Fuzzy Inference-Based Control Approach for Thermal-Visual Comfort and Air Quality in Indoor Environments

JEAN J. SAADE (1), ALI H. RAMADAN (2)
ECE Department
American University of Beirut
Faculty of Engineering and Architecture
P.O.Box: 11-0236, Riad El-Solh 1107 2020, Beirut
LEBANON

Abstract: - This paper presents a fuzzy inference-based control approach for the adjustment and maintenance, according to users’ preferences, of air quality, thermal and visual comfort for buildings’ occupants while minimizing energy consumption. First, the control objectives and criteria are described and their models are provided. Then, the designed fuzzy controller along with the criteria models are simulated using MatLab/Simulink. The simulation results are depicted for each control criterion and the efficiency of the presented approach is verified. It is shown that this approach is capable of responding to fixed and variable users’ preferences and eliminating overshoots and oscillations without the need for any adaptive procedure.

Key-Words: - Fuzzy controller; Inference; Energy consumption; Thermal-visual comfort; Air quality.

1 Introduction

An important part of today’s technological developments are centered on the design of machines, which are capable of performing tasks that require intelligence. Due to the inability of binary logic and classical mathematics to provide a satisfactory tool for designing such intelligent machines, various technological tools, such as fuzzy logic and inference, artificial neural networks, etc., have been invented for use towards achieving the previously-noted objective. The aim of fuzzy inference is to provide approximate mathematical models expressed using vague and imprecise linguistic terms, which are involved in conditional “if-then” rules [1,2,3].

In situations where disturbances, uncertainty and modifications occur, it would not be feasible to provide precise models using classical mathematics. Approximate models based on fuzzy inference as a smart design or control technique have been shown to be more appropriate [1,2,3,4]. In this paper, therefore, a fuzzy inference-based control approach for the achievement of indoor thermal-visual comfort and air quality satisfaction while reducing energy consumption is presented.

Efficient management of energy in buildings and maintenance of indoor comfort in acceptable margins, using intelligent design tools, has been the focus of some researchers in recent years [4,5]. Several alternative solutions have been presented and evaluated in [4] in order to adjust and preserve air quality, thermal and visual comfort for buildings' occupants while reducing energy consumption and taking users’ preferences into account. Among these solutions and according to the presented results, the adaptive fuzzy PD controller ensured the best reduction in overshoots and oscillations and, hence, the lowest energy consumption.

In this study, a fuzzy inference-based control approach for the adjustment of the parameters or criteria, which have a direct influence on the thermal and visual comforts and air quality in indoor environments, is offered. Both fixed and variable user’s preferences, as they relate to temperature affecting thermal comfort, carbon dioxide concentration affecting indoor air quality and illuminance level influencing visual comfort, have been adopted. Whenever a user requests a desired level for any of the mentioned criteria, the fuzzy inference system, in conjunction with the criteria models, responds to his request while eliminating overshoots and oscillations. Hence, a minimization of energy waste has been achieved without the need for adaptivity.

2 Control Objectives, Criteria and Models

The objectives of the control strategy are the following:

- Adjustment and maintenance of thermal-visual comfort and indoor air quality criteria according to users’ preferences [4,5,6].
• Minimizing building energy consumption for heating/cooling, lighting and ventilation processes through the avoidance of overshoots and oscillations [4]. These objectives are to be achieved by using a fuzzy logic controller that works in conjunction with furnished criteria models at a certain zone level of the building. The involved criteria and their corresponding models are detailed in what follows.

2.1 Thermal comfort
Thermal comfort is usually determined by the Predicted Mean Vote (PMV) introduced by Fanger [6]. The PMV depends on temperature, relative humidity, mean radiant temperature, air velocity, activity level, and clothing parameter. However, since temperature is the main contributing factor among those mentioned above, we have chosen it as the main criterion to be controlled for the achievement of thermal comfort. Moreover, users’ desired temperature levels have been selected to be between 15°C and 50°C.

