Applied Mathematics & Information Sciences
An International Journal

Design and Implementation of CMAC-PMV Thermal Comfort Controller Based on a ZigBee Communication

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Received: 11 Feb. 2012; Revised 16 May 2012; Accepted 01 Jul. 2012

Abstract: Combining transmission of the indoor environmental parameter, e.g. temperature, humidity, air velocity to a PC through a ZigBee module, this work integrates wireless transmission technique with sensors to build a smart controller for home electronics. With Visual Basic .NET 2008 as the software development tool, developed on the basis of a cerebellar model articulation controller (CMAC), a predicted mean vote (PMV) is thus yielded according to all the data sensed. Subsequently, a fuzzy logic controller is introduced into an air conditioning system in such a way that a comfortable living ambiance is achieved and maintained as well effectively in terms of energy saving concern. In the end, using a wireless local area network (WLAN), a smart portable device is made applicable to a long distance monitoring and control system over the air conditioner. Furthermore, the time complexity required in a conventional PMV is hence improved as a consequence of the powerful CMAC learning ability.

Keywords: Predicted mean vote, Cerebellar model articulation controller, Fuzzy, ZigBee.

1 Introduction

There had been a pursuit of a comfort ambiance since the early days of human history. However, due to the variation in races and cultures, the comfort sensation may vary across this planet. For the purpose of a precise and effective description of such sensation, it must be defined in an objective and scientific manner. What is referred to as "comfort" by humans? The answer is essentially the thermal comfort index sensed by human in the outdoor or indoor ambiance. Yet it is a task of great difficulty to well define the individual's thermal comfort index owing to two major concerns, the first of which is the stimulus caused from the ambiance, and the second is related to individual's physical status. Up to now, it remains a controversial issue on the analysis of the index, attributed to temperature, humidity, clothing worn, among other factors. Proposed by the Danish scholar P. O. Fanger [1], PMV, the most widely applied algorithm, is developed based upon the ISO 7730 standard. For instance, by Emerson Donaisky, the index is analyzed with the use of PMV according to the indoor and outdoor humidity [2], integrated with sensor system built for automation, residence, hospitals, etc. [3]. In this work as a way to resolve the difficulties encountered in the implementation of a real time system due to the time complexity required, a combination of CMAC and PMV, referred to as CMAC PMV [4], is presented. Taking advantage of the powerful CMAC learning ability to learn PMV index, the substitution of trained samples results in the consequence intended. As the smart home systems [5,6] become vastly popular, an increasing number of home automatic devices are required to improve human's life quality. The introduction of Zigbee enables smart systems to fit into human's daily life [7–9]. For instance, with a Zigbee module integrated into a TV, a remote control, a building access system, a light bulb, a game machine, an air conditioning system, among other home electronics, the house lighting, temperature, electrical appliances and a safety smart controller is hence implemented. By doing so, the light can be remotely switched on in a direct manner, the light is dimmed automatically the moment the TV set is powered on, or the TV itself is made muted while some one is on the phone. Furthermore, with peripherals equipped with ZigBee, various environmental information is transmitted to a central control unit. Accordingly, a universal remote controller (URC) [10,11] is proposed as a unit to control a variety of home appliances. For the reason that various appliances are linked to the URC using corresponding infrared signal, URC must be able to identify the intended signal from the rest, a task needed to be done for sure. Proposed by a number of researchers, ZigBee is combined with an infrared conversion module to overcome this link problem from various home consumer electronics to URC [12]. In brief, all it takes to control all the home electronics is merely a ZigBee remote controller, compared to those required in the conventional case.

According to a power company, a statistics indicates that a temperature setting increment of 1 $°C$ results in a 6%power saving in an air conditioner, and the temperature setting, ranging from 26 to 28 $°C$, is recommended as the optimal range. In most cases, more energy than required is consumed as a consequence of an inappropriate temperature setting of an air conditioner, resulting in a great deal of CO2 emission, the primary cause of the global warming, against the idea of energy saving and carbon reduction proposed by theWorld Heath Organization (WHO). Aimed at an automatic temperature tuning to reach a comfortable indoor ambiance, the PMV formula is applied effectively to the home electronics automation in this work for the energy saving purpose. Equipped with a wireless transmission module, a smart switch, as the key issue here, is designed to well control the air conditioner in such a way that a superior indoor thermal comfort index is rendered.

