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DESIGN AND DEVELOPMENT OF FANGER MODEL AND FUZZY LOGIC BASED CONTROLLER FOR AIR CONDITIONERS

Keh-Kim Kee, Angelo Emanuel Robin, William K.S Pao

ABSTRACT

Air conditioner is an essential appliance to provide human comfort environment for individual needs. For a tropical country, Malaysia has temperature fluctuation between 29 ˚C to 34 ˚C and humidity in range of 70% to 90%, air conditioner is essentially used to achieve user comforts particularly thermal comfort. However, satisfying the needs of human comfort by using air conditioner often cause the over-consumption of energy due to lack of use of intelligent and efficient control. The traditional air conditioners are typically run at constant and fixed speed has limited options to control conditioned air temperature at reduced energy consumption and achieving human thermal comfort of conditioned space. In this study, the physical parameters of Fanger's model and Predicted Mean Vote (PMV) are used to design an innovative air conditioner controller, which is adaptively controlled by fuzzy logic to drive both fan and cooler speed by taking consideration of cooling effect of air flow variation. With the developed algorithm and controller prototype, energy consumption is optimised or minimised for the best financial outcome without sacrifice of human comfort. To validate the performance of the proposed model, the results from both microcontroller prototype and MATLAB simulation are compared for validation purpose. It has shown that both results exhibits less than 1% performance deviation in terms of computation and the potential of energy saving up to 49%

Keywords: Thermal Comfort; PMV, Air Velocity, Adaptive, Energy Saving, Efficiency, Fuzzy Logic

INTRODUCTION

For tropical country like Malaysia with temperature fluctuates between 29 ˚ C to 34 ˚ C and humidity in the range of 70% to 90% (Daghigh R., 2015), air conditioner has become an essential part of living life to maintain human comfort. There are many types of air conditioners namely split-unit type, centralized unit and window air conditioner (Bright, 2015). These appliances are commonly used to provide human comforts of occupants, particularly thermal comfort by cooling the air temperature and decrease of humidity for so-called "conditioning" of the air space. However, satisfying the needs of human comfort without intelligent control always causes overconsumption of energy of air conditioner. In addition, rapid development of economic buildings constructions has also caused an increment of power consumption year by year (Carbon, 2012). As a result, over-consumption of air conditioning energy is commonly found up to 75% (Saha S., 2014).

Air temperature, humidity and air velocity are three parameters which significantly affect human thermal comfort. The conventional ON/OFF control of air conditioner has limitations namely limited user options to control the temperature and humidity, and the manual operation is designed with constant parameters without consideration of dynamic nature of environment. For instance, while the temperature is set at 24 ˚ C, the cooling will take place until room temperature reaches the set point and the compressor is turn off. Thereafter, the room temperature will increase rapidly before the compressor is turn on again. The frequent on-off cycles can significant affect the user comfort level and power supply problems such high surges in power consumption and energy inefficacy. Thus, an intelligent and adaptive control mechanism by taking user thermal comfort into account is required.

Fuzzy logic has been widely used for adaptive control with outstanding performance in many application domains. The fuzzy logic based controllers can decide the desired output of air conditioner system by taking the crisp inputs from sensors, and convert it with fuzzification. The fuzzy rules are set in the inference engine and the crisp output is produced with defuzzificaiton for adaptive control signal. The main objective of this project is to design and develop an embedded system controller based on Fanger model of thermal comfort which can adaptively control the operation of air conditioner by considering the environmental parameters with fuzzy logic control. Data of three influencing factors namely air temperature, humidity and air velocity are collected by using sensors with Predicted Mean Vote (PMV) are used for adaptive comfort level control based on fuzzy logic to drive the output of both compressor speed and fan speed. The adaptive signal is generated in accordance to actual environment condition which optimally adjusts the thermal comfort at minimal energy consumption. The paper is organised as follows. In section 2, we review the background and related works. Section 3 describes the proposed system and architecture will be shown. In section 4, the system implementation of the proposed system is examined with experimental results. Finally, conclusion and future work are given.

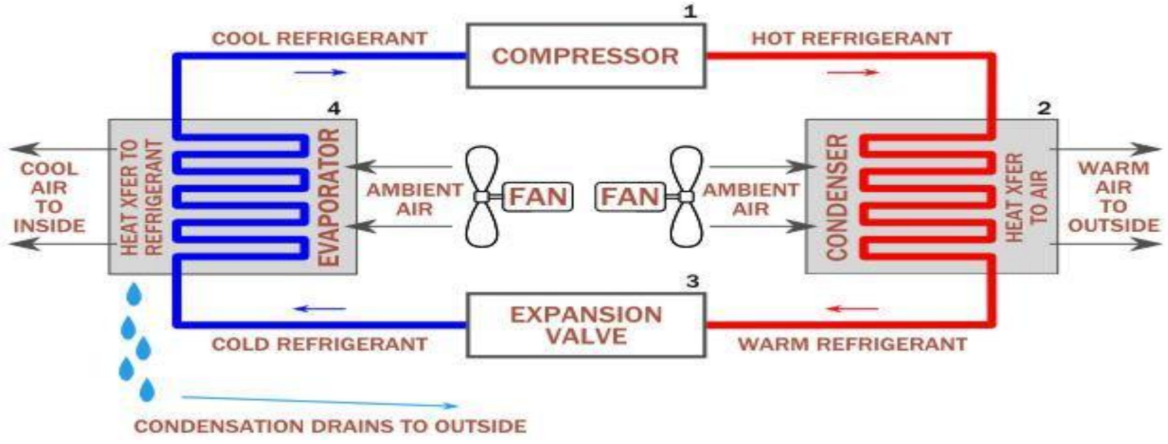
LITERATURE REVIEW

In this section, background knowledge and related work are reviewed. First we discuss the basic principles of air conditioner and Fuzzy Logic. Then we discuss the thermal comfort based Fanger's model and its parameters of PMV and PPD. The effects of air velocity on thermal comfort are described. Lastly, we discuss several related works to date.

Basic Principle of Air Conditioner

Air conditioner is used as temperature control, dehumidifier and air filtering to achieve human comforts of the occupants in buildings. Its operation is based on phase conversion by using the refrigerant as depicted in Figure 1. The cool refrigerant in compressor changes its state from gas to liquid which the heat is pass through the condenser and fin coil for dissipation outside of the building. As the gas cools down, the refrigerant turns back to liquid and forced into the expansion valve to form mist. As the pressure drops and expansion of the material results in rapid cooling of the fluid. At the evaporator coil, the cool air blows to cool down the space and finally the cycle repeat again (Chris W., 2014).

Figure 1: Air Conditioning System Diagram



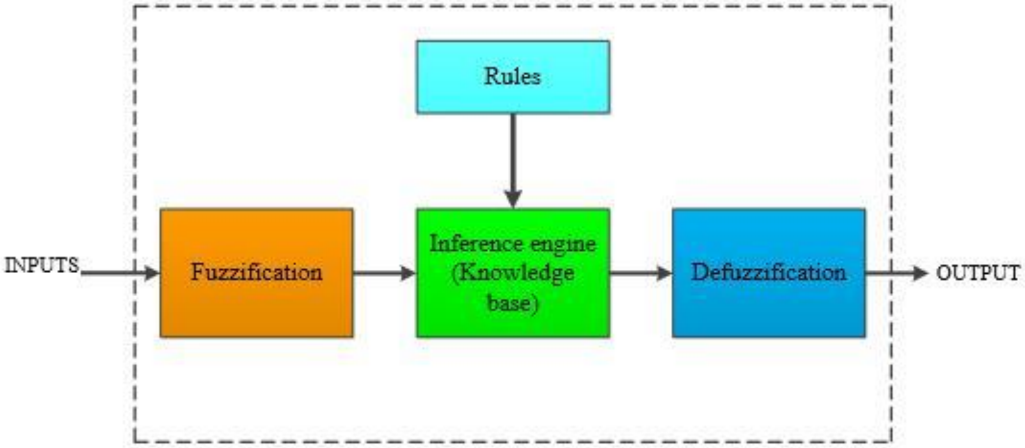
Source: Woodford C. (2014)

Fuzzy Logic

Fuzzy logic is an intelligent system that imitates the logic of human thought and used as a solution in many control problems. It was first proposed by L. A. Zadeh of the University of California at Berkeley in 1965 (Zadeh L., 1965). Fuzzy logic extends the traditional logic 0 and 1 into the concept of partial truth which the machines are able to understand and respond to human concept such as tall, short, hot, cold and etc. It is commonly employed in the applications such as washing machines, vehicles, cameras and others (Tarun K., 2013).

