

A fuzzy neural network based fan regulator for the ceiling fan to enhance thermal comfort

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Abstract:

The thermal comfort of the indoor occupant is assessed with the assessment indicators and is described in the standard such as ASHRAE 55 and ISO 7730. This study aims to develop a fuzzy neural network based fan regulator for ceiling fan to enhance thermal comfort. A fuzzy neural network is developed based on relation between inputs (temperature, humidity) and output (air speed) to satisfy the assessment indicators and are used in the fan regulator system to enhance the thermal comfort. The performance of the fan with a fuzzy neural network regulator is compared with the preferred air condition based on data from ASHRAE 55 and found satisfactory through simulation. To verify the effectiveness of the fuzzy neural network based fan regulator, an experimental set up was developed in real-time environment to compare the fan with fuzzy neural network regulator with a fan without a regulator, a fan with an ordinary manually controlled regulator. It is found that the fan with a fuzzy neural network regulator maintained comfort levels 100 % in the winter season while 58 % in the summer season respectively. Also, it is found that the fan with a fuzzy neural network regulator is 50 % energy saving compared to a fan without a regulator and 33 % energy saving compared to a fan with an ordinary manually controlled regulator.

Highlights:

1. Developed a fuzzy neural network based fan regulator
2. The speed of the fan is adjusted to satisfy the thermal comfort
3. Energy saving during night time due to slowing down of fan speed as temperature and humidity varies
4. 50 % energy saving when compared to a fan without a regulator in Coimbatore
5. 33% energy saving as compared to a fan with a regulator in Coimbatore

Keywords: Thermal comfort; Fuzzy Neural Network; Regulator; Air Speed; Energy Saving

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1. Introduction

The electric fan is a device that mimics the natural flow of air in the environment to create a breeze and circulate air in a region. They are used in the domestic/industry for comfort, ventilation, and cool down the material temperature (DeGaspari 1999), (Adeloye 2017). The temperature and the humidity of the indoor vary as the time of the day changes and as climate changes. Under such conditions, the user needs to change the speed of the fan to attain the level of comfort. The speed of the fan is varied by the user using a manual speed regulator or remote-controlled speed regulator. The variable speed of the fan does not reduce the temperature but the breeze created by the fan takes away the perspiration making our body cools off. However, the variable speed of the fan reduces/increase the thermal comfort under different temperature and humidity condition respectively.

A large population of human being spends 80-90% of their time indoors (Castilla et al. 2013). During change in weather condition, the user has to reduce or increase the speed of the fan either by manually rotating the regulator or by fetching out the

remote control and adjusting to the comfort level causing the disturbance to the work or sleep cycle. Also it will lead to power loss as low speed is sufficient during the night time due to a decrease in temperature. In the case of elderly people and bedridden patients, they need to adjust the fan speed to meet their comfort level, it becomes very difficult for them to adjust by themselves and in some cases it requires others' support to do it. Also some people find it annoyance and perhaps frustration to get up from their seat to control the speed of the ceiling fan (Kanchanasatian 2017). Alternatively, the automatic air conditioner system can provide better cooling in terms of thermal comfort at uneconomical price and energy loss for people in developing countries (Shah et al. 2014), (Lipczyńska, Schiavon, and Graham 2018).

The comfort level offered by the ceiling fan is defined in terms of thermal comfort which is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55) (Schiavon, Hoyt, and Piccioli 2014). The thermal comfort is computed with physical

quantities like air temperature, air velocity, humidity, and mean radiant temperature and personal quantities like clothing and activity. The thermal comfort of the indoor is assessed by assessment indicators such as temperature-humidity-wind index, mean radiant temperature, Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), and Standard Effective Temperature (SET).

Under thermal comfort condition, self-reported productivity like alertness, level of concentration, and work productivity are not affected is reported in (Lipczynska, Schiavon, and Graham 2018). It also found that energy usage decreases one-third as the relative humidity decreases and provide cooling thermal comfort. (Ho, Rosario, and Rahman 2009) analysed the effect of ceiling fan in an air-conditioned environment by numerical simulation and computed PMV. The result showed that as air speed increases with the help of ceiling fans, thermal comfort increases towards the cooler side of the psychrometric chart and allowed higher air temperature while maintaining the same comfort.

(Singh 2018) investigated the effects of gender, age, seasonal differences, and exposure of occupants to heat absorbed in the roof, on their thermal responses in naturally ventilated apartments and found that females are more sensitive to temperature change than males and elderly people more sensitive to thermal changes. (Indraganti 2011) found that the subjects are comfortable between 26.0 °C and 32.5 °C which is higher than the range specified by Indian codes. (Manu et al. 2016) proposed the India model for adaptive comfort model wherein Indian office occupants are more adaptive than predicted by ASHRAE-55 and EN15251 models. The thermal comfort based on PMV is developed based on the steady state room condition, healthy adults individuals in a defined age group and not based on real world condition, children, the elderly, or the unhealthy is reported in (Humphreys and Nicol 2002).

In order to overcome the shortcoming with the conventional PMV models, adaptive PMV (de Dear 1998) with only one parameter namely outdoor air temperature and extended PMV (Ole Fanger and Toftum 2002) with PMV and local typical local climates are modelled. however, control mechanism causes instabilities unnecessary energy use is reported in (Ngarambe, Yun, and Santamouris 2020). (Moon and Kim 2010) developed an adaptive neural network based model to predictive PMV using temperature and humidity as input and as adaptive control neural network based model to overshoot/undershoot free control variable from PMV predicted. (Mba, Meukam, and Kemajou 2016), (Moon 2015), (Mustafaraj, Chen, and Lowry 2010) used different parameter to train an adaptive neural network and predicted the indoor temperature

and humidity. The adaptive models thus developed have inconsistency in the types of variables, suffer from inaccuracies as they do not consider several important elements and are less generalizable. But they can be simple and can be implemented easily in the building systems.