2 Predicted mean value

Proposed by Danish scholar P.O. Fanger in 1972, the thermal comfort theory is employed to predict the mean thermal sensation vote, referred to as PMV, on a standard scale for a large number of individuals, according to which an indoor environment comfort index is defined, by the international standard organization (ISO), as the ISO 7730 standard. Over decades, PMV remains widely applied in the thermal field even though numerous studies on the issue of the thermal comfort have been achieved. Using the thermal sensation model, developed based upon a PMV formula, a thermal comfort index [13] of PMV is expressed as

$$PMV = (0.303e^{-0.036M} + 0.028)L \tag{2.1}$$

where L denotes the human thermal load, evaluated as

$$\begin{aligned} L &= (M - W) \\ &- 3.05\times10^{-3}\times[5733 - 6.99(M - W) - P_a] \\ &- 0.42\times[(M - W) - 58.15] \\ &- 1.7\times10^{-5} M(5876 - P_a) \\ &- 0.0014M(34 - t_a) \\ &- 3.96\times10^{-8}\times f_{cl}\times[(t_{cl} + 273)^4 \\ &- (\bar{t}_r + 273)^4] - f_{cl}h_c\times(t_{cl} - t_a) \end{aligned} \tag{2.2}$$

Subsequently, t_{cl} , h_c and f_{cl} are determined respectively by the equations listed as follows.

$$\begin{aligned} t_{cl} &= 35.7 - 0.028(M - W) \\ &- I_{cl}\{3.96\times10^{-8}\times f_{cl}\times[(t_{cl} + 273)^4 \\ &- (\bar{t}_r + 273)^4] + f_{cl}h_c\times(t_{cl} - t_a)\} \end{aligned} \tag{2.3}$$

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} & for\ 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v_{air}} \\ 12.1\sqrt{v_{air}} & for\ 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{v_{air}} \end{cases} \tag{2.4}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290I_{cl} & for\ I_{cl} \le 0.078m^2\cdot°C/W \\ 1.05 + 0.645I_{cl} & for\ I_{cl} > 0.078m^2\cdot°C/W \end{cases} \tag{2.5}$$

where

M = the metabolic rate (W/m^2) or (met)

W = the external work (W/m^2), which is identical zero in most cases

P_a = the partial vapour pressure (P_a)

$\bar{t}_r$ = the mean radiant temperature ($°C$)

V_{ar} = the relative air velocity (m/s)

I_{cl} = the thermal resistance of clothing ($m^2\cdot°C/w$)

t_a = the air temperature ($°C$)

h_c = the convective heat transfer coefficient ($w/m^2\cdot°C$)

f_{cl} = the ratio of surface area of the clothed body to that of the nude body.

Equation (2.2) can be solved iteratively for the PMV for various combinations of parameters, such as the metabolic rate (activity level), the clothing, the air temperature, the mean radiant temperature, the relative air velocity and the relative humidity. Furthermore, using 7-level thermal sensation scale, the thermal comfort index is measured as: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cold), -2 (cool) and -3 (cold). Shown in Figure. 2.1. are the parameters representing various thermal comfort indices. To provide a comfortable indoor ambiance, it is recommended by ISO to maintain a PMV of 0 ± 0.5.

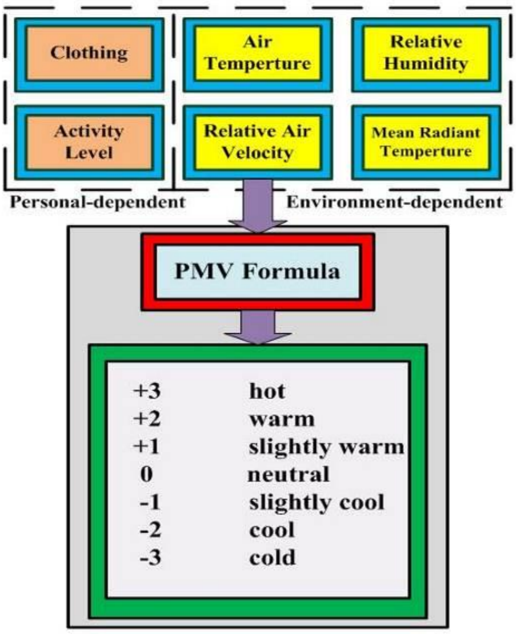

Figure. 2.1. The relation between PMV and thermal comfort indices

3 CMAC PMV

As seen in the previous section, it is known that PMV is a complex formula expressed in an iterative form. As a way to resolve the tedious computing process, this work uses CMAC PMV, an algorithm developed based on a CMAC neural network. Input parameters to CMAC PMV are six major factors identical to those as referred above. Quantified, coded, given active memory address, such major factors are generated with a summed up weighting value, through the CMAC neutral network, which are then adjusted and compared with the ideal output values. This process proceeds until the learning process is completed. With input parameters processed by CMAC, an output is hence yielded after summing up all the active weighting memories, the result of PMV value learned by CMAC. Illustrated in Figure. 3.1. is the evaluation model of the CMAC PMV algorithm.

