, air-conditioner computes control parameters and pumps fresh air to whole the room such that *PMV* at every corner is kept as near 0 as possible, that means, it makes occupants comfortable in whole room. The control parameters are radiant temperature, relative humidity, energy for dehumidification, energy for cooling/heating, and pointing times. In our model, air-conditioner can change the direction of the fresh air stream. A position may be pointed less or more than another position if necessary. Control parameters make temperature and humidity change at each corner according to the trend that composition of six factors creates a comfortable environment for occupant.

7.2 Thermal model

Let's assume that the three parameters air ve-

locity, activity level, and clo-value are fixed and configured by users. The operation of air-conditioner gives effect to air temperature, humidity, and radiant temperature to minimize *PMV* absolute. Now, we consider some thermal equations at each corner by using thermal model in [10].

Nomenclature

t_m	Mixed temperature of recirculation and outdoor air
t_{oa}	Outdoor temperature
t_{ia}	Indoor temperature
g_m	Mixed humidity of recirculation and outdoor air
g_{oa}	Outdoor humidity
g_{ia}	Indoor humidity
m_{oa}	Outdoor air mass
m_s	Mixed air mass
β	coil contact factor
t_{ac}	Air-conditioner temperature
g_{ac}	Air-conditioner humidity
t_c	Temperature after cooling
g_c	Humidity after dehumidification
t_{newia}	New indoor temperature (after a duty cycle)
g_{newia}	New indoor humidity (after a duty cycle)
Q_T	Energy using for cooling
Q_G	Energy using for dehumidification
C_{pa}	Specific heat of humid air
h_{fg}	Latent heat of vaporization of water
t_{ind}	Indication time to the sensor

Air temperature and humidity at each corner are changed according three following processes.

- Mixing of recirculation and outdoor:

$$\begin{aligned} t_m &= xt_{oa} + (1-x)t_{ia} \\ g_m &= xg_{oa} + (1-x)g_{ia} \end{aligned} \quad (6)$$

- Cooling and dehumidification by temperature and humidity from the air-conditioner:

$$\begin{aligned} t_c &= t_m - \beta(t_m - t_{ac}) \\ g_c &= g_m - \beta(g_m - g_{ac}) \end{aligned} \quad (7)$$

- Air-conditioner supply:

$$\begin{aligned}
 t_{newia} &= t_c - \frac{Q_T t_{ind}}{m_s C_{pa}} \\
 g_{newia} &= g_c - \frac{Q_G t_{ind}}{m_s h_{fg}}
 \end{aligned}
 \tag{8}$$

From (6), (7), and (8), we obtain

$$\begin{aligned}
 t_{newia} &= t_c - \frac{Q_T t_{ind}}{m_s C_{pa}} \\
 &= t_m - \beta(t_m - t_{ac}) - \frac{Q_T t_{ind}}{m_s C_{pa}} \\
 &= (1 - \beta)t_m + \beta t_{ac} - \frac{Q_T t_{ind}}{m_s C_{pa}} \\
 &= (1 - \beta)[xt_{oa} + (1 - x)t_{ia}] + \beta t_{ac} - \frac{Q_T t_{ind}}{m_s C_{pa}} \\
 &= (1 - \beta)xt_{oa} + (1 - \beta)(1 - x)t_{ia} + \beta t_{ac} - \frac{Q_T t_{ind}}{m_s C_{pa}} \\
 &= A_T + B_T t_{ia} + \beta t_{ac} - C_T Q_T t_{ind}
 \end{aligned}
 \tag{9}$$

Where

$$\begin{aligned}
 A_T &= (1 - \beta)xt_{oa} \\
 B_T &= (1 - \beta)(1 - x) \\
 C_T &= \frac{1}{m_s C_{pa}}
 \end{aligned}
 \tag{10}$$

Similarly, we also have equation for updating humidity as follows:

$$g_{newia} = A_G + B_G g_{ia} + \beta g_{ac} - C_G Q_G t_{ind}
 \tag{11}$$

Where

$$\begin{aligned}
 A_G &= (1 - \beta)xg_{oa} \\
 B_G &= (1 - \beta)(1 - x) \\
 C_G &= \frac{1}{m_s g_{hf}}
 \end{aligned}
 \tag{12}$$

7.3 Estimating system parameters

In our system, air-conditioner only knows t_{ia} , t_{ac} , Q_T , g_{ia} , g_{ac} , Q_G , and t_{ind} at current time and in the past. The other parameters which can be represented in A_T , B_T , C_T , A_G , B_G , C_G , and β are unknown. Thus, we use Least Mean Square Estimator (LMSE) to estimate them. It leads to

solve a 4th linear equation system.

Let k be the iteration we need to estimate A_T , B_T , C_T , and β . Assume that N previous iterative data t_{ia} , t_{ac} , Q_T , and t_{ind} are given.