(Wen-Tsai Sung 2024) built an indoor thermal comfort environmental monitoring system through the internet of things architecture system. It uses a fuzzy system and three ways of controlling the thermal comfort by measuring ambient temperature, relative humidity, and indoor wind speed and controlling by the air conditioner, humidifier, dehumidifier, and fan. (Atthajariyakul and Leephakpreeda 2005) computed PMV using feed forward neural network model by measuring wet bulb temperature and globe temperature and found result in agreement with conventional PMV model. (Yao and Xu 2010) built a back propagation neural network with Fanger's six variables and predicted PMV with 5 % error in accuracy. (Castilla et al. 2013) developed adaptive neural network model and polynomial model and reported that better results from neural network model with less computational cost and reduced number of sensor making it possible to be used in real-time control. (Garnier et al. 2014) developed low-order adaptive neural network based models to predict the future PMV value and thereby controlling the thermal comfort in the multi-zone Heating Ventilation and Air Conditioning (HVAC) system of a residential building.

(Chaudhuri et al. 2018) developed a predictive model based on random forests to estimate the thermal comfort of occupants. The inputs are physical environmental elements like air temperature, global temperature, relative humidity, and air velocity and physiological elements like skin temperature, pulse rate, blood oxygen saturation and blood pressure of the young population. The physiological elements are measured by means of wearable devices. (Lu 2024) developed a predictive model based on random forests to predict thermal sensation votes using indoor air temperature, skin temperature, and clothing surface temperature collected using infra-red. The prediction based on machine learning algorithms are significantly higher than that of the traditional PMV models but traditional PMV model are generalizable as there is consistency in the input variables and easily deployable in new buildings.

(Ngarambe, Yun, and Kim 2024) developed deep neural network model to estimate the occupant clothing insulation levels by means of outdoor environmental factors like temperature and humidity. (Na and Kim 2024) developed a deep learning model to estimate the metabolic rates of individual occupants using physiological data by means of Internet of Things (IoT) based kinetic cameras. The data related to clothing insulation and

activity level are difficult to obtain as it is affected by many factors like culture, dress code, and gender. For a simpler fan control the clothing insulation and metabolic rates can be kept constant as the people use clothing based on environmental condition and higher cost can be reduced by eliminating the wearable IoT sensors on individual occupants respectively. Energy savings in thermal comfort is reported in (Ferreira et al. 2012) with a discrete model based predictive control, fuzzy logic based controller in (Hussain et al. 2014) and smart system to predict PMV employing fuzzy logic with input from IoT sensors network in (Wen-Tsai Sung 2024), (Collotta et al. 2014).

In the previous studies, the thermal comfort under HVAC is analysed and the range of assessment indicators such as PMV, PPD and SET are described. This study aims to develop a fan regulator system that automatically varies the fan speed based on temperature and humidity so that the assessment indicators are maximum satisfied and reduce energy consumption. The section 2 describes the various thermal comfort assessment indices. The section 3 describes the fuzzy neural network control. The section 4 describes the result and discussion. The section 5 describes the experimental setup and result and the section 6 concludes the paper.

2. Thermal comfort assessment method

The thermal comfort of the indoor is assessed by assessment indicators such as temperature-humidity-wind index, Mean radiant temperature, PMV, PPD, and SET. They provide us with an important basic assessment method while building an indoor thermal comfort control system. In this study, PMV, PPD and SET are used.

2.1 The Predicted Mean Vote (PMV)

The thermal comfort of the occupants can be modelled using the PMV. The six parameters of air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing are used to calculate the PMV (Ho, Rosario, and Rahman 2009). As per the ASHRAE thermal sensation scale, the PMV ranges from -3 to +3 as follows: -3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm and 3 = hot.

2.2 The Predicted Percentage Dissatisfied (PPD)

The thermal dissatisfaction of the occupant is estimated based on the PPD which gives the percentage of dissatisfaction of thermal comfort of the occupant at PMV (Ho, Rosario, and Rahman 2009). For neutral PMV value, the value of PPD is 5%. So, if the value of PPD is less than 20%, it is considered as 80% satisfactory by the occupants.

2.3 The Standard Effective Temperature (SET)

The SET is defined as the body temperature of a person calculated at an imaginary environment having a relative humidity of 50 %, air speed of 0.1 m/s, with an activity level of 1.0 met and a clothing level of 0.6 clo will be equal to the person in the actual environment (Wen-Tsai Sung 2024).

2.4 Cooling Effect (CE)

The CE at elevated air speed as the value that, when subtracted from both the air temperature and the mean radiant temperature, yields the same SET value under still air as in the first SET calculation under elevated air speed (Wen-Tsai Sung 2024).

The thermal comfort based on these assessments are too complex and cannot be applied for real-time application as such. Therefore, a fuzzy neural network is designed in the next session to simplify the implementation using a microcontroller.

3. Fuzzy Neural Network (FNN) regulator

A FNN system is developed to mimic the thermal comfort system. The fuzzy logic is used to estimate the PMV value while the neural network is used to tune the weights of fuzzy membership function so that the value of PPD is less than 20% or the maximum possibility of lesser value when it is above 20%. In real-time all the values such as air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing cannot be found as it varies from one person to another. (For example, in a hotel room, the server will have different metabolic rate and the customer will have different metabolic rate. The persons in a office will wear different types of clothing). Therefore, for an optimal situation, the temperature and the humidity are considered as the input and the air speed is considered as the output. The FNN designed to satisfy the combined effect of PMV, PPD and SET. The typical FNN system is shown in figure 1. consists of two inputs (x, y), five layers and one output function layer (García et al. 2014).