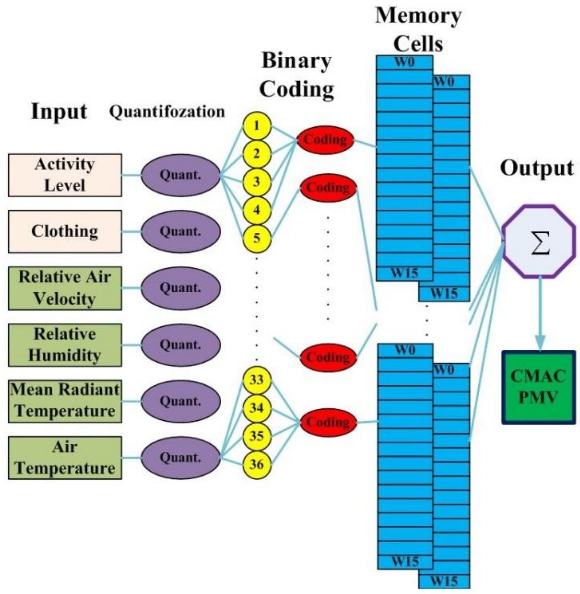

Figure. 3.1. A neural network illustration of CMAC PMV

Input parameters to learning samples are mostly analog signals. Therefore, the CMAC neural network is required to perform quantization on the input parameters prior to the subsequent task. Input parameters, in the range of $[X_{\min}, X_{\max}]$, are quantized with an identical quantization level q_x. A large number of quantization levels leads to a great input parameter resolution at the cost of more memories. Input values, within the above range, are quantized as 0 to $(q_x - 1)$. Otherwise, the quantized values, lower than $X_{\min}$, are modified to 0, those, higher than $X_{\max}$, are adjusted to $(q_x - 1)$. As shown below in Figure. 3.2., the quantization level $(q_x - 1)$ is set to 64, and then the resultant quantization level index falls within the range of 0 to 63.

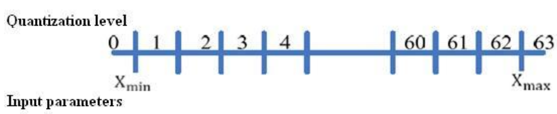

Figure. 3.2. Illustration of the input parameter quantization

The mapping mechanism is illustrated in Figure. 3.3. with an instance as follows. Encoded as 001101011111011100010110110010010100, the input vector is partitioned into nine segments, each containing four bits, and then rearranged in sequence from the least to the most signification bits. Nine active addresses are associated with the association memory, that is, A1=3, A2=5, A3=15, A4=7, A5=1, A6=6, A7=12, A8=9, and A9=4, respectively.

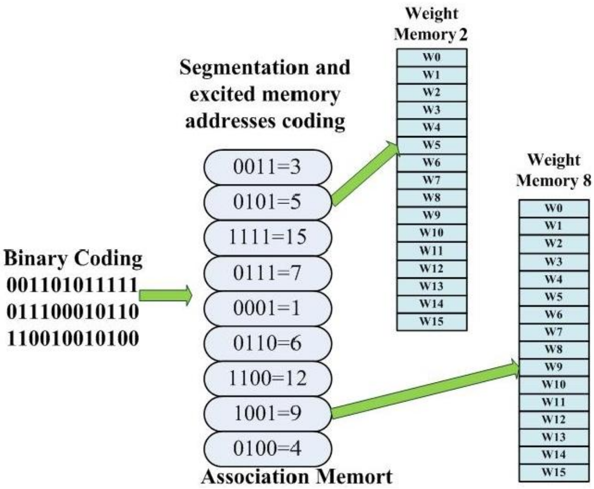

Figure. 3.3. The mapping mechanism between associated addresses and memories

Next, considering the mapping between the active addresses and the associated weighting values in the weighting memory, all the active weighting values are summed up to yield the output of CMAC PMV, that is