Fuzzy logic system consists of four components namely fuzzier, inference engine, fuzzy rule base and defuzzier as depicted in Figure 2. At Fuzzifier, the crisp inputs are converted to into suitable linguistic variables through Fuzzification process whereby the membership functions are defined. With the inference engine, the Fuzzy Rules, i.e. IF-THEN rules derived from the input linguistic values and output linguistic variables which are extracted from expert knowledge and experience in application domain. Finally, the Defuzzier produces the final crisp value from the output linguistic values.

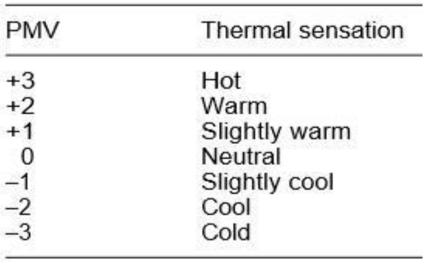
Figure 2: Fuzzy Logic Block Diagram



Thermal comfort and Fanger's Model

Thermal comfort is the condition of mind which expresses the satisfaction of conditioned space of occupants with thermal environment. According to Fanger's model, thermal comfort can be quantified if the parameters of environmental factors and personal factors namely air temperature, radiant temperature, air velocity and relative humidity, clothing insulation and activity level are known (Fanger P., 1967). In term of bodily sensations, it is a sensation of hot, warm, slightly warmer, neutral, slightly cooler, cool and cold. From the physiological point of view, thermal comfort occurs when there is a thermal equilibrium in the absence of regulatory sweating between the heat exchange between the human body and the environment (Stachowicz, 1986). Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are two indices used to describe thermal comfort by using heat balance equations and empirical studies. The 7-point Likert scale of PMV ranging from Hot (+3) to Cold (-3) is used to define user's thermal comfort condition as illustrated in Table 1.

Table 1: 7-point Likert scale of PMV and Thermal Sensation



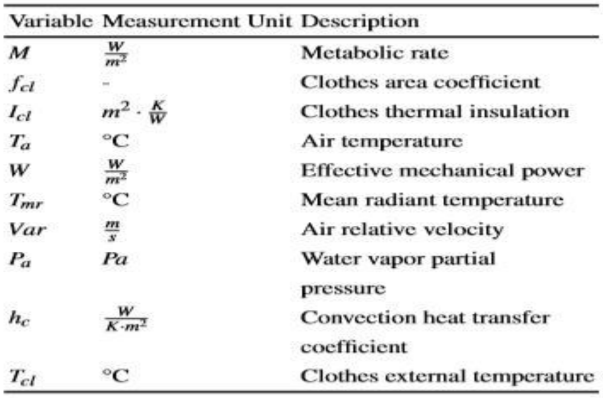
PMV	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

Source:ASHRAE (2013)

The model is currently adopted by ASHRAE as an ISO standard to define user thermal comfort condition (ASHRAE, 2013). The equation of PMV is shown in Equation 1 with variables used in Table 2

$$\begin{aligned} PMV = {} & [0.303.e^{-0.036.M} + 0.028].\{(M - W) - 3.05.10^{-3}.[5733 - 6.99.(M - W) - Pa] \\ & - 0.42.(M - W - 58.15) - 1.72\ X\ 10^{-5}.M.(5869 - Pa) \\ & - \left(0.0014.M.(34 - Ta) \pm \frac{1}{I_{cl}}.\left(T_{cl} - 35.7 + 0.028.(M - W)\right)\right\} \ldots\ldots \text{(1)} \end{aligned}$$

Table 2: Description and Measure Units used in PMV Equation

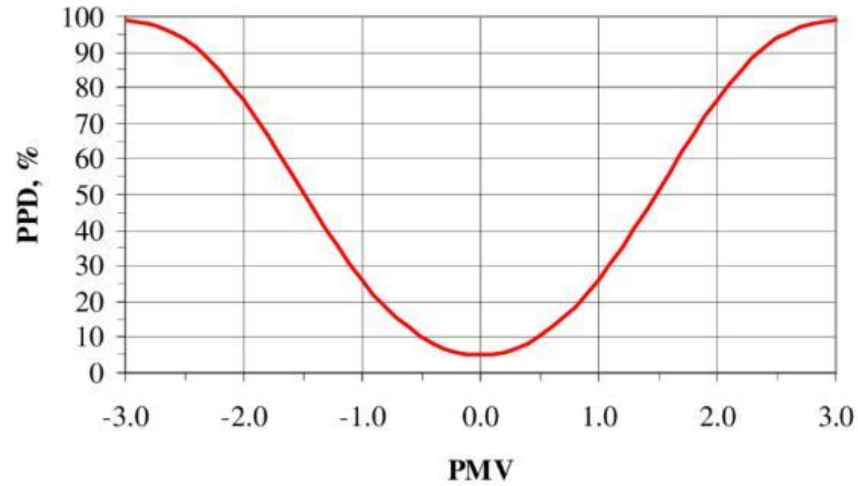


Variable	Measurement Unit	Description
M	$\frac{W}{m^2}$	Metabolic rate
f_{cl}	-	Clothes area coefficient
I_{cl}	$m^2 \cdot \frac{K}{W}$	Clothes thermal insulation
T_a	°C	Air temperature
W	$\frac{W}{m^2}$	Effective mechanical power
T_{mr}	°C	Mean radiant temperature
Var	$\frac{m}{s}$	Air relative velocity
P_a	Pa	Water vapor partial pressure
h_c	$\frac{W}{K \cdot m^2}$	Convection heat transfer coefficient
T_{cl}	°C	Clothes external temperature

When the PMV scale is at 0 which is neutral, the individual should feel comfortable and the Predicted Percentage of Dissatisfied is minimum at 5%. As PMV moves farther from 0 (neutral), the PPD is correspondingly increased. The data was collected from large group of people placed in different climate chamber condition and make them pick out a position in the scale describing their comfort sensations. All the environment and individual factors then derived from the data. The mathematical function and relationship of PMV and PPD based on individual thermal studies represented in Equation 2 and Figure 3 respectively.