The first layer contains the membership function assigned to each input (x, y) where x is temperature and y is humidity. Figure 2 shows the thermal comfort chart according to ASHRAE 55 under different temperature (°C) and relative humidity (%) with clothing at 0.5 clo and metabolic rate 1 met (Schiavon, Hoyt, and Piccioli 2014). The thermal comfort chart classifies the environment into different zones like cool, slightly cool, neutral, warm, slightly warm, and hot based on temperature and humidity. Based on that, the membership function for input temperature is derived as cool, slightly cool, neutral, warm, slightly warm, and hot, and is shown in Figure 3 (a). The membership function for input relative humidity are derived as very low, low, normal, medium, high, and very high

and is shown in Figure 3(b). The second layer contains the identified rules considering the inputs from the membership functions and is given in table 1. Example, rule 1: $x = \text{cool}$, $y = \text{very low}$ and $z = R1$; rule 2: $x = \text{slightly cool}$, $y = \text{very low}$ and $z = R2$. The normalized firing strength of each rule (w_1 , w_2) calculated in the third layer. The fourth layer contains linear functions which are functions of the input signals ($R1 = p1*x1 + q1*y1 + r1$, $R2 = p2*x2 + q2*y2 + r2$, where $p1$, $p2$, $q1$, $q2$, $r1$, $r2$ are constant). The fifth layer sum up all the incoming signals. Here weighted average method is used for defuzzification at the fifth layer.

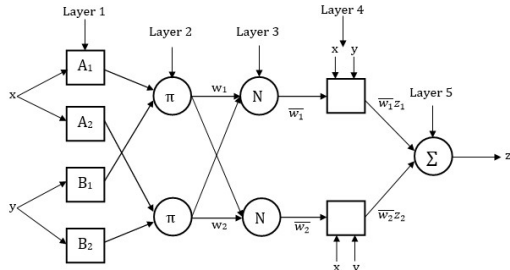


Figure 1. The typical FNN system

The maximum limit of air speed is set at 2 m/s as the occupants in the Indian buildings were found to tolerate a wider range of temperatures when compared with Western contexts where lower temperature limits entrench an energy demand through a greater reliance on air conditioning (Thomas 2017), (Vijayalaxmi 2009).

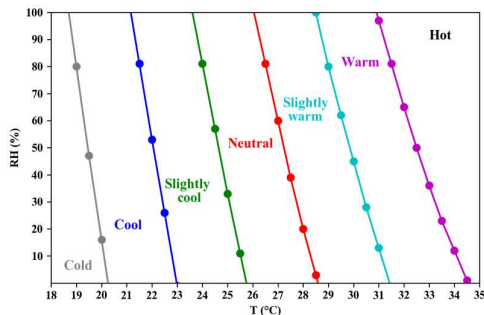
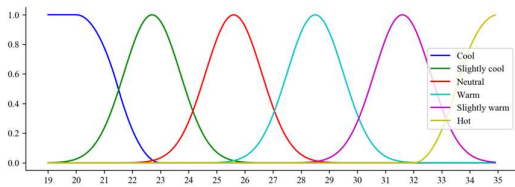
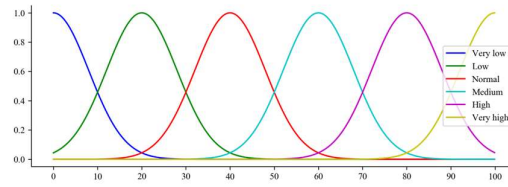


Figure 2. Thermal comfort under different temperature (°C) and relative humidity (%)



(a) Input membership functions for the temperature (°C).



(b) Input membership functions for the relative humidity (%).

Figure 3. The membership functions

For effective operation, the parameters of the membership functions must be tuned by training data to satisfy equation (1), (5), and (7). The training data is obtained from the thermal comfort chart present in (Schiavon, Hoyt, and Piccioli 2014). The back propagation algorithm is used to update the weights of the layers. The data set is split in to two as training data (70%) and testing data (30%) to avoid over fitting the FNN model. The root-mean-square error is used to minimize the error in training and the error was 0.0326 with 30 epoch. The training was done in Fuzzy Logic Toolbox of MATLAB. The relation between the input and the output which is the control surface of the trained data is as shown in figure 4. The trained FNN is tested for the performance in the next session.

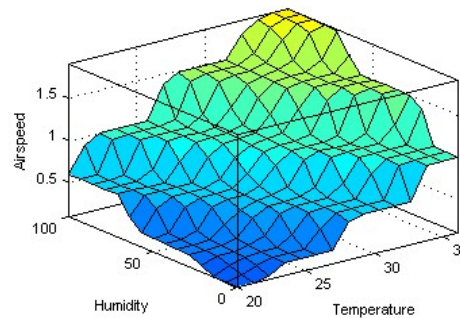


Figure 4. The fuzzy rules

4. Result and discussion

4.1. Simulation result

In order to evaluate the performance of the proposed system, two simulations are carried in MATLAB/Simulink environment. The simulation setup is shown in figure 5. It consists of inputs blocks, neuro fuzzy logic block, thermal comfort assessment indicator block and the output block. The input block receives mean radiant temperature which is same as air temperature of the particular day, air speed = 0 m/s, humidity of the particular day, clothing is taken as 0.5 clo and metabolic rate as 1 met. The neuro fuzzy logic block predicts the air speed based on the trained data. The assessment indicator block calculates the SET, PMV and PPD. The output block stores the results.