$$y = \sum_{j=1}^{k} W_j^{a_j} \tag{3.1}$$

where k is the active number of the memory, a_j the active address of the memory, and W_j the weighting value. The weighting values are updated based on the gradient desired descent method so that an intended training signal is reached by the mapping. Thus, a learning process is adopted to modify the weights through an updating function using the difference between the set of desired parameters and that generated by the CMAC for each training pattern. The updating function is expressed as

$$\hat{W}_j = \overline{W}_j + \mu \frac{\varepsilon_i}{k} \tag{3.2}$$

where j denotes the stage index of the training process, $\overline{W}_j$ and $\hat{W}_j$ the weighting value before and after the jth updating stage respectively, μ a learning rate, ε_i the output error between the intended training signal and output signal , and i the number of learning data.

The learning process will terminate as the difference between the parameter sets generated by the network and those intended for the sampled patterns falls within a specified tolerance. With one of the supervisor learning for various patterns of CMAC here, the least square error, as the learning performance, is defined as

$$E = \sum_{j=1}^{D} (y_j - 1)^2 \tag{3.3}$$

where D denotes the number of pattern data, and y_j the sum of the weighting values of the jth step. A positive number ε is defined as the tolerance $(\varepsilon > 0)$ and the learning will be terminated in case of $E > \varepsilon$.

The procedure of the proposed CMAC PMV is detailed as follows.

Step 1: Set up the CMAC model. Discretize and quantize the input variables into n associated levels and draw a relative level numbering from 0 to $2^n - 1$.

Step 2: Perform a binary coding on the input vector level.

Step 3: Partition the code into nine segments, each containing four bits, and then rearranged in sequence from the least to the most signification bits.

Step 4: Modify the weighting values in the weighting memory according to active memory addresses.

Step 5: Given the training patterns, then initialize the learning algorithm of CMAC.

Step 6: Discretize these 6 input parameters, and finish the coding procedure, i.e. activating memory, summing up all the active weighting values and determining the output value of CMAC PMV.

Step 7: Confirm the CMAC PMV whether the thermal comfort level lies between +0.5 and the -0.5.

Step 8: Until the value of PMV is obtained and lie in the range of an intended comfort level, skip back to step 5 and modify the indoor temperature setting for the interned comfort.

4 Hardware link and system design

It is known from Section 3 that the PMV index is precisely evaluated by the substitution of six parameters into a trained CMAC structure.

Subsequently, the PMV index is applied to an air conditioning system control. To begin with, the ambiance data sensed are transmitted from sensors to a coordinator, with the use of a ZigBee module, and then to a PC through RS-232, while the air velocity, measured by a wind gauge, is directly delivered to the PC through RS-232 as well. According to the thermal comfort index evaluated with a CMAC PMV formula, the system response is determined by a fuzzy logic controller, and displayed at the same time on PDA through a WLAN. The overall system link is illustrated in Figure. 4.1..

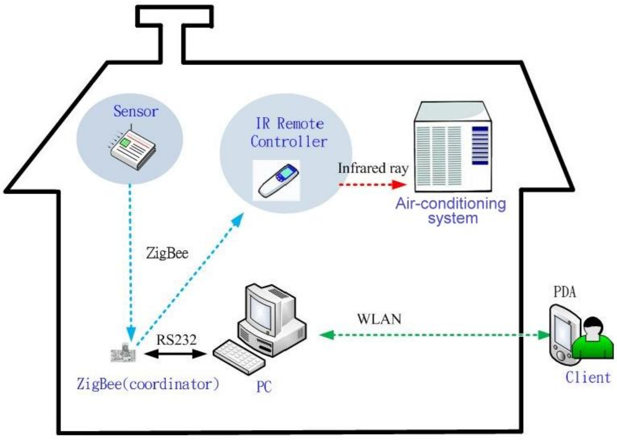

Figure. 4.1. The system link

The design procedures are stated as follows.

Step 1: Design an interface to PC. As the first step, Visual Basic .NET 2008 is utilized as the interface development tool, by which an RS-232 interface is developed with serial port and baud rate specified, and another interface for the data reception of temperature, humidity, and air velocity is built subsequently. Finally, the environmental data, sensed by an end device FT-6251, is transmitted to a coordinator FT-6250, through ZigBee, and then to the PC by way of RS-232.