From previous section, we have

$$\begin{aligned}
 t_{ia}(k-i) &= A_T + B_T t_{ia}(k-i-1) + \beta t_{ac}(k-i-1) - \\
 &C_T Q_T(k-i-1)t_{ind}(k-i-1) \forall i = \overline{1, N-1}
 \end{aligned}$$

A_T , B_T , C_T , and β should be minimize the following function

$$\begin{aligned}
 f(A_T, B_T, C_T, \beta) &= \sum_{i=0}^{N-1} (t_{ia}(k-i) - A_T + B_T t_{ia}(k-i-1) + \\
 &\beta t_{ac}(k-i-1) - C_T Q_T(k-i-1)t_{ind}(k-i-1))^2
 \end{aligned}$$

$f(A_T, B_T, C_T, \beta)$ is a quadratic function of A_T , B_T , C_T , and β . Thus, A_T , B_T , C_T , and β satisfy the equation $\nabla f(A_T, B_T, C_T, \beta) = 0$. Therefore, it leads to following equation system:

$$\begin{cases}
 N_4 + \left[\sum_{i=0}^{N-1} t_{ia}(k-i-1) \right] B_T + \left[\sum_{i=0}^{N-1} t_{ac}(k-i-1) \right] \beta - \left[\sum_{i=0}^{N-1} Q_T(k-i-1)t_{ind}(k-i-1) \right] C_T = \sum_{i=0}^{N-1} t_{ia}(k-i) \\
 N \left[\sum_{i=0}^{N-1} t_{ia}(k-i-1) \right] A_T + \left[\sum_{i=0}^{N-1} t_{ia}^2(k-i-1) \right] B_T + \left[\sum_{i=0}^{N-1} t_{ia}(k-i-1)t_{ac}(k-i-1) \right] \beta - \\
 \left[\sum_{i=0}^{N-1} Q_T(k-i-1)t_{ind}(k-i-1)t_{ia}(k-i-1) \right] C_T = \sum_{i=0}^{N-1} t_{ia}(k-i)t_{ia}(k-i-1) \\
 N \left[\sum_{i=0}^{N-1} t_{ac}(k-i-1) \right] A_T + \left[\sum_{i=0}^{N-1} t_{ac}(k-i-1)t_{ia}(k-i-1) \right] B_T + \left[\sum_{i=0}^{N-1} t_{ac}^2(k-i-1) \right] \beta - \\
 \left[\sum_{i=0}^{N-1} Q_T(k-i-1)t_{ind}(k-i-1)t_{ac}(k-i-1) \right] C_T = \sum_{i=0}^{N-1} t_{ac}(k-i)t_{ac}(k-i-1) \\
 N \left[\sum_{i=0}^{N-1} Q_T(k-i-1)t_{ind}(k-i-1) \right] A_T + \left[\sum_{i=0}^{N-1} t_{ia}(k-i-1)Q_T(k-i-1)t_{ind}(k-i-1) \right] B_T + \\
 \left[\sum_{i=0}^{N-1} t_{ac}(k-i-1)Q_T(k-i-1)t_{ind}(k-i-1) \right] \beta - \left[\sum_{i=0}^{N-1} Q_T^2(k-i-1)t_{ind}^2(k-i-1) \right] C_T = \sum_{i=0}^{N-1} t_{ind}(k-i)Q_T(k-i-1)t_{ind}(k-i-1)
 \end{cases}$$

Similarly, we have equation system for A_G , B_G , C_G , β

$$\begin{cases}
 N_4 + \left[\sum_{i=0}^{N-1} g_{ia}(k-i-1) \right] B_T + \left[\sum_{i=0}^{N-1} g_{ac}(k-i-1) \right] \beta - \left[\sum_{i=0}^{N-1} Q_G(k-i-1)t_{ind}(k-i-1) \right] C_G = \sum_{i=0}^{N-1} g_{ia}(k-i) \\
 N \left[\sum_{i=0}^{N-1} g_{ia}(k-i-1) \right] A_T + \left[\sum_{i=0}^{N-1} g_{ia}^2(k-i-1) \right] B_T + \left[\sum_{i=0}^{N-1} g_{ia}(k-i-1)g_{ac}(k-i-1) \right] \beta - \\
 \left[\sum_{i=0}^{N-1} Q_G(k-i-1)t_{ind}(k-i-1)g_{ia}(k-i-1) \right] C_G = \sum_{i=0}^{N-1} g_{ia}(k-i)g_{ia}(k-i-1) \\
 N \left[\sum_{i=0}^{N-1} g_{ac}(k-i-1) \right] A_T + \left[\sum_{i=0}^{N-1} g_{ac}(k-i-1)g_{ia}(k-i-1) \right] B_T + \left[\sum_{i=0}^{N-1} g_{ac}^2(k-i-1) \right] \beta - \\
 \left[\sum_{i=0}^{N-1} Q_G(k-i-1)t_{ind}(k-i-1)g_{ac}(k-i-1) \right] C_G = \sum_{i=0}^{N-1} g_{ac}(k-i)g_{ac}(k-i-1) \\
 N \left[\sum_{i=0}^{N-1} Q_G(k-i-1)t_{ind}(k-i-1) \right] A_T + \left[\sum_{i=0}^{N-1} g_{ia}(k-i-1)Q_G(k-i-1)t_{ind}(k-i-1) \right] B_T + \\
 \left[\sum_{i=0}^{N-1} g_{ac}(k-i-1)Q_G(k-i-1)t_{ind}(k-i-1) \right] \beta - \left[\sum_{i=0}^{N-1} Q_G^2(k-i-1)t_{ind}^2(k-i-1) \right] C_G = \sum_{i=0}^{N-1} t_{ind}(k-i)Q_G(k-i-1)t_{ind}(k-i-1)
 \end{cases}$$

Solving above linear equation systems, we can estimate A_T , B_T , C_T , A_G , B_G , C_G , and β easily.

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