A fuzzy neural network based fan regulator for the ceiling fan to enhance thermal comfort

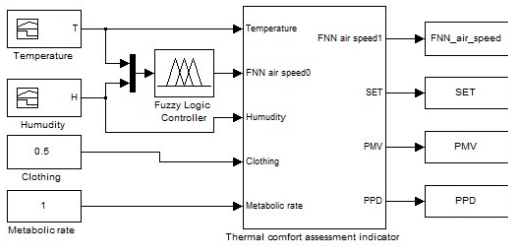


Figure 5. Simulation of FNN air speed predictor and thermal comfort assessment indicators. The first simulation was carried out on 16th January 2024 which is one of the coldest day of the year in Coimbatore and the proposed system predicts the air speed for that day. In order to evaluate the performance of the FNN, it is compared with preferred air speed. The preferred air speed is calculated as follows: The temperature (°C), relative humidity (%), fixed clothing at 0.5 clo and fixed metabolic rate 1 met are inputted to the CBE Thermal Comfort Tool: online tool for thermal comfort calculations and visualizations (Schiavon, Hoyt, and Piccioli 2014), then the air speed is input to the tool and is adjusted and the air speed which gives the low value of PMV, 5% of PPD and low value of SET is chosen as preferred air speed.

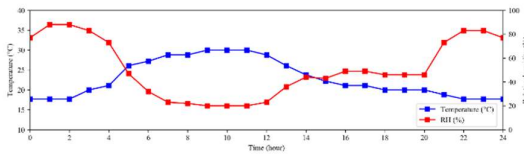


Figure 6. Temperature (°C) and relative Humidity (%) of 16th January 2024. Figure 6. shows the temperature (°C) and relative humidity (%) of 16th January 2024. The temperature typically ranges from 17.7 °C to 30 °C and the relative humidity typically ranges from 20 % to 88 %.

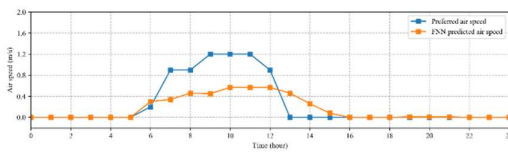


Figure 7. Preferred air speed and FNN predicted air speed for 16th January 2024. Figure 7. shows the preferred air speed and FNN predicted air speed for 16th January 2024. The preferred air speed is calculated manually from the online tool for thermal comfort calculations and visualizations. The FNN predicted air speed is the air speed predicted by the FNN. It can be observed from the figure 7 that the prediction made by the FNN is less than the preferred air speed manually set.

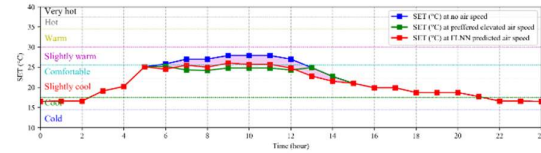


Figure 8. SET under no air speed, preferred air speed and FNN predicted air speed respectively for 16th January 2024.

Figure 8. shows the SET under no air speed, preferred air speed, and FNN predicted air speed respectively for 16th January 2024. The SET is within the comfortable region for the predicted air speed by the FNN. CE is SET under no air speed minus SET under FNN predicted air speed. The area shaded is the CE created by the FNN predicted air speed. The adjusted temperature is equal to the original air and mean radiant temperatures minus the CE. Also from the figure 8, it can be seen that due to the use of FNN, the temperature is changed from slightly warm condition to comfortable condition.

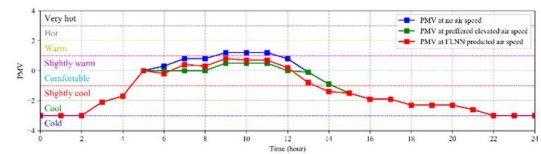


Figure 9. PMV under no air speed, preferred air speed and FNN predicted air speed respectively for 16th January 2024.

Figure 9. shows the PMV under no air, preferred air speed, and FNN predicted air speed respectively for 16th January 2024. The PMV is under a warm region for no air speed. The PMV is under a slightly warm region for the predicted elevated air speed. The PMV is under a slightly warm region for the predicted air speed by the FNN and it is almost in par with PMV for predicted elevated air speed.

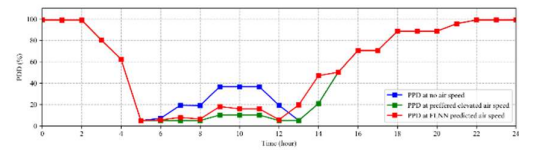


Figure 10. PPD under no air speed, preferred air speed and FNN predicted air speed respectively for 16th January 2024.

Figure 10. shows the PPD under no air speed, preferred air speed, and FNN predicted air speed respectively for 16th January 2024. The PPD under no air speed is 20% for the entire day. The PPD from 5th hour to 13th hour is under 20 % for preferred air speed, and FNN predicted air speed and the remaining period is above 20 due to natural cooling. The PPD of the FNN elevated air speed is almost in par with preferred elevated air speed.

The second simulation was carried out on 1st April 2024 which is one of the hottest day of the year in Coimbatore and the proposed system predicts the air speed for that day.

A fuzzy neural network based fan regulator for the ceiling fan to enhance thermal comfort



Figure 11. Temperature (°C) and Relative Humidity (%) of 1st April 2024

Figure 11. shows the temperature (°C) and relative humidity (%) of 1st April 2024. The temperature typically ranges from 25 °C to 38.8 °C and the relative humidity typically ranges from 20 % to 100 %.