Step 2: An air conditioner system controller design as pictured in Figure. 4.2., built with a chip HT622, an IR remote control is triggered through a ZigBee module FT-6260. With a 3V relay as a triggering component, the command over the air conditioner is carried out through the conduction of the 3V relay powered by the ZigBee module.

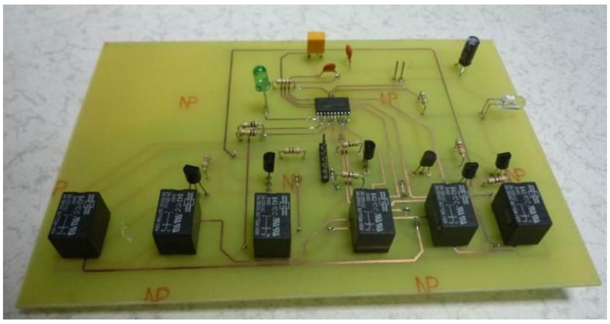

Figure. 4.2. An entity photo of an infrared emission device

Step 3: A fuzzy logic controller design. Taking into account two parameters, i.e. the indoor temperature and the temperature drop between the indoor and outdoor ambiances, the PMV index is then tuned by a fuzzy logic controller. In the case of a hot outdoor ambiance, the indoor temperature is required to be a little cooler than expected regularly to make human a comfortable environment when entering a building. For the purpose of a fuzzy logic controller implementation, through the Matlab FIS editor, the membership functions, corresponding to the parameters referred previously, are defined to provide the output, based upon which the PMV index is tuned. Presented in Figures. 4.3. to 4.5. are the membership function plots made by the FIS editor.

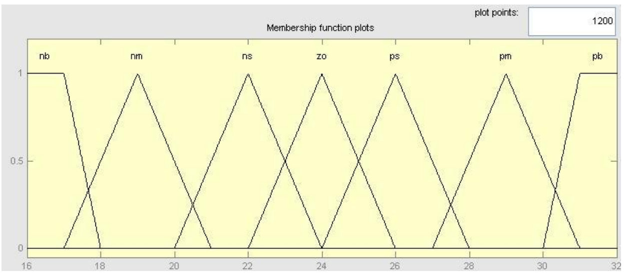

Figure. 4.3. Indoor temperature membership function

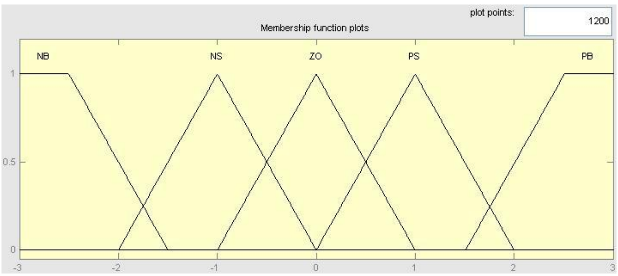

Figure. 4.4. Temperature drop membership function between the indoor and outdoor temperatures

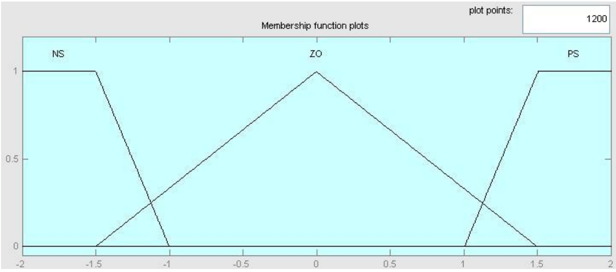

Figure. 4.5. Output membership functions

Subsequently, we now proceed to edit fuzzy rule base in rule editor, and then an outcome is yielded by conducting an inference rule base. Tabulated in Table. 4.1. is a fuzzy rule table. Integrated into the back end of CMAC PMV, the well designed fuzzy logic controller is then employed to make a decision whether to tune the PMV index. The indoor temperature range, from 16 to 32 $°C$, is divided into seven intervals, i.e. from NB to PB, while the temperature drop is defined as the difference between the outdoor and the indoor temperature, with the indoor as the reference. For instance, an outdoor temperature of 32 $°C$ and an indoor of 28 $°C$ yield a temperature drop of 2 $°C$, denoted as +2. Tabulated in Table. 4.2. are the outcome and index tuning encountered in three cases.