$$PPD(PMV) = 100 - 95.exp(-0.03353PMV^4 - 0.2179PMV^2) \ldots\ldots(2)$$

Figure 3: PMV and PPD Curve

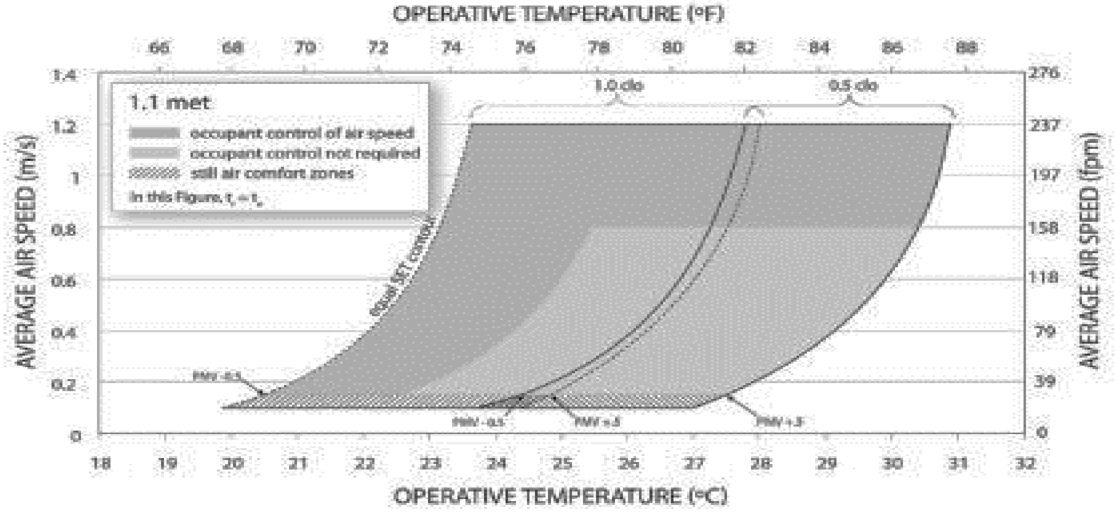


Effect of Air Velocity on Thermal Comfort

Air velocity is a parameter that relates to the consideration of heat loss by convection. It is directly related to the amount of energy exchanged in this physical process. Air movement can have a significant influence on human thermal comfort. The computation of standard effective temperature (SET) from ASHRAE Thermal Comfort Tool can be used to demonstrate the increased cooling effect due to variation of air flow (ASHRAE, 2013). For the condition of 35^{o}C air temperature, mean radiant temperature of 35^{o}C, 70% of relative humidity, and personal factors of 1.0 MET and 0.22 clo, SET values has found as 29.3^{o}C and 36.3^{o}C at air velocity of 1.0 m/s and 3.0 m/s respectively. It implies that an increased cooling effect of a uniform air speed from 0.15 m/s to 3.0 m/s can be seen to be 7.0^{o}C, based on the SET difference obtained. The air velocity is likely to complement the cooling effect of air conditioner by air speed control to achieve better energy efficiency.

According to ASHRAE Standard 55-04, the effect of air speed for thermal comfort can be illustrated graphically by the chart of acceptable ranges of operative temperature limit (to) and average air speed (va) as depicted in Figure 4. It has been shown that above 0.2 m/s of average air velocity, the increase of air flow results an increase of to (upper and lower) for comfort zone. In term of energy saving due to cooling effect of 7^{o}C (at 3.0 m/s) with fan control, it has been experimentally found 7-10% of net energy saving per degree thermostat rise. One of the studies found that 5^{o}C cooling effect can save up to 50% of energy saving (Aynsley R., 2006).

Figure 4: Acceptable ranges of operative temperature limit (t_o) and average air speed (v_a).



Source:ASHRAE (2013)

Existing Intelligent Controllers of Air Conditioners

There were several related works and studies on the controllers of air conditioners. Vikas Kumar et al. (Kumar V., 2014) has proposed the use of Fuzzy Logic controller for air conditioner to maintain human comfort while achieving energy conservation in hospital. FL controller adopts the parameters of air temperature, humidity and oxygen content, to generate adaptive control signal to drive air conditioner, specific to health institute. However, cooling effect of air flow was not taken into consideration. Tarun Kumar Das et al. (Tarun K., 2013) has presented a combined FL controller design to control both humidity and temperature only while other parameters are assumed constant. The temperature controller obtains ambient temperature to compare with the set point in order to the output speed of cooling/heating fan while the humidity controller is used to adaptively control the humidifier and exhaust fan. The proposed model was simulated in MATLAB/Simulink environment. Similarly, Lucio Ciabattoni et al (Ciabattoni L., 2015) has designed an indoor thermal comfort FL controller by considering two scenario cases. The office scenario adopts constant indoor comfort temperature while the residential scenario with PMV index is adaptively changed according to seasons. Henry N et al (Nasution, H., 2016) proposed indoor temperature control of split unit air conditioning system by using Fuzzy Logic. The adaptively controlled compressor able to achieve thermal comfort with up to 37% energy saving as compared to the traditional controller. It has been shown that the potential cooling effect of air velocity in thermal comfort was ignored by previous researchers, and there exists a literature gap of study to maximize thermal comfort and energy efficiency of air conditione.

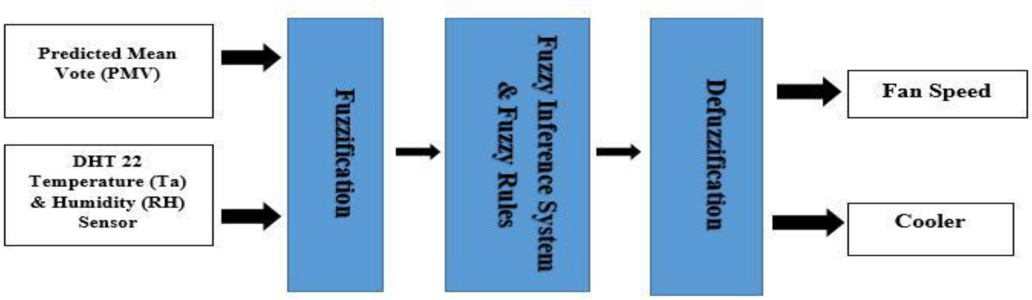
METHODOLOGY

This section introduces the design of a Fanger's model based controller for air conditioner and its implementation with the prototype. The controller prototype was tested in a conditioned space. To evaluate the system performance, MATLAB simulation of Fuzzy Logic control is simulated for the comparison purpose.

Hardware Design

The Fanger's model based controller for air conditioner consists of ATMEL's ATmega328P microcontroller, sensors and actuators. DHT22 sensor and air flow sensor are used to collect the parameters for PMV calculation while others such as activity level, clothing insulation and mean radiant temperature are assumed constant. Figure 5 depicts the block diagram of Fuzzy Logic controller with three main parts of Fuzzification, Fuzzy Inference System and Fuzzy Rules, and Defuzzification.

Figure 5: Block Diagram of Fuzzy Logic Controller



The inputs of PMV, temperature and relative humidity are converted to linguistic variables in Fuzzification process with 3 membership functions. Fuzzy arithmetic and criterion are applied based on the input variables with certain If-Then rules are designed based on occupant thermal comfort in a room. The rules are set based on expert knowledge and experience to change the output parameters according to the different conditions of input parameters. Then, the final output defuzzified by using Centre of Area (CoA) method to drive the speed of cooler and fan respectively.

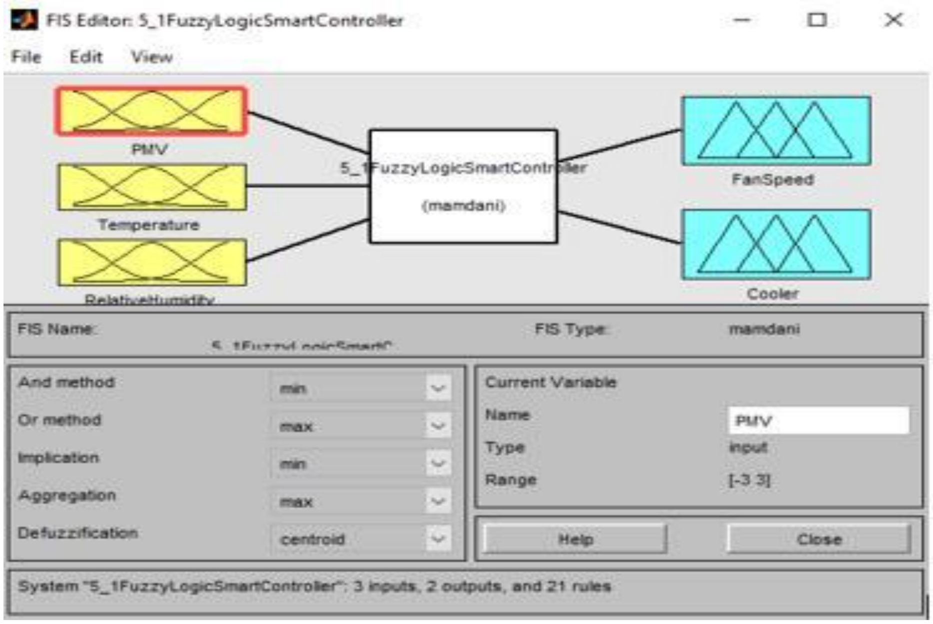
The cooler and fan speed is continuously adjusted in accordance to the input parameters and the intelligence (fuzzy logic). The humidity and temperature in the room to is adaptively adjusted and keep the conditioned space in comfort zone, i.e. PMV of ±0.5. It is noted that during the comfort zone, only fan speed will be controlled while the cooler speed is kept at minimum to reduce the power consumption. While the condition is beyond comfort zone, both fan speed and cooler speed will be adaptively adjusted according to the proposed control algorithm.