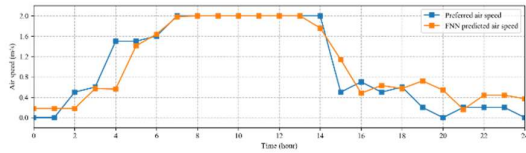


Figure 12. Preferred air speed and FNN predicted air speed respectively for 1st April 2024

Figure 12. shows the preferred air speed and FNN predicted air speed for 1st April 2024. The prediction made by the FNN is in par with the preferred air speed manually set.

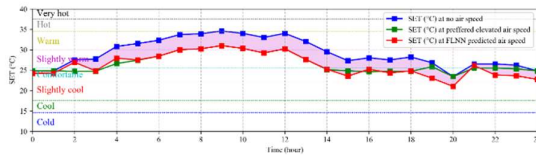


Figure 13. SET under no air, preferred air speed and FNN predicted air speed respectively for 1st April 2024

Figure 13. shows the SET under no air, preferred air speed, and FNN predicted air speed respectively for 16th January 2024. The SET at no air speed reaches warm and hot region. The SET of FNN is in line with the preferred air speed set however the SET crosses warm region at 9th hour and within the comfortable region in the night time. Also from the figure 13, it can be seen that due to the use of FNN, the temperature is changed from warm condition to slightly warm condition.

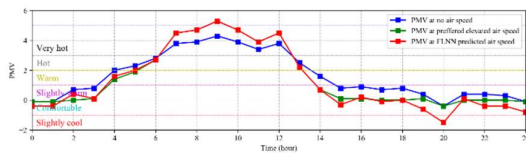


Figure 14. PMV under no air, preferred air speed and FNN predicted air speed respectively for 1st April 2024

Figure 14. shows the PMV under no air, preferred air speed, and FNN predicted air speed respectively for 16th January 2024. The PMV is under very hot region for no air. The PMV of FNN is in line with the preferred air speed set however the PMV is under a very hot region as the air heats up from 6th hour to 13th hour.

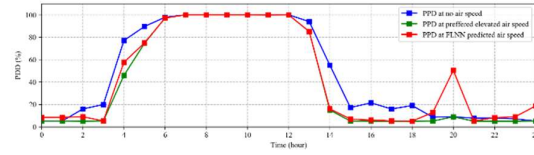


Figure 15. PPD under no air, preferred air speed, and FNN predicted air speed respectively for 1st April 2024

Figure 15. shows the PPD under no air, preferred air speed and FNN predicted air speed respectively for 16th January 2024. The PPD under no air speed is always not under 20% (from 2nd hour to 18th hour). The PPD at FNN predicted air speed is in line with the preferred elevated air speed. However, the PPD of FNN predicted air speed and PPD of preferred elevated air speed (from 3rd hour to 14th hour) is above 20 % and the remaining period is below 20 % due to natural cooling.

From Figure 6 to 15, it can be seen that the above predicted air speed is in line with the preferred values of air speed, PMV, SET, and PPD respectively. However, the value SET is not within comfortable region, PMV is not within the comfortable region and PPD is not within 20 %. This can be only achieved by the use of heating ventilation air conditioning system and this however is not the scope of this paper. This paper develops a simple fan regulator that automatically changes the air speed of the ceiling fan within its operating range to satisfy maximum possible values of SET, PMV, and PPD and to achieve energy conservation and provide thermal comfort in developing countries. Also the proposed FNN can effectively replace the frequent fan speed changing operation especially during the night times.

4.2. The relation between air speed and Rotation Per Minute (RPM)

The ceiling fan is made from the induction motor and the speed of the induction motor is controlled by the varying the applied voltage. And the air speed depends on the RPM of the induction motor. Therefore the RPM required for the particular air speed is calculated (Raftery et al. 2024) as, The area-weighted average air speed (SO) is

$$SO_{avg} = 0.99 \times \frac{D}{R} - 0.06 \times \frac{H}{D} + 0.11 \times \frac{D}{1.7} + 0.024 + 0.250 \quad (1)$$

where,

D - Diameter of ceiling fan (m)

R - Square room size (m)

H - Height of ceiling fan from floor (m)

The fan air speed (SF) at the rated airflow is

$$SF_{rated} = \frac{4 \times Q}{\pi \times D^2} \quad (2)$$

The fan air speed at the operating rotational speed is

$$SF_{at\ RPM} = SF_{rated} \times \frac{RPM}{Maximum\ RPM}$$

(3)

The estimated area-weighted average air speed for a seated occupant is

$$AS = SF_{at\ RPM} \times SO_{avg}$$

(4)

Therefore, the RPM is calculated as,

$$RPM = \frac{AS \times Maximum\ RPM}{SO_{avg} \times SF_{rated}}$$

(5)

For domestic applications there is a possibility of using different types of fan with sweep leading to varying RPM and the air delivery. The different types of fan with sweep and their air delivery is listed in Table 1.