Table. 4.1. Fuzzy rule table

	Ta				
IT	PB	PS	ZO	NS	NB
PB	PS	PS	PS	ZO	ZO
PM	PS	PS	ZO	ZO	ZO
PS	PS	ZO	ZO	ZO	ZO
ZO	PS	ZO	ZO	ZO	NS
NS	ZO	ZO	ZO	ZO	NS
NM	ZO	ZO	ZO	NS	NS
NB	ZO	ZO	NS	NS	NS

Note: Ta represents the temperature drop and IT the indoor temperature

Table. 4.2. Relations between outcomes and PMV

Output	NS	ZO	PS
Thermal comfort index	-1	No adjustment	+1

As seen in Table. 4.2., the outcome ZO signifies that there is no need to tune the index, while the outcome NS indicates that the index is required to be tuned a level down toward slightly cool, and the outcome PS a level up toward slightly warm. Finally, corresponding to the function keys in an air conditioner, the index is tuned as hot, warm, slightly warm, neutral, slightly cool, cool and cold. As presented in Table. 4.3., in response to an outcome Hot, the air conditioner is switched automatically to Cold promptly, an outcome Neutral, the air conditioner remains unaffected, and an outcome Cold, the air conditioner operates toward an indoor temperature of 30 $°C$. The thermal comfort is hence maintained with seven levels of temperature tuning.

Table. 4.3. Relations between outcomes and function keys

Comfort level	Hot	Warm	Slightly warm
Air-conditioning function keys	Cold promptly	Strong cold	Weak cold
Comfort level	Neutral	Slightly cool	cool
Air-conditioning function keys	None	26°C	28°C

Step 4: The link design between a PDA and a PC. With a PDA as a remote control, the residence as well as the air conditioner status can be monitored in a remote manner. Firstly, with a PDA interface linked to PC by way of WLAN, the environmental data sensed is transmitted to the PDA, through which the air controller is controlled using TCP/IP protocol and a Client/Server network. Illustrated in Figure. 4.5. is the Socket operation principle.

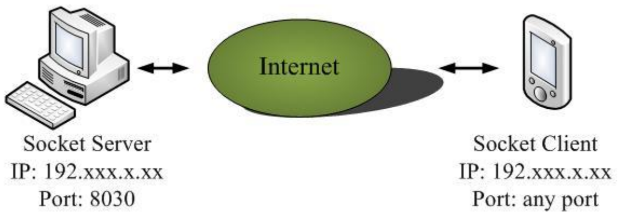

Figure. 4.5. Socket operation principle

Subsequently, the link between the PDA and PC is established for data transmission. The indoor temperature and humidity are transmitted from PC to the PDA, which sends a command, back to PC, whether to power on the air conditioner.

5 Experiment Results Analysis

The results are analyzed in the following four aspects, that is, the comparison between ISO and CMAC PMV, environmental parameter simulations, scene modes and a PDA monitoring system.

5.1 Comparison results between ISO PMV and CMAC PMV

Compared in the same context, the results by CMAC PMV, tabulated in Table. 5.1., are in good agreement with those by ISO PMV, a validation of the CMAC PMV approach.

Table. 5.1. Experimental PMV indices conducted by ISO PMV and CMAC PMV

Temperature	15	16	17	18	19	20
ISO PMV	**-4.59**	**-4.20**	**-3.80**	**-3.41**	**-3.01**	**-2.61**
CMAC PMV	**-4.60**	**-4.20**	**-3.80**	**-3.40**	**-3.05**	**-2.61**
Temperature	21	22	23	24	25	26
ISO PMV	**-2.21**	**-1.80**	**-1.39**	**-0.98**	**-0.57**	**-0.15**
CMAC PMV	**-2.21**	**-1.82**	**-1.38**	**-0.98**	**-0.57**	**-0.15**
Temperature	27	28	29	30	31	32
ISO PMV	**0.27**	**0.70**	**1.12**	**1.55**	**1.98**	**2.43**
CMAC PMV	**0.28**	**0.69**	**1.12**	**1.55**	**1.97**	**2.43**

(Activity level：1.0met, Clothing：0.5clo, Air velocity：0.2m/s, Humidity：70%)