In this work, the embedded computation and fuzzy logic algorithm are implemented by ATMEL's ATmega328P microcontroller running at clock speed of 16MHz. Featured with modified Harvard RISC architecture of processor, low-cost, flash memory size of 32KB and SRAM of 2KB with input-output pins are well-suited the application requirement.

Software Design

The program coding of algorithms and Fuzzy Logic for ATmega328P microcontroller is written in C under Arduino Integrated Development Environment (IDE). The control algorithms include Fuzzy Logic and Lookup Table are implemented in microcontroller for stand-alone application. In order to verify the practicability and performance of computation in microcontroller, the same algorithms also implemented in MATLAB Fuzzy Logic Toolbox whereby both results are obtained for performance comparison purpose. Figure 6 shows the implementation of control algorithms with Matlab FIS Editor of Fuzzy Logic Toolbox.

Figure 6: Matlab Fuzzy Logic Toolbox



FIS Name: 5_1FuzzyLogicSmartC
FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

Current Variable
Name: PMV
Type: input
Range: [-3 3]

System "5_1FuzzyLogicSmartControler": 3 inputs, 2 outputs, and 21 rules

Program Flow Chart and algorithm

In order to adaptively control air conditioner based on Fanger's model of thermal comfort, an algorithm is proposed as follows and illustrated in Figure 7.

Step 1: Obtain the input parameters from the sensors

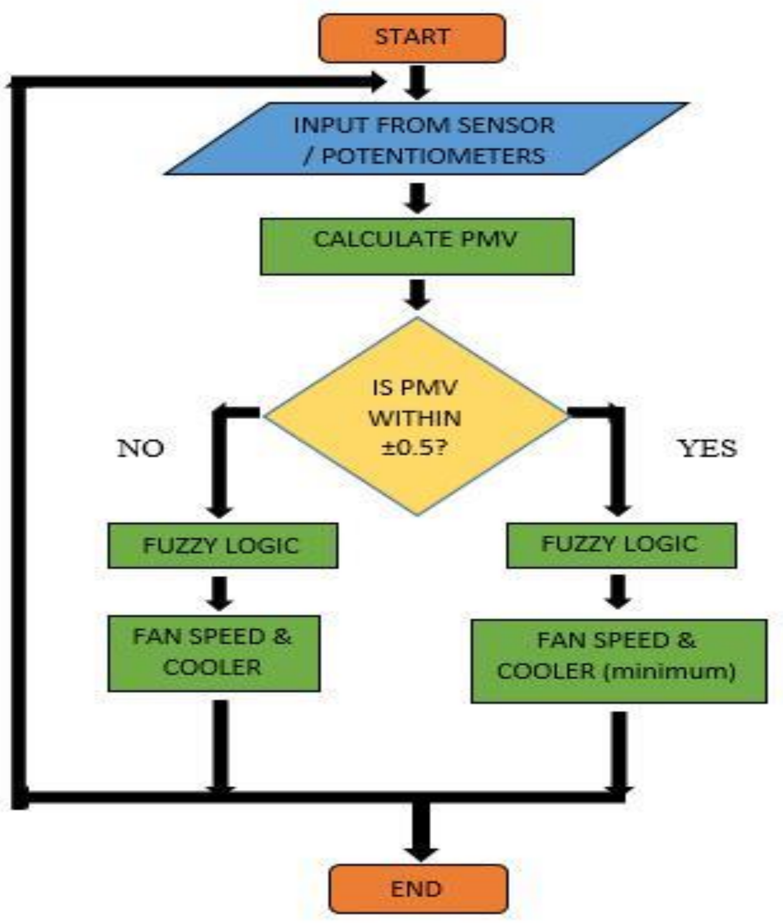
Step 2: Calculation of PMV of current state of conditioned space

Step 3: Check the current PMV is within +-0.5 (comfort zone)

> *If it is in comfort zone, enters the energy saving mode (controls fan speed adaptively only while the compressor speed remains minimum).*
>
> *Or else, control both the fan speed and compressor speed adaptively by Fuzzy Logic.*

Step 4: Cycle repeat to Step 1 and loops.

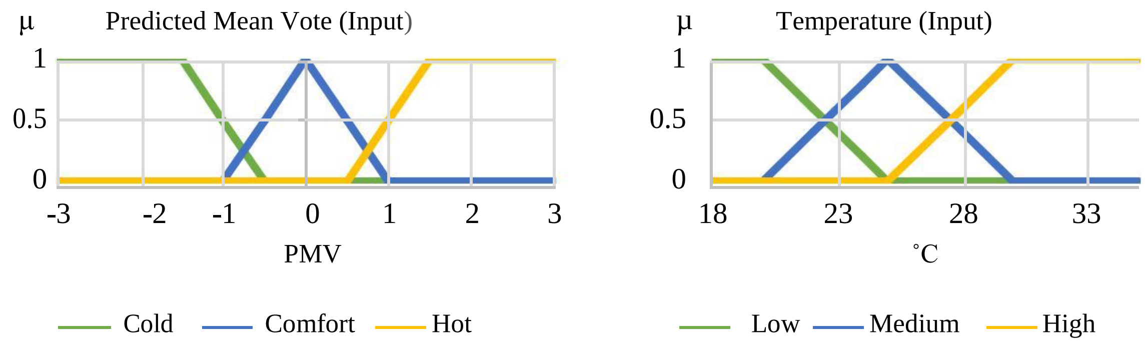
Figure 7: Flow Chart of Fuzzy Logic Controller.



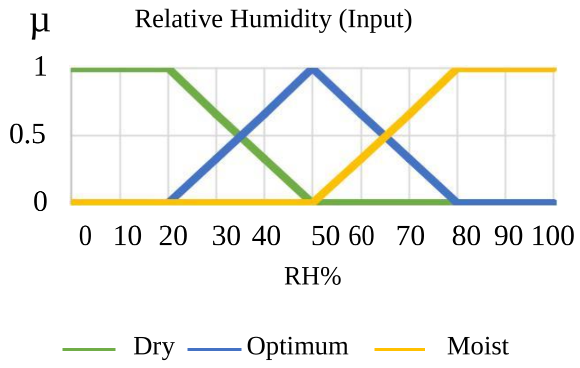
Fuzzification

The input variables of the proposed controller are PMV, temperature and relative humidity. The membership function for input and output variables are determined with the help of expert experience. Triangular and trapezoidal membership functions are used due to computation simplicity for embedded system application. Meanwhile, the output are the fan speed and cooler speed which similarly have 5 membership functions. The PMV input is ranging from -3 to 3, the temperature input is ranging from 18 to 36˚C and humidity range is from 0 to 100 %. The output fan speed and cooler speed are ranging from 0 to 100%. For this project, PMV are calculated from the inputs of temperature, humidity and air velocity while other parameters such as mean radiant temperature, metabolic rate and clothing insulation are assumed constant. Figure 8 (a), (b) and (c) shows the input membership functions of input and Figure 9 (a) and (b) illustrates the output membership functions of the intelligent controller fuzzy logic design.