Table 1. Air speed from the air delivery

| S L N o. | D (m) | R (m) | H (m) | Po we r (w att s) | Ra ted R P M | Air deli ver y (C M M) | Air Deli ver y (cu. m ³ /s) | A S (m/ s) |
|-------------------|------------------|------------------|------------------|----------------------------------|--------------------------|--|---|-------------------------|
| 1. | 0.6 | 2 | 3 | 64 | 90 | 120 | 2.00 | 2.19 |
| 2. | 0.9 | 2 | 3 | 60 | 39 | 155 | 2.58 | 2.35 |
| 3. | 1.05 | 2.5 | 3 | 66 | 37 | 195 | 3.25 | 2.20 |
| 4. | 1.2 | 3 | 3 | 70 | 37 | 230 | 3.83 | 2.03 |
| 5. | 1.4 | 3 | 3 | 80 | 28 | 270 | 4.50 | 2.04 |

Table 4 shows that if the diameter of the ceiling fan is properly chosen for the required room size, then air speed is in and around 2 m/s. So the air speed predicted by the FNN can be applied to any domestic fan. In this paper, the most common ceiling fan with 1.2 m diameter is used for analysis.

4.3. The relation between RPM and voltage

From the measured value of RPM and the voltage of a ceiling fan under five-speed with power consumption are tabulated in Table 2.

Table 2 The different speed of the fan regulator number with power consumption

| Speed | Speed (RPM) | Speed (m/s) | Voltage (V) | Power (W) |
|---------|-------------|-------------|-------------|-----------|
| Speed 1 | 74 | 0.4 | 82 | 27.8 |

| | | | | |
|---------|-----|------|-----|------|
| Speed 2 | 107 | 0.56 | 109 | 34 |
| Speed 3 | 153 | 0.84 | 131 | 40.6 |
| Speed 4 | 266 | 1.45 | 149 | 48.6 |
| Speed 5 | 370 | 2 | 220 | 70 |

The relation between the voltage and speed (RPM) is estimated using the cubic fit and related as $y=1.1598e-05 x^3-7.1621e-03x^2+1.6588x-1.3681$ (6)

where x is the speed (RPM) and y is the voltage

4.4. The relation between firing angle and voltage

The voltage and firing angle are related as

$$\alpha = \sqrt{0.004v}$$

(7)

where v is the voltage

4.4. Experimental setup

The experimental setup of fan regulator system consists of a switched-mode power supply, microcontroller (for fuzzy logic control), temperature and humidity sensor, and driver circuit. Figure 16 represents the block diagram of the FNN fan regulator.

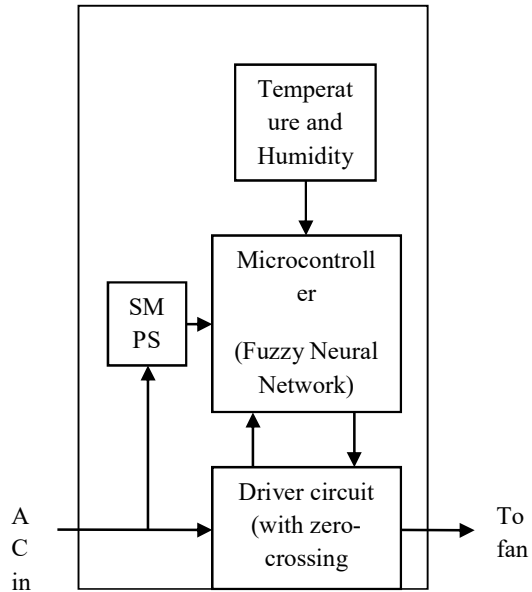


Figure 16. The block diagram of the FNN fan regulator

Switched-mode power supply: A switched-mode power supply is used to step down voltage from 230V AC to 5V DC. The LRIPL103 5V,2A is used as the switched-mode power supply module to power up the microcontroller.

Sensors: The sensors are used to measure temperature and the humidity and sends the sensed data to the microcontroller. The DHT11 which is a

temperature and the humidity sensor is used to send data to the microcontroller.

Microcontroller: The microcontroller is used to implement the FNN. Based on the temperature and humidity values, the FNN in the microcontroller generates an air speed which is converted into RPM by equation (5), convert into a required voltage by equation (6), and again converted into firing angle α by equation (7) and generates a Pulse Width Modulation (PWM) signal corresponding to it at the output port in synchronization with zero-crossing detector. The ATmega328 microcontroller is used to implement the FNN.

The driver circuit: The driver circuit has a zero-crossing detector employing optocoupler which detects the zero crossings and sends it to the microcontroller and is used for the commutation of the driver circuit. The driver circuit varies the output voltage based on the PWM signal from the microcontroller. The AC light dimmer module is used as the driver circuit.

FNN regulator: The FNN regulator is connected near to the ceiling fan and the FNN regulator setup is shown in figure 17.

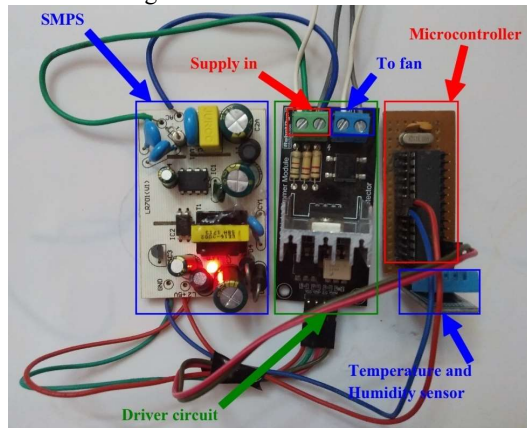


Figure 17. An experimental set up of FNN regulator

4.5 Experimental result

In order to evaluate the performance of the proposed system in a real-time environment, experiments were conducted on two different days to compare the performances of fan with proposed FNN regulator with an ordinary regulator and without a regulator respectively. The experiment was conducted in three identical 10 x 10 room with two windows respectively. The first room is fitted with fan without regulator. The fan without regulator will be running without any speed control for the entire time it is turned on. It is turned on/off by the collective decision of 5 volunteer members in the room based on the climatic condition. The second room is fitted with fan with regulator. The fan with ordinary regulator has a speed regulator with five-speed as listed in Table 2. The fan with ordinary regulator is manually adjusted to the maximum comfort by varying air speed with minimal speed

change i.e. the fan regulator position is varied by the collective decision of five volunteers in the room based on the climatic condition. The third room is fitted with fan with proposed FNN regulator. The fan with the proposed FNN regulator automatically generates speed based on the trained data.