Temperature	15	16	17	18	19	20
ISO PMV	**-2.22**	**-1.96**	**-1.69**	**-1.42**	**-1.16**	**-0.89**
CMAC PMV	**-2.23**	**-1.96**	**-1.69**	**-1.42**	**-1.18**	**-0.89**
Temperature	21	22	23	24	25	26
ISO PMV	**-0.63**	**-0.37**	**-0.12**	**0.14**	**0.41**	**0.67**
CMAC PMV	**-0.63**	**-0.38**	**-0.11**	**0.15**	**0.41**	**0.67**
Temperature	27	28	29	30	31	32
ISO PMV	**0.94**	**1.20**	**1.47**	**1.75**	**2.02**	**2.30**
CMAC PMV	**0.94**	**1.20**	**1.48**	**1.75**	**2.02**	**2.31**

(Activity level：1.2met, Clothing：0.7clo, Air velocity：0.1m/s, Humidity：50%)

5.2 Ambiance parameters simulation

The PMV index is now simulated in the presence of six parameters (2 personal-dependent and 4 environmental ones), that is, the temperature, the humidity, the air velocity, the radiance, the clothing and the activity level. The activity level together with clothing, shown in Tables. 5.2. and 5.3., is made according to the ISO 7730 standard and the ASHRAE Standard 55 [14].

Table. 5.2. Relation between activity levels and metabolic rate

Activity level	Metabolic rate
Sleep	0.7
Sat	1
Sitting in office	1.2
Back and forth	1.7
Driving	1.0~2.0
Cooking	1.6~2.0
Dance	2.4

Table. 5.3. Relation between seasons and clothing

Season	Clothing clo
Spring	0.5
Summer	0.7
Fall	0.7
Winter	0.9

With the indoor temperature considered as the major concern, the index simulation is made with minor concerns such as sleeping, sitting idly, sitting in office and pacing around, over a air velocity range of 0.1 to 0.3 m/s, a clothing range of 0.5 to 0.7clo, and a humidity range of 40% to 70%. As presented in Figure. 5.1., the block-A displays the environmental parameter settings, block-B the comfort level evaluated by CMAC PMV, and block-C the air conditioner response. As tabulated in Table. 5.4., the simulation outcome is related to such seven environmental parameters. Pictured in Figure. 5.2., an infrared emission circuit, commanded by a PC through a ZigBee, activates specific relays to perform corresponding functions.

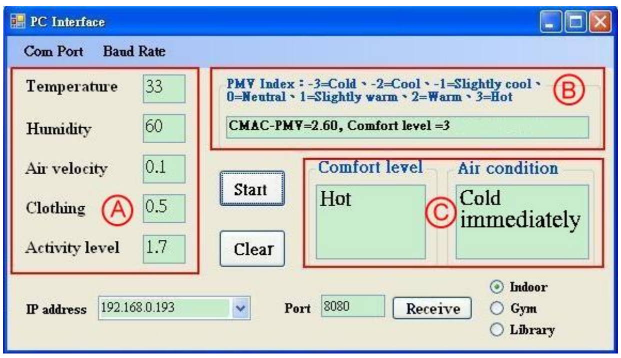

Figure. 5.1. The simulation of environmental parameter.

Table. 5.4. Simulation Results of seven environmental parameters

Simulation environmental parameters				
Temperature (℃)	Relative Humidity (%)	Air velocity (m/s)	Activity level (met)	Clothin (clo)
33	60	0.1	1.7	0.5
30	50	0.15	1	0.6
28	55	0.15	1.2	0.5
26	45	0.15	1	0.7
24	40	0.2	1.2	0.5
22	50	0.1	1	0.5
19	45	0.15	0.7	0.7

Output			
Temperature (℃)	Classification	State comfort	Air-conditioning settings
33	3	Hot	Cold immediately
30	2	Warm	Strong cold
28	1	Slightly warm	Weak cold
26	0	Neutral	None
24	-1	Slightly cool	26℃
22	-2	cool	28℃
19	-3	cold	30℃

Figure. 5.2. A combination of a ZigBee modules and an infrared emission device

5.3 Scene modes

In this work, the comfort index is as well considered, within a gymnasium and a library. The intended temperatures in both cases are expected to be lower than those in most cases. Thus, ahead of the index evaluation, the temperature parameters are elevated by a temperature increment of 2 $°C$ and 1 $°C$ in the gymnasium and the library, respectively. For instance, in the interior to the gymnasium at a temperature of 26 $°C$, the temperature parameter is set to 28 $°C$. Displayed in Figs. 5.3. to 5.5. are the comfort indices in the same condition for the regular interior, the gymnasium and the library.