Figure 8: Input Membership Functions

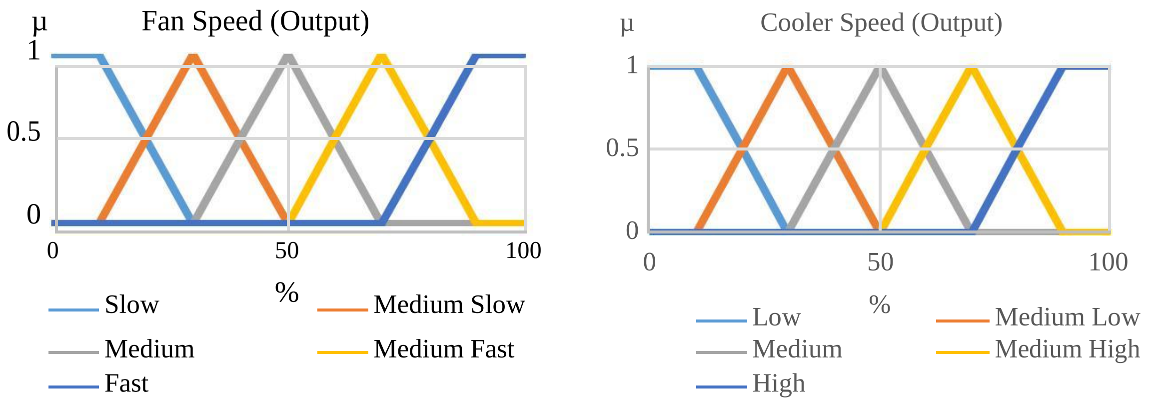


(a) PMV Input (b) Temperature Input



(c) Humidity Input

Figure 9: Output Membership Functions



(a) Fan Speed Output (b) Cooler Speed Output

Fuzzy Rule Base

Fuzzy Rule Base consists of linguistic "If-Then" is considered as the expert knowledge or experience in specific application domain. The proposed controller adopts 21 Fuzzy rules to construct Mamdani Fuzzy Inference with 3 input variables (PMV, temperature and relative humidity) and 2 output variables (fan speed and cooler speed). Table 3 shows the Fuzzy Rule Base with "If-Then" rules adopted.

Table 3: Fuzzy Rule Base

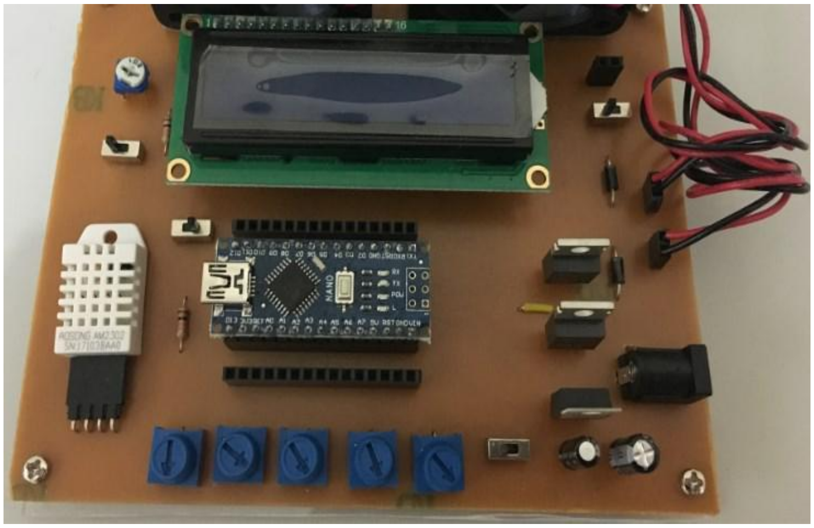
			Input				**Output**	
Rule	**PMV**		**Ta**		**RH**		**Fan Speed**	**Cooler**
1	Cold	And	Low	And	Dry	Then	Medium Slow	Low
2	Cold		Low		Optimum		Medium Slow	Low
3	Cold		Low		Moist		Medium Slow	Low
4	Cold		Medium		Dry		Medium	Low
5	Cold		Medium		Optimum		Medium Slow	Low
6	Cold		Medium		Moist		Medium Slow	Low
7	Comfort		Low		Dry		Medium	Low
8	Comfort		Low		Optimum		Medium Slow	Low
9	Comfort		Low		Moist		Medium Slow	Low
10	Comfort		Medium		Dry		Medium	Low
11	Comfort		Medium		Optimum		Medium	Low
12	Comfort		Medium		Moist		Medium	Low
13	Comfort		High		Dry		Fast	Low
14	Comfort		High		Optimum		Fast	Med. Low
15	Comfort		High		Moist		Fast	Med. Low
16	Hot		Medium		Dry		Medium	Medium
17	Hot		Medium		Optimum		Medium	Medium
18	Hot		Medium		Moist		Medium	Medium
19	Hot		High		Dry		Fast	Med. High
20	Hot		High		Optimum		Fast	High
21	Hot		High		Moist		Fast	High

The output of the Fuzzy system is still vague and need to be converted or need to be defuzzified to get the value and make it useful for real application. Methods of defuzzification methods include Centroid of Area (COA), Height method, Maxima methods etc. COA, which also called as Centre of Gravity (CoG) has been chosen for defuzzification due to the reasons of common and ease of use. It calculates and determines the center of gravity of the scaled output fuzzy set to provide the crisp value for real application, i.e. fan and cooler speeds.

RESULTS AND DISCUSSION

In this section, we describe the implementation of Fanger's model based controller for air conditioner and the experimental results. A prototype of controller was implemented for the testing of control algorithm and result analysis as shown in Figure 10. The main input parameters are obtained from the sensors while other parameters are assumed constant. The embedded system with ATMEL's microcontroller is programmed to implement control algorithms proposed.

Figure 10: Top View of The Prototype



The prototype includes an ATmega328P microcontroller which is program coded to calculate PMV of current conditioned space. PMV index varies with three input parameters namely ambient temperature, relative humidity and air velocity. Other parameters include mean radiant temperature of 28 ˚C, insulation level of clothing is 0.57 Clo (for typical attire in tropics) and metabolic rate of 1.2 Met or 69.78 W/m2 (seated, relax, sedentary work) are remained constant. Table 4 shows the PMV calculation by ATmega328p microcontroller.

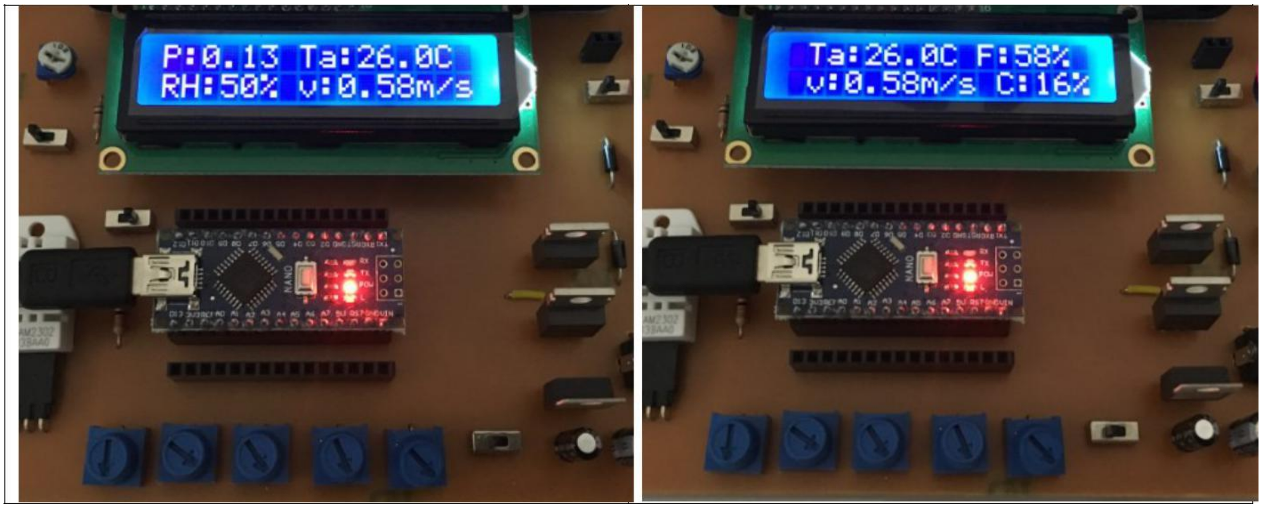
Table 4: PMV Calculation by ATmega328P Microcontroller.

PMV	Temperature (˚C)	Relative Humidity (%)	Air Velocity (m/s)
1.08	29.0	75.1	0.75
0.73	27.8	71.0	0.66
0.67	27.6	70.6	0.67
0.45	26.8	69.6	0.64
0.30	26.2	68.3	0.60
0.12	25.4	66.5	0.55
0.08	25.2	65.5	0.53
-0.10	24.6	58.1	0.50
-0.30	23.8	58.1	0.50
-0.50	23.0	57.7	0.50

Experimental Results of Proposed Algorithm by Hardware Prototype

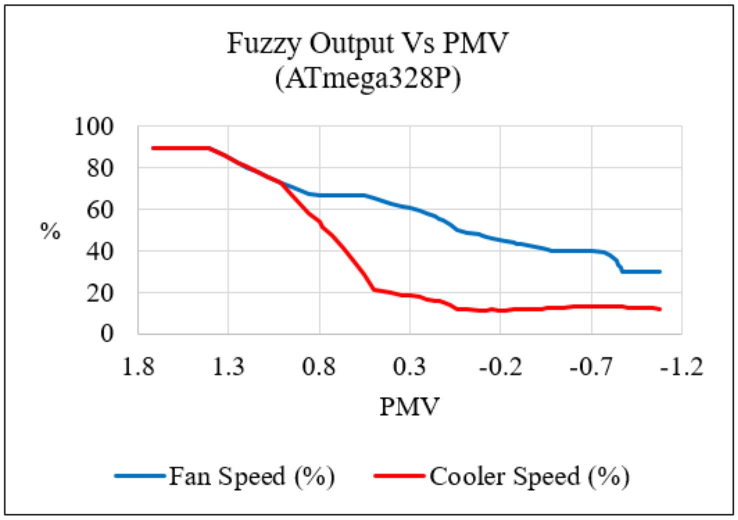
As in Figure 11, PMV as ‘P’ = 0.13, Air Temperature as ‘Ta’ = 26˚C, Relative Humidity as “Rh” = 50 %, Air Velocity as ‘v’ = 0.58 m/s are the parameter for the input and the result of defuzzified output value for fan speed as ‘F’= 58 % and cooler speed ‘C’= 16 %.

Figure 11: Input parameters and controlled output values



When PMV index falls within the comfort zone, i.e. ±0.5, the controller is operated in energy saving mode whereby only the fan speed is adjusted at 58% to maintain PMV in comfort meanwhile the cooler compressor speed at minimum of 16% for energy conservation purpose. Figure 12 depicts the variation of fuzzy output generated from experimental results with constant parameters of mean radiant temperature of 28 ˚C, metabolic rate MET of 1.2 or 69.78 W/m2 and 0.57 Clo.

Figure 12: Fuzzy Output Generated from Experimental Results

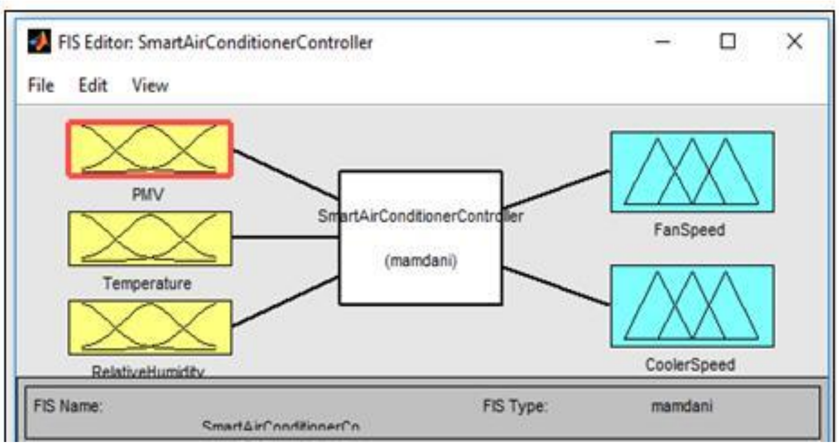


The fan speed (blue line) of controller is adaptively varied with PMV while it is dependent on the variation of temperature and humidity parameters. While the conditioned space is hot (i.e. PMV > 0), the evaporator coils and condenser are used as cooler to adjust air temperature by replacing hot air in the room space with cool air. At the same time, the fan speed can be used with cooling effect to maintain human thermal comfort (PMV) within comfort zone (PMV of ±0.5) at minimum use of the compressor to adjust air temperature. As a result, controlling the cooling effect of fan speed control can achieve conservation of energy while maintaining thermal comfort.

Simulation Result of the Proposed Algorithm by MATLAB Simulation

MATLAB Fuzzy Logic Toolbox is used to design fuzzy logic implementation with Fuzzy Inference System (FIS). The proposed control algorithm is designed for simulation and validation purposes as shown in Figure 13. The results from both the hardware prototype and MATLAB simulation are obtained and compared to validate the prototype performance of control algorithm implementation in microcontroller.

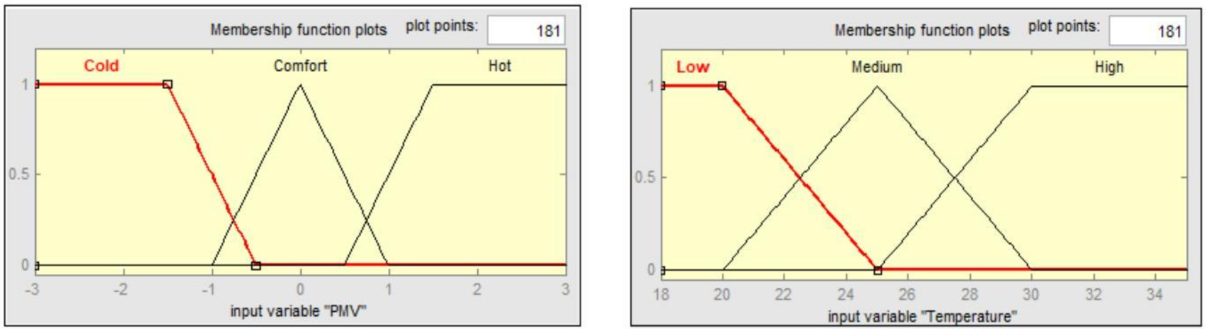
Figure 13: MATLAB Fuzzy Logic Toolbox Editor.



FIS Name: SmartAirConditionerCo
FIS Type: mamdani

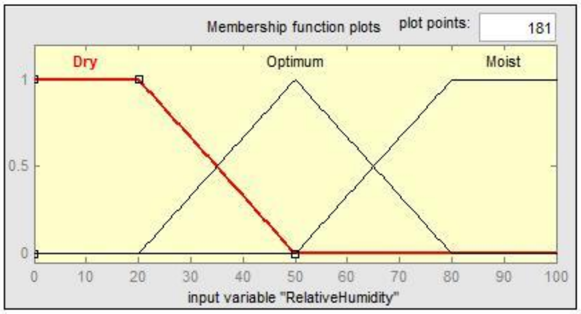
The same membership functions (inputs and outputs) and fuzzy rules of Mamdani Fuzzy Inference implemented in ATmega328P microcontroller and MATLAB simulation with Fuzzy Logic Toolbox as shown in Figure 14 and Figure 15. There are 21 Fuzzy rules are designed and implemented in the Fuzzy Inference System of Rule Editor as shown in Figure 16. The Fuzzy Rule Viewer and 3D Output Surface of the proposed controller are illustrate in Figure 17.