The first experiment was conducted on 18th January 2024. The figure 18 shows the air speed comparisons of a fan without a regulator, fan with ordinary regulator and a fan with FNN regulator respectively for 18th January 2024.

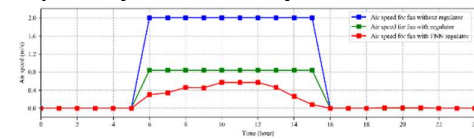


Figure 18. Air speed comparisons of a fan without a regulator, fan with ordinary regulator and a fan with FNN regulator respectively for 18th January 2024

From figure 18, it can be seen that fan without regulator is running at 5 times higher speed than that of fan with FNN regulator except for 2 hours from 10th hour to 12th hour, fan without regulator is running at 3.33 times higher speed than that of fan with FNN regulator. The fan with the regulator is running 2 times higher speed than that of fan with FNN regulator except for 2 hours from 10th hour to 12th hour, fan without regulator is running at 1.33 times higher speed than that of fan with FNN regulator.

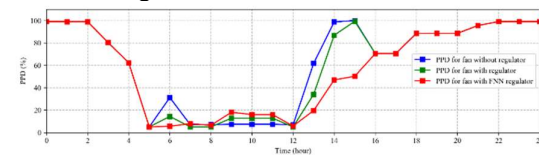


Figure 19. PPD comparisons among fan without a regulator, with regulator and FNN regulator respectively for 18th January 2024

From Figure 19, it can be seen that the PPD from 5th hour to 13th hour is under 20 % for fan without a regulator, fan with ordinary regulator and FNN regulator and the remaining period is above 20 % due to natural cooling. However, the PPD is better for the fan with FNN regulator than a fan with and without regulator for 6 hours from 12th hour to 18th hour.

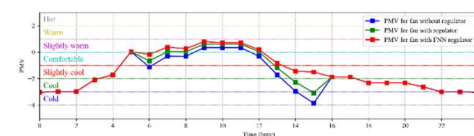


Figure 20. PMV comparisons among fan without a regulator, with regulator and FNN regulator respectively for 18th January 2024

From the Figure 20, it can be seen that the PMV is better for the fan with FNN regulator than a fan with and without regulator for 7 hours from 6th hour to 13th hour and is best for the fan with FNN regulator than a fan with and without regulator for 4 hours from 14th hour to 17th hour.

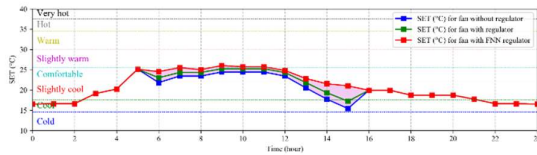


Figure 21. SET comparisons among fan without a regulator, with regulator and FNN regulator respectively for 18th January 2024

From Figure 21, it can be seen that the SET for the fan with the FNN regulator is better than a fan with and without regulator respectively.

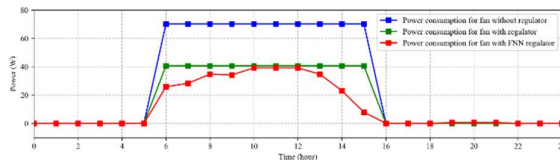


Figure 22. Power comparisons among fan without a regulator, with regulator and FNN regulator respectively for 18th January 2024

From Figure 22, it can be seen that fan without regulator is consuming two times higher power than that of fan with FNN regulator. The fan with the regulator is consuming power almost in line with fan with FNN for 6 hours from 5th hour to 11th hour. And the fan with the regulator is consuming constant power for 4 hours from 12th hour to 16th hour while there is a decreasing level of power consumption by the fan with FNN regulator. And the fan with the regulator is consuming power for 2 hours from 16th hour to 18th hour when there is no need for a fan at that time. From Figure 18 to 22, it is found that the fan with a FNN regulator maintained comfort levels 100 % in the winter season.

The second experiment was conducted on 3rd April 2024. The Figure 23 shows the air speed comparisons of a fan without a regulator, fan with ordinary regulator and a fan with FNN regulator respectively for 3rd April 2024.

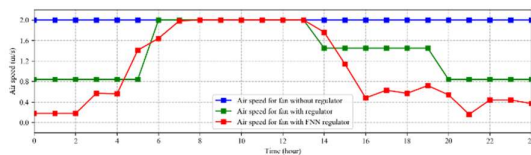


Figure 23. Air speed comparisons among fan without a regulator, with regulator and FNN regulator respectively for 3rd April 2024

From figure 23, it can be seen that fan without regulator is running approximately four times higher speed than that of fan with FNN regulator for 12 hours during the night time from 0th hour to 4th hour, 16th hour to 24th hour. The fan with the regulator is running approximately at one-fourth higher speed for 4 hours from 12th hour to 16th hour, approximately half speed higher for 3 hours from 15th hour to 18th hour, approximately double speed higher for 9 hours during the night time from 19th

hour to 24th hour and 1st hour to 4th when compared to the fan with FNN regulator.