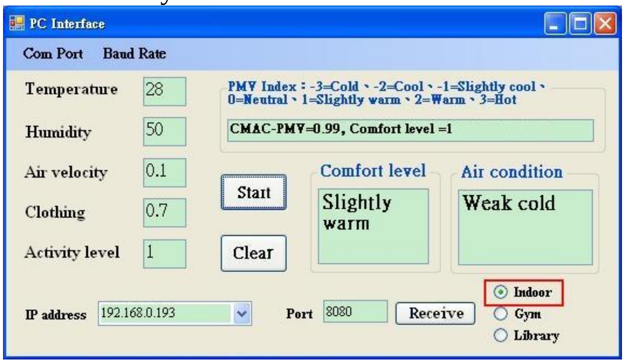

Figure. 5.3. An indoor PMV index

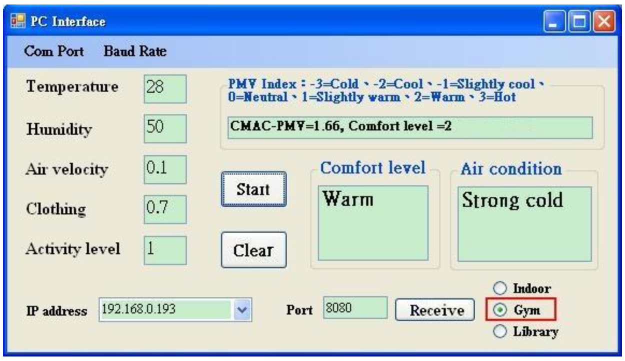

Figure. 5.4. A PMV index within a gymnasium

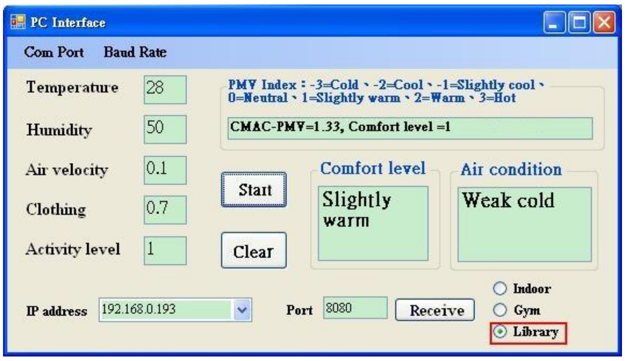

Figure. 5.5. PMV index within a library

As compared between Figs. 5.3. and 5.4., in the same context, the comfort indices, corresponding to the regular interior, and the gymnasium, are slightly warm and hot, respectively. As expected, various ambiance results in various comfort indexes for the purpose of the accomplishment of the optimal comfort sensation as well as the optimized air conditioner control.

5.4 PDA monitoring

As for the PDA monitoring, setting up the PC IP address and port, the data transmission link is established in a way that 1. presses the Receive key on the PC to initialize a server, 2. enters such IP address into the PDA, and 3. presses the Connect key. As pictured in Figure. 5.6., the temperature and humidity is transmitted to and then registered on the PDA, and in Figure. 5.7., enter open/close to power on/off the air conditioner. The moment the PC receives the message open/close, a command is issued to turn on/off the air conditioner, through the ZigBee module combined with the infrared emission device.

Figure. 5.6. Humidity reading, sent from a PC, is registered on a PDA

Figure. 5.7. Enter Open to power on an air conditioner

6 Conclusion

It is validated by the simulation in this work that the proposed CMAC PMV, in place of a tedious conventional PMV formula, is a scheme applicable to the precise determination of the thermal comfort index, and through a ZigBee module and an infrared remote control, the comfort index is thus maintained as a consequence of the optimized air conditioner control on the issue of energy saving and carbon reduction. At length, with a PDA as a smart mobile device, linked to a PC through a WLAN, the residence status is monitored, and the air conditioner is controlled as well any time by a person mile away. Unlike a conventional home automation, the comfort index, by CMAC PMV in this work, is determined according to such parameters as the air velocity, the clothing, the activity level, etc, other than temperature and humidity. Taking more parameters into account, the system developed enables the air conditioner to be operated toward the specified temperature setting at intended cooling rates.

Acknowledgements

The financial support provided to this study by the National Science Council of the R.O.C. under Grant Nos. NSC-99-2221-E-167-027 is greatly appreciated.

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