Figure 14: Input Membership Functions.



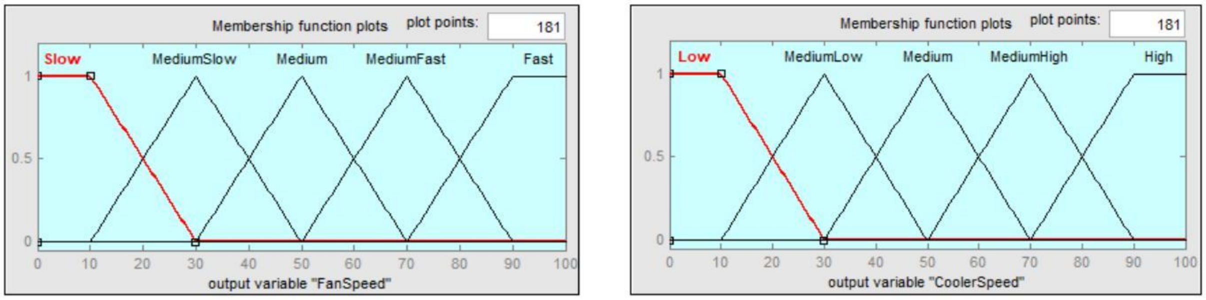
(a) PMV input membership function.

(b) Temperature input membership function



(c) RH input membership function

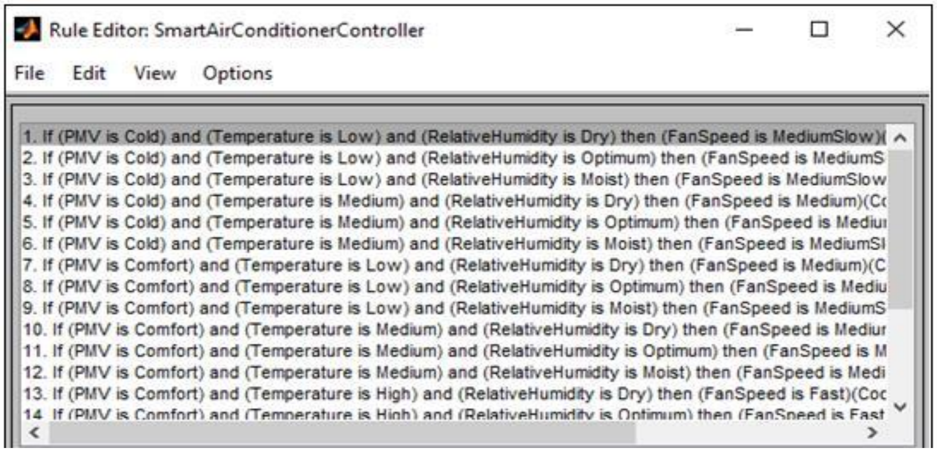
Figure 15: Output Membership Functions.



(a) Fan Speed Output membership function.

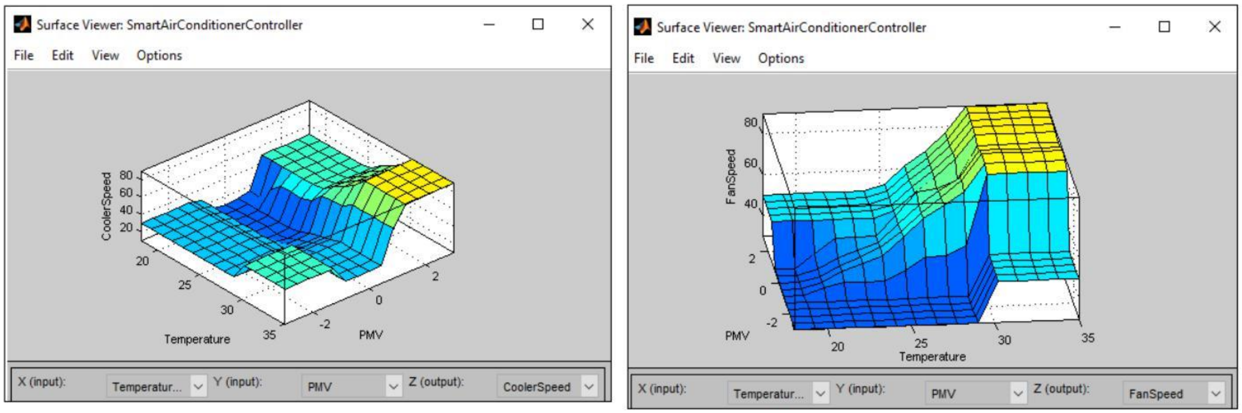
(b) Cooler Speed Output membership functio

Figure 16: Fuzzy Rules In Mamdani Fuzzy Inference System Rule Editor.



```
1. If (PMV is Cold) and (Temperature is Low) and (RelativeHumidity is Dry) then (FanSpeed is MediumSlow)(
2. If (PMV is Cold) and (Temperature is Low) and (RelativeHumidity is Optimum) then (FanSpeed is MediumS
3. If (PMV is Cold) and (Temperature is Low) and (RelativeHumidity is Moist) then (FanSpeed is MediumSlow
4. If (PMV is Cold) and (Temperature is Medium) and (RelativeHumidity is Dry) then (FanSpeed is Medium)(C
5. If (PMV is Cold) and (Temperature is Medium) and (RelativeHumidity is Optimum) then (FanSpeed is Mediu
6. If (PMV is Cold) and (Temperature is Medium) and (RelativeHumidity is Moist) then (FanSpeed is MediumS
7. If (PMV is Comfort) and (Temperature is Low) and (RelativeHumidity is Dry) then (FanSpeed is Medium)(C
8. If (PMV is Comfort) and (Temperature is Low) and (RelativeHumidity is Optimum) then (FanSpeed is Mediu
9. If (PMV is Comfort) and (Temperature is Low) and (RelativeHumidity is Moist) then (FanSpeed is MediumS
10. If (PMV is Comfort) and (Temperature is Medium) and (RelativeHumidity is Dry) then (FanSpeed is Mediu
11. If (PMV is Comfort) and (Temperature is Medium) and (RelativeHumidity is Optimum) then (FanSpeed is M
12. If (PMV is Comfort) and (Temperature is Medium) and (RelativeHumidity is Moist) then (FanSpeed is Medi
13. If (PMV is Comfort) and (Temperature is High) and (RelativeHumidity is Dry) then (FanSpeed is Fast)(Co
14. If (PMV is Comfort) and (Temperature is High) and (RelativeHumidity is Optimum) then (FanSpeed is Fast
```

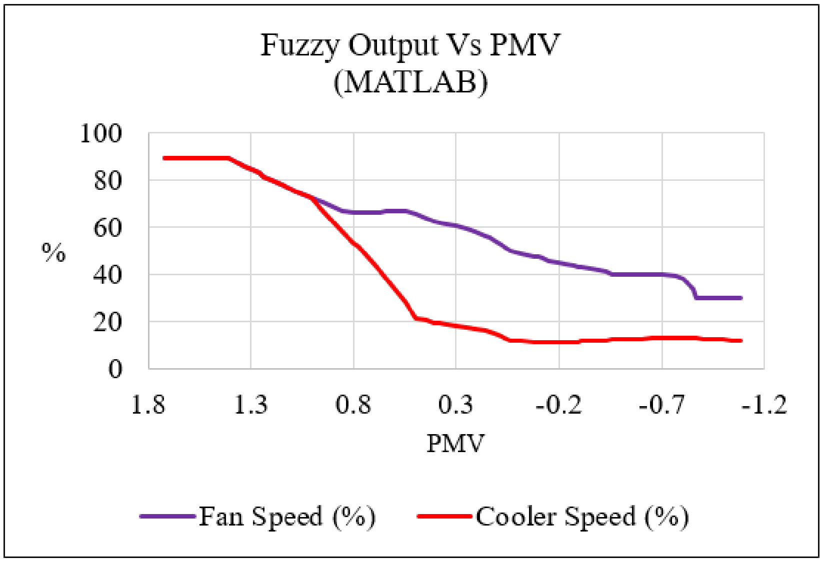
Figure 17: Fuzzy Logic Surface Viewer



(a) Fan speed (b) Cooler speed

The proposed controller output from MATLAB simulation is shown in Figure 18. It is clearly shown that identical results are obtained from both proposed prototype of controller and MATLAB simulation.

Figure 18: Fuzzy Output Generated from MATLAB Fuzzy Logic Toolbox



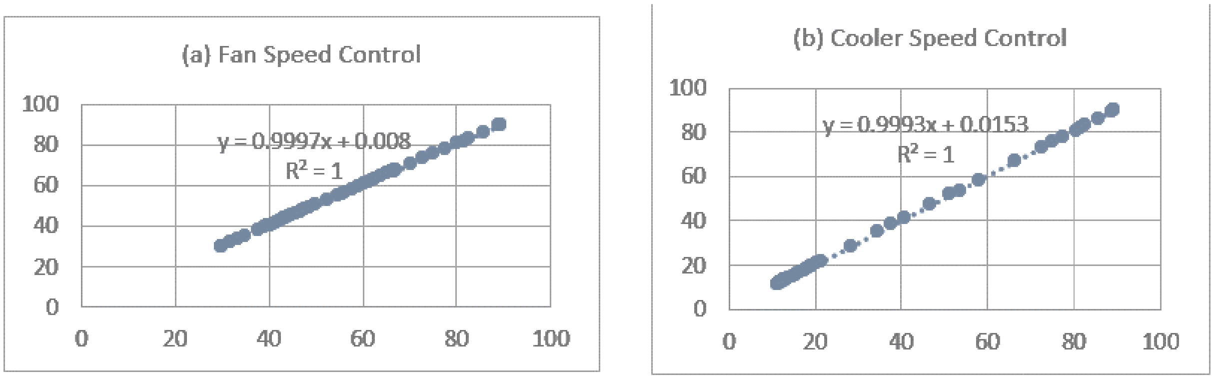
Percentage of Error

To evaluate the computation performance of proposed controller with embedded system, the error percentage of Equation (3) is measured and calculated based on the results of the proposed controller prototype and MATLAB simulation of the same algorithm implemented.

$$\% \, Error = \left| \frac{Simulation\ value - Experimental\ value}{Simulation\ value} \right| x\ 100\% \ldots..(3)$$

The computation performance of the proposed model is validated with the result from MATLAB simulation from the coefficient of determination, R^2 for goodness of fit. R^2 result at 1 indicates the good fitness of regression, as shown in Figure 19. The error percentage is kept less than 0.7%.

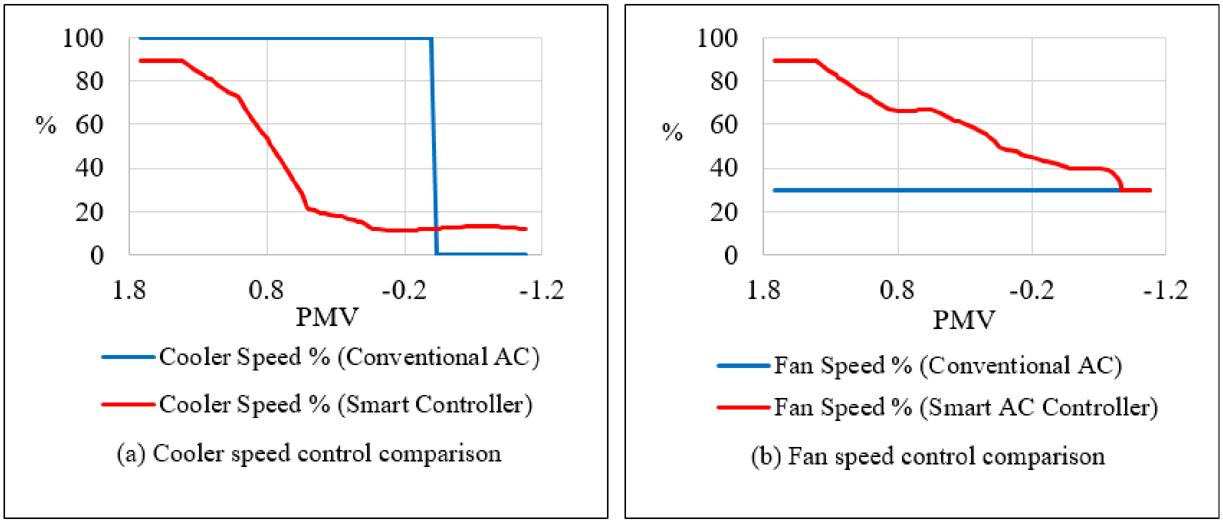
Figure 19: Comparison of Fuzzy Outputs of The Prototype And MATLAB Simulation



Comparison of Controllers for Conventional AC and the Proposed Design

In this section, the performance of air conditioner for conventional controller and the proposed controller are compared. Conventional air conditioner works by turning on (full cycle) and then turn off when room temperature reach preset temperature which causes discomfort and power problems. Meanwhile the proposed controller works by varying its cooler output from high speed when temperature or PMV is hot, and at minimum speed when temperature is low or when PMV reach comfort zone of ±0.5 by varying air velocity (i.e. fan speed) to achieve thermal comfort required. As for energy consumption of the compressor, the smart air conditioner controller can save up to 49% of energy compared with the conventional air conditioner. The percentage are calculated from the difference of area under the curve of conventional air conditioner and the curve of smart air conditioner controller in between PMV 1.72 and 0.04 from the graph in Figure 20 (a).

Figure 20: Comparison of Conventional and The Proposed Controllers for Speed Control.



(a) Cooler speed control comparison

(b) Fan speed control comparison

As an assumption, the conventional air conditioner preset temperature set to 23 ˚C and fan speed at low or 30%. In Figure 20 (a), the cooler speed (blue line) for conventional AC runs at full cycle and turn off when reach preset temperature at the power rating of 1 horsepower or 746W. Meanwhile for the smart controller (red line), the cooler varies its speed from fast when temperature or PMV is hot and slows down to minimum when PMV is in comfort zone of ±0.5 due to cooling effect of air flow variation. As the energy consumption of fan is a small fraction to the cooler (compressor), thereby the potential of energy saving exists for the proposed controller.

CONCLUSION

In this paper, we have proposed a smart air conditioner controller with adaptive mode based on Fanger's model that provides optimum thermal comfort for users with minimum energy consumption. PMV of 7-point likert scale and other parameters are taken into consideration to adaptively control the fan speed and compressor speed to maintain PMV within ±0.5 along with energy saving achievement. The results from both the prototype and MATLAB simulation proved the significant performance and feasibility of the new smart control to overcome the drawbacks of conventional air conditioner with limited option to control air conditioner and thermal comfort. All objectives of this project have been met which are to determine the thermal comfort of occupant in a built environment, to design intelligence system based on Fanger's model of thermal comfort with minimum energy consumption with 49% energy saving potential and verified the feasibility of proposed system with MATLAB simulation with less than 1% error percentage found. The future works will include several features to improve the system performance and reliability. Refining the fuzzy logic membership functions which are best suited to the application. In addition, neuro-fuzzy system with good learning algorithm can be utilized for enhanced intelligence for the proposed controller.

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