We considered that temperature is driven by applied current [3]. Accordingly, the following mathematical transfer function of the thermal model has been considered:

$$ Temp(s) = \frac{1}{s + 0.0001} I_1(s) $$

(1)

Transforming the Equation (1) into the time domain, yields

$$ \frac{dtemp(t)}{dt} = i_1(t) - 0.0001 ttemp(t) $$

(2)

Figure 1 shows the representation of the differential equation in (2) in Simulink. In the figure, we have

$$ f(u) = (u[1] - 0.0001 \cdot u[2]) $$

(3)

![Figure 1. Thermal model in Simulink.](image)

2.2 Visual comfort
The controlled parameter for achieving visual comfort has been selected as the illuminance level, measured in Lux [4,7]. The preferred light level in a room depends primarily on the type of activity. Common favourable levels vary between 300 and 1000 Lux [4]. The electric power needed to achieve a specific illuminance level can be expressed as follows:

$$ P = \frac{b}{\eta_s \eta_l l_s} $$

(4)

where, $P$ is the electric power, $b$ is the illuminance level, $\eta_s$ is the light source efficiency, $\eta_l$ is the room lighting efficiency and $l_s$ is the amount of light, expressed in Lumen, that can be emitted by the source per Watt.

The purpose of a lamp is to convert electrical power into light. Different lamps do this with varying efficiencies and the light emitted from a source depends on the type of source. In our project we chose a GLS lamp type with $l_s = 15$. The light equipment efficiency expresses the percentage of light that goes to the room out of that emitted by the light equipment. The room lighting efficiency expresses how much of the light is absorbed by the room before entering the activity area. Light equipment efficiency and room lighting efficiency influence each other. Common values of the product $\eta_s \eta_l$ are in the range from 0.3 to 0.6. The 0.5 value has been chosen. Replacing $\eta_s \eta_l$ and $l_s$ in Equation (4), yields

$$ P = \frac{b}{7.5} $$

(5)

Equation (5) was used to convert the user’s desired illuminance levels into power values. The electric power to the light equipment is in the first place caused by an electric current. Based on this fact, we adopted the same mathematical transfer function of the thermal model indicated in Section 2.1 to be implemented in the visual model. After achieving a power level in the controlling process, it can be reconverted to light level using $b = 7.5P$. This has been used to display the controlled power along with the achieved illuminance level.

The transfer function of the adopted visual model is given by

$$ \frac{P(s)}{l_2(s)} = \frac{1}{s + 0.0001} $$

(6)

Transforming Equation (6) into the time domain, we obtain

$$ \frac{dp(t)}{dt} = i_2(t) - 0.0001 p(t) $$

(7)
Figure 2(a) shows the representation of the differential equation in (7) in Simulink, where \( f(u) \) is as in Equation (3). Figures 2(b) and 2(c) are Simulink representations of the Lux-Watt and Watt-Lux conversions.

![Simulink representation of differential equation](image)

(a)

![Simulink representation of Lux-Watt conversion](image)

(b)

![Simulink representation of Watt-Lux conversion](image)

(c)

Figure 2. Simulink representations of: (a) Visual model, (b) Watt-Lux converter and (c) Lux-Watt converter.

2.3 Indoor air quality

The quality of air in indoor environments is mainly influenced by the concentration of pollutants. In this context, the CO\(_2\) concentration (measured in ppm) has been chosen because it is a dangerous pollutant that could exist in buildings. Improving the air quality involves the use of a motor, which drives a fan in order to push the polluted air to the outside. The DC motor is driven by applied voltage and its equivalent circuit is shown in Figure 3.

![Model of a DC motor](image)

Figure 3. Model of a DC motor

As mentioned earlier in this subsection, the motor is used to drive a fan in order to push existing pollutants (mainly CO\(_2\)) to the outside. Usual CO\(_2\) concentrations are found to vary between 600 and 800 ppm [4]. Hence, whenever the CO\(_2\) concentration, denoted by [CO\(_2\)], increases (decreases) within this range, the DC motor angular speed, expressed in round per minute (RPM) and being determined by the applied voltage, should be increased (decreased). Moreover, we proposed and used in this study two empirical linear equations which perform [CO\(_2\)]-to-RPM and RPM-to-[CO\(_2\)] conversions, respectively. The first conversion is used in the controlling process, which consists of achieving a suitable angular speed. The second conversion is performed in the post-controlling process to display the controlled RPM along with the achieved [CO\(_2\)].