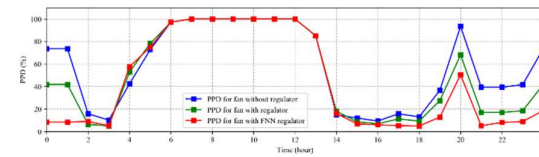


Figure 24. PPD comparisons among fan without a regulator, with regulator and FNN regulator respectively for 3rd April 2024

From Figure 24, it can be seen that the PPD is better for fan with FNN regulator than a fan with and without regulator for 11 hours from 14th hour to 19th hour, from 21st hour to 24th hour and 0th hour to 3rd hour.

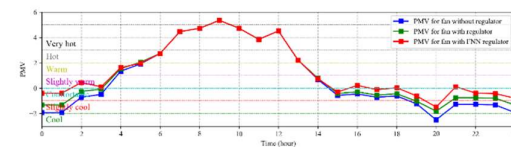


Figure 25. PMV comparisons among fan without a regulator, with regulator and FNN regulator respectively for 3rd April 2024

From Figure 25, it can be seen that the PMV is same for fan without a regulator, fan with the regulator and FNN regulator for 8 hours from 5th hour to 13th hour. The fan with the regulator is almost in line with the FNN regulator for 24 hours from 0th hour to 4th hour, from 13th hour to 24th hour and under comfortable conditions.

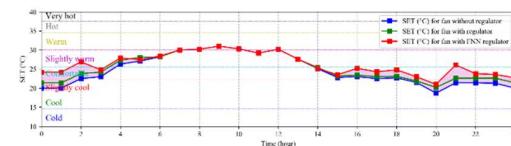


Figure 26. SET comparisons among fan without a regulator, with regulator and FNN regulator respectively for 3rd April 2024

From Figure 26, it can be seen that the SET for the fan with the FNN regulator is better than a fan with and without regulator respectively.

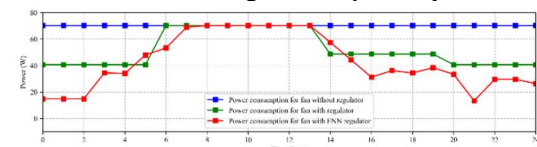


Figure 27. Power comparisons among fan without a regulator, with regulator and FNN regulator respectively for 3rd April 2024

From Figure 27, it can be seen that fan without regulator is consuming approximately double the times power than that of fan with FNN regulator for 12 hours during the evening and night time from 0th hour to 4th hour and 16th hour to 24th hour. The fan with the regulator is consuming power almost in line with fan with FNN for 12 hours from 6th hour to 18th hour. And double times the power for 2 hours from 0th hour to 2nd hour and one-tenth of

power for 4 hours from 20th hour to 24th hour than that of fan with FNN regulator. From Figure 23 to 27, it is found that the fan with a FNN regulator maintained comfort levels 58.3 % in the summer season.

In addition to the above used dates 16th January 2024 and 1st April 2024, 23rd February 2024 and 24th August 2024 which are the mid-day between 16th January 2024 and 1st April 2024 are used to calculate the average energy consumption throughout the year and listed in the Table 3.

Table 3. Energy consumption by a fan without a regulator, with regulator and with FNN regulator respectively

| Sl. No. | Date | E1 (kWh) | E2 (kWh) | E3 (kWh) |
|--|--------------------------------|--------------|--------------|--------------|
| 1. | 16 th January 2024 | 0.702 | 0.406 | 0.308 |
| 2. | 23 rd February 2024 | 0.983 | 0.919 | 0.669 |
| 3. | 1 st April 2024 | 1.755 | 1.300 | 1.079 |
| 4. | 24 th August 2024 | 1.123 | 0.672 | 0.291 |
| Average energy consumption per fan per year | | 480.4 | 335.5 | 235.2 |

From Table 3, the average energy consumption by a fan without regulator is two times higher than that of fan with FNN regulator and the average energy consumption by the fan with the regulator is 1.4 times higher than that of fan with FNN regulator. The fan with the FNN regulator will save 245.2 unit of energy when compared to a fan without regulator and 100.3 unit of energy when compared to a fan with regulator respectively. Therefore, the energy saved by the fan with FNN regulator is around 50 % that of the fan without a regulator and around 33 % than that of fan with the regulator. The FNN regulator can prevent overcooling effect during winter by reducing the fan speed and improve cooling in the incremental stage as the climatic condition varies in the summer.

The FNN regulator is designed based on the assumption that the fan is operated in the recommended space with proper ventilation. The FNN regulator is placed in the switch box and so the temperature and humidity sensor receives the ambient condition near to the switch box. The relation between the voltage and air speed is derived based on the average of torque speed characteristic of the commonly available ceiling fans. It cannot improve the thermal comfort when the temperature is less than 26 °C and humidity 100 % and when the temperature is greater than temperature 34 °C and humidity 20%.

Conclusion

A FNN based fan regulator for ceiling fan was developed to enhance the thermal comfort. A relation between inputs (temperature, humidity) and output (air speed) is developed through a FNN to satisfy the assessment indicators and used in the fan regulator system to enhance the thermal comfort. The performance of the fan with a FNN regulator is compared with the preferred condition and found satisfactory through simulation. In order to evaluate the performance of the proposed system in a real-time environment, experiments were conducted on two different days to compare the performances of fan with proposed FNN regulator, an ordinary regulator and without a regulator respectively. It is found that the fan with a FNN regulator is in par with the simulation results. Also, the fan with a FNN regulator is 50 % energy saving compared to a fan without a regulator and 33 % energy saving compared to a fan with the ordinary regulator.

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