Based on Equation (12), the used transfer function of the DC motor is given by

\[
\frac{W(s)}{V(s)} = \frac{K_t}{(sL + R)(s^2 + D) + K_t K_b}
\]

(12)

Applying inverse Laplace transform to the above transfer function results in the following differential equation:

\[
\frac{w(t)}{i(t)} = \frac{2130}{s^2 + 950s + 26}
\]

(13)

In the above equations, \( V(t) \) is the applied voltage, \( i(t) \) is the circuit current, \( v_{\text{emf}}(t) \) is the back electromotive force, \( T(t) \) is the torque of the motor and \( W(t) \) is the motor angular speed. \( R, L, K_b, K_s, J, D \) and \( T_L \) are respectively the circuit resistance, circuit inductance, back electromotive force constant, motor torque constant, moment of inertia, viscous coefficient and load torque. The DC motor characteristic equations can be used to obtain the following input-output transfer function:
\[
\frac{d^2 w(t)}{dt^2} = 2130v(t) - 950 \frac{dw(t)}{dt} - 26 w(t)
\] (14)

The mathematical presentation of the used equations for [CO₂] to RPM conversion and de-conversion are respectively as follows:

\[
\text{RPM} = 0.4 \cdot [\text{CO}_2] - 220
\] (15)

\[
[\text{CO}_2] = \frac{\text{RPM} + 220}{0.4}
\] (16)

Figure 4 depicts the representation of the DC motor differential equation in (14) in Simulink, where

\[
f(u) = 2130 \cdot u[1] - 950 \cdot u[2] - 26 \cdot u[3]
\] (17)

The Simulink representation of Equations (15) and (16) are also shown in Figure 4.

\[
V
\] (a)

\[
[\text{CO}_2]
\] (b)

\[
\text{RPM}
\] (c)

Figure 4. Simulink representations of: (a) Air quality model, (b) [CO₂]-to-RPM converter and (c) RPM-to-[CO₂] converter.

3 Fuzzy Inference System

In this section, a fuzzy logic controller for the criteria explained in Section 2 is devised and this is based on the use of fuzzy inference. For each criterion included in the control objectives or its directly linked parameter, the error and error variation have been considered as the input variables of the fuzzy controller. Hence, the error and change in error for the temperature, electric power and RPM are the fuzzy controller input variables. The controller output variables are the currents I₁ and I₂ and voltage V (see Figures 1, 2, 4 and 5).

\[
\begin{align*}
\text{Temp}_e & \\
\Delta \text{Temp}_e & \\
\text{P}_e & \\
\Delta \text{P}_e & \\
\text{RPM}_e & \\
\Delta \text{RPM}_e & \\
\end{align*}
\]

\[
\begin{align*}
\text{I}_1 & \\
\text{I}_2 & \\
V & \\
\end{align*}
\]

Figure 5. Implemented fuzzy controller

The membership functions assigned over the controller inputs and outputs variables are shown in Figures 6 and 7. The linguistic variables used are N, Z and P, where N means negative, Z means zero and P means positive. The complements of N, Z and P are also used for the change of error in temperature, power and RPM. The membership functions of the fuzzy logic controller include both triangular and trapezoidal forms. The fuzzy inference rules are 27 “if-then” rules. Tables 1, 2 and 3 demonstrate the inference rules for the error and change in error as they relate to the criteria that need to be controlled by controlling their affecting quantities; i.e., I₁ for temperature, I₂ for illuminance-related power and V for [CO₂]-related RPM. The type of fuzzy inference engine is Mamdani and the fuzzy outputs are defuzzified by the center of gravity procedure.

As has been mentioned earlier in this study, the fuzzy logic controller described above, is supposed to work in conjunction with the models of the criteria introduced in Section 2 in order to satisfy the control objectives. For this to be achieved, the fuzzy controller with some initial, yet reasonable assignment of membership functions and rules and the criteria models with initially assigned constants in their transfer functions were mounted in the Simulink tool available under Matlab. Then a large number of simulation runs were executed for numerous fixed and variable user’s preferences related to temperature, illuminance level and carbon dioxide concentration. The performed simulation runs helped a great deal in tuning the membership functions ranges and break points, the constants involved in the transfer functions of the criteria and their models and also in the adjustment of the
conversion models so as to arrive at the final fuzzy controller design and models settings.

This has led to a near perfect achievement of the control objectives as described in Section 2. That is, the final system has been obtained as one that is capable of satisfying desired criteria levels according to users’ choices and in a very short time duration. Elimination of overshoots and oscillations has, in addition, been reached. It is worth noting here as well that the achieved smoothness in the control surfaces, shown in Figures 8-10, of the final fuzzy controller has been observed as one of the contributing factors to the obtained avoidance of overshoots and oscillations in the system responses.

Figure 6. Membership functions for fuzzy controller inputs: (a) temperature error, (b) change in temperature error, (c) power error, (d) change in power error, (e) RPM error and (f) change in RPM error.
Figure 7. Membership functions for fuzzy controller outputs: (a) current $I_1$, (b) current $I_2$, and (c) voltage.

Table 1. Inference rules for the thermal model.

<table>
<thead>
<tr>
<th>$I_1$</th>
<th>$\Delta T_{\text{Temp}_e}$</th>
<th>N</th>
<th>Z</th>
<th>P</th>
<th>N$_c$</th>
<th>Z$_c$</th>
<th>P$_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Temp}_e$</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N$_c$</td>
<td>N$_c$</td>
<td>N$_c$</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

Table 2. Inference rules for the visual model.

<table>
<thead>
<tr>
<th>$I_2$</th>
<th>$\Delta P_e$</th>
<th>N</th>
<th>Z</th>
<th>P</th>
<th>N$_c$</th>
<th>Z$_c$</th>
<th>P$_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_e$</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N$_c$</td>
<td>N$_c$</td>
<td>N$_c$</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

Table 3. Inference rules for the fan model.

<table>
<thead>
<tr>
<th>$V$</th>
<th>$\Delta \text{RPM}_e$</th>
<th>N</th>
<th>Z</th>
<th>P</th>
<th>N$_c$</th>
<th>Z$_c$</th>
<th>P$_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{RPM}_e$</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N$_c$</td>
<td>N$_c$</td>
<td>N$_c$</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

Figure 8. Control surface for $I_1$ versus temperature error and change in error.

Figure 9. Control surface for $I_2$ versus power error and change in error.

Figure 10. Control surface for voltage versus RPM error and change in error.
4 Simulation and Results

This section presents the results of some simulations performed on the fuzzy logic controller and criteria models obtained at the end of the tuning and design stage that has been described in Section 3. Fixed and variable users’ preferences (or set points), as they relate to the criteria of the control objectives, have been considered. These are shown in Figures 11-13 for fixed set points and in Figures 14-16 for variable set points. The Simulink implemented system is shown in Figure 17. For fixed preferences, the following values have been used in the performed simulations: Temperature=$25^\circ$C, illuminance level = 650 Lux and $[\text{CO}_2]=700$ ppm. The variable preferences have been modelled using random generators providing various set points at various time intervals for temperature, illuminance level and $[\text{CO}_2]$ within the limits indicated in Section 2 of these control criteria.

![Figure 11. Controlled temperature level (fixed) versus time.](image1)

![Figure 12. Controlled illuminance level (fixed) versus time.](image2)

![Figure 13. Controlled $[\text{CO}_2]$ (fixed) versus time.](image3)

Figure 11, 12 and 13 show that the designed fuzzy system used in conjunction with the criteria models has been capable of achieving the desired criteria levels in about 1 second and this has been done without any noticeable overshoots nor oscillations about the desired set points at the steady state. The same observations can be made in the variable set points simulations as in Figures 14-16. Minimization of energy consumption becomes ensured by the virtue of the obtained elimination of overshoots and oscillations. Hence, the presented results show that the control objectives specified in Section 2 have been satisfied by the presented fuzzy inference-based control approach.

![Figure 14. Controlled temperature level (variable) versus time.](image4)

![Figure 15. Controlled illuminance level (variable) versus time.](image5)
5 Conclusions

In this paper, a fuzzy inference-based control approach for the adjustment of the criteria, which have a direct influence on the thermal and visual comfort and air quality in indoor environments, has been presented. The criteria involved in the control objectives have been described and their models have been provided. Then, using the fuzzy inference methodology and the offered criteria models a fuzzy logic controller has been designed to work in conjunction with the criteria models so as to achieve the stated objectives of the considered control strategy. Actually, the final design of the fuzzy controller and criteria models has been obtained after a lengthy procedure of simulations, testing and tuning using the Simulink tool available under MatLab.

The end result turned out to be a system that is capable of responding efficiently to users’ desired levels, whether fixed or variable, of the criteria that determine the thermal and visual comforts and air quality inside buildings. The presented system has, therefore, been shown capable of achieving the user’s specified set points for temperature, illuminance level and carbon dioxide concentration in very short time duration while eliminating overshoots and oscillations. Consequently, minimum energy consumption becomes guaranteed.

References: