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DEVELOPMENT OF INTELLIGENT ALGORITHMS FOR INDOOR AIR QUALITY CONTROL THROUGH NATURAL VENTILATION STRATEGIES

G Sutherland, G Eftaxias, M Santamouris, D Asimakopoulos

University of Athens
Department of Applied Physics
University Campus
Building PHYS-5
157 84 Athens
GREECE

Tel: +30 1 728 4841
Fax: + 30 1 729 5282
E-mail: gordon@dap.uoa.gr

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G. Sutherland, G. Eftaxias, M. Santamouris, D. Asimakopoulos
University of Athens, Department of Applied Physics,
University Campus, Building PHYS-5, 157 84 Athens, Greece
Phone: +30 - 1 - 7284841, Fax: +30 - 1 - 7295282
email: gordon@dap.uoa.gr

ABSTRACT

Simulations have been performed to investigate the performance of intelligent algorithms for control of indoor air quality through natural ventilation strategies whilst simultaneously meeting the requirements of thermal and visual comfort. The proposed control algorithms are founded on the knowledge base of the building physics and support the control of natural ventilation through control of the window opening, whilst simultaneously controlling the lighting, heating and cooling systems of the building. The concentration level of CO_2 is taken as the indicator of indoor air quality, whilst predicted mean vote, interior illuminance levels and the daylight glare index have been adopted as the high level controlled parameters for thermal and visual comfort respectively. The impact of the controller on the overall indoor environment has been investigated.

INTRODUCTION

Energy conscious design and energy management in buildings is of paramount importance, both as a means of contributing to security and diversity of energy supplies and also as a means of combating the environmental impact of excess energy consumption on both a global and local scale. Energy consumption in buildings cannot be considered without also accounting for the well being and comfort of the occupants, and experience has shown that building occupants are often not satisfied with the strictly controlled conditions in well sealed buildings. Factors such as indoor air quality and the sick building syndrome, lead to a requirement for utilising the available environmental energy sources to a maximum whilst optimising energy consumption. The use of environmental energy sources is one of the major elements of energy conscious design in buildings, and with it come parallel implications for indoor air quality, thermal comfort and visual comfort.

Intelligent control techniques using fuzzy logic controllers offer the possibility of meeting the required indoor comfort conditions by selectively controlling the building plant and the opening of apertures. The challenge is to meet thermal comfort, visual comfort and indoor air quality requirements simultaneously, whilst minimising energy consumption. The control conflicts arising with respect to the requirements, together with those arising from the necessity to avoid rapid switching of the control system, therefore have to be addressed.

The procedure adopted for the development of the intelligent, rule-based fuzzy control algorithms is to use detailed and simplified models of the building environment, validate the simplified models via comparison with the detailed models, and to compare various fuzzy logic control strategies using these models. A detailed dynamic single zone building model including thermal and mass transport, daylighting and artificial lighting components has been implemented in the MATLAB/SIMULINK environment and the Fuzzy Logic Toolbox of MATLAB has been used to implement the fuzzy logic controller.

MATHEMATICAL MODELLING

A large number of tools are available for simulation of the indoor environment in buildings, however in order to facilitate the combined simulation of the controller and building, the building physics models have been implemented using open architecture programming in the SIMULINK environment.

The building model consists of a zone air temperature model, heat transfer through enclosure structures, heat transfer through fenestration, radiative heat exchange in the interior of the zone, radiative heat exchange at the exterior of the zone, natural ventilation model, CO_2 concentration model, relative humidity model, lighting model including daylight, artificial lighting and glare, and an outdoor environment model including solar radiation and temperature.

For the purpose of the development of the fuzzy rule base, a simplified empirical model can be used to offer a general correlation for calculation of the air flow rate, or the mean air velocity in a zone. This is important from the point of view of the thermal comfort rule base as well for dissipation of indoor pollutants. For the purpose of developing a control algorithm based on the possible or probable air flow rate, this method is therefore suitable.

The British Standards Method has been adopted in order to obtain a realistic representation of the air flow inside the zone with single sided ventilation, wherin ventilation can be due to the effect of the wind or to the temperature diference, Allard (1998). In the case of the former, the air flux Φ is:

$$\Phi = 0.025\, A\, V \ (m^3/s)$$

where:

A : opening surface (m^2)

V : wind velocity (m/s)

In the latter case the wind flux is:

$$\Phi = C_d \frac{A}{3} \sqrt{\Delta T g H_2 / T}$$

where:

C_d : decrease flux coeficient (-)

g : acceleration due to gravity (kg/m^2s)

ΔT : difference between indoor and outdoor temperature (K)

T : average of indoor and outdoor temperature (K)

H_2 : opening height (m)

A simplified calculation of C_d can be obtained from the equation:

$$C_d = 0.0835\, (\Delta T / T)^{-0.3}$$

and the heat transfer per unit time due to ventilation is:

$$\begin{aligned} Q &= m\, c_{pair}\, \Delta T = \rho_{air}\, V_{airchange}\, c_{pair}\, \Delta T / dt \\ &= \rho\, c_{pair}\, \Delta T\ \ V_{airchange}/dt \\ &= \rho_{air}\, c_{pair}\, \Delta T\ \ \Phi \end{aligned}$$

KNOWLEDGE BASE AND FUZZY INFERENCE SYSTEM

The objective of the research activity is to investigate the applicability of fuzzy rule-based controllers for global indoor environmental control and to determine the most appropriate fuzzification, inference and deffuzification procedures. The rule base for the controller can be constructed with two different approaches. The first approach is to combine sets of rules which address particular aspects of indoor environmental control. In this instance, one rule set concerns control of visual comfort, with another rule set for thermal comfort and a third rule set for indoor air quality. The defuzzification process is then used to address the conflicts which arise between the control actions for the three categories for indoor environmental control. A second option is to construct a set of rules incorporating knowledge of building behaviour which in effect will amount to the number of inputs to the controller multiplied by the number of fuzzy sets describing those inputs. A first set of membership functions and three parallel rule sets for indoor environmental control, based on the first option, are presented.

The concentration level of CO_2 in the indoor environment is commonly adopted as the indoor air quality index, despite the fact that the concentration of total volatile organic compounds and smoke which could be harmful to the occupants health could possibly remain high even at low CO_2 concentration levels. The natural variations and random fluctuations in the outdoor wind conditions rule out the use of classical control techniques such as ON/OFF and PID, where the goal of the controller would be to maintain the CO_2 concentration below a certain crisp set point defined by the user. The change in window opening area has been proposed as the output parameter for a fuzzy logic controller for indoor air quality control under natural ventilation, whilst two parameters are proposed as inputs to the fuzzy controller, these being the CO_2 concentration and its derivative; Bruant et al (1996), Dounis et al (1996). An alternative control parameter is the window opening area.

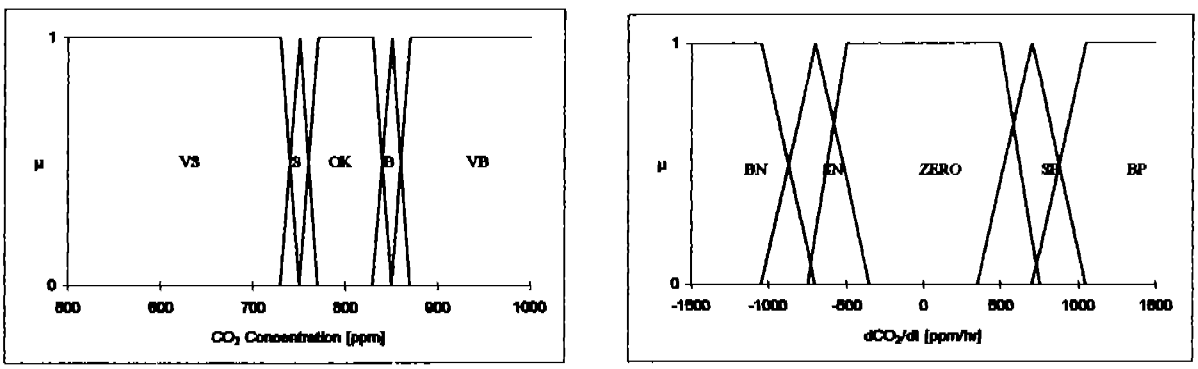

Fig. 1: Fuzzy set membership functions for indoor air quality control (controller input)

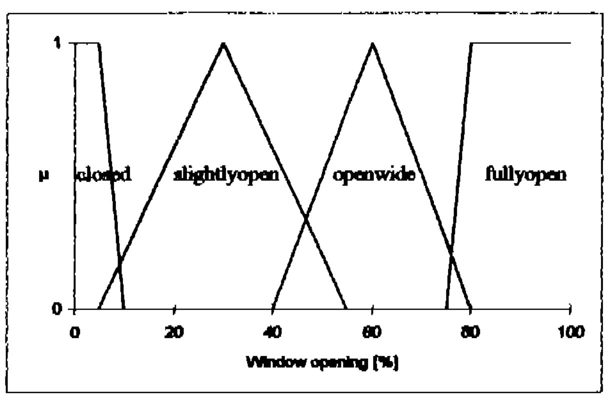

Fig. 2: Fuzzy set membership functions for window opening (controller output)

The rule set for indoor air quality control consists of the following 25 rules:

If (co2 is VS) and (dco2/dt is BN) then (window is closed)
If (co2 is VS) and (dco2/dt is SN) then (window is closed)
If (co2 is VS) and (dco2/dt is ZE) then (window is closed)
If (co2 is VS) and (dco2/dt is SP) then (window is closed)
If (co2 is VS) and (dco2/dt is BP) then (window is closed)
If (co2 is S) and (dco2/dt is BN) then (window is closed)
If (co2 is S) and (dco2/dt is SN) then (window is closed)
If (co2 is S) and (dco2/dt is ZE) then (window is closed)
If (co2 is S) and (dco2/dt is SP) then (window is slightlyopen)
If (co2 is S) and (dco2/dt is BP) then (window is slightlyopen)
If (co2 is OK) and (dco2/dt is BN) then (window is closed)
If (co2 is OK) and (dco2/dt is SN) then (window is closed)
If (co2 is OK) and (dco2/dt is ZE) then (window is closed)
If (co2 is OK) and (dco2/dt is SP) then (window is slightlyopen)
If (co2 is OK) and (dco2/dt is BP) then (window is slightlyopen)
If (co2 is B) and (dco2/dt is BN) then (window is slightlyopen)
If (co2 is B) and (dco2/dt is SN) then (window is slightlyopen)
If (co2 is B) and (dco2/dt is ZE) then (window is slightlyopen)
If (co2 is B) and (dco2/dt is SP) then (window is openwide)
If (co2 is B) and (dco2/dt is BP) then (window is openwide)
If (co2 is VB) and (dco2/dt is BN) then (window is slightlyopen)
If (co2 is VB) and (dco2/dt is SN) then (window is openwide)
If (co2 is VB) and (dco2/dt is ZE) then (window is openwide)
If (co2 is VB) and (dco2/dt is SP) then (window is fullyopen)
If (co2 is VB) and (dco2/dt is BP) then (window is fullyopen)

In a similar manner, membership functions and rule sets have been constructed for indoor thermal comfort and visual comfort control. Whilst indoor air temperature is one indicator of indoor thermal comfort, the actual response of a building occupant is a result of the temperature, mean radiant temperature, relative humidity and air movement, as well as the clothing and activity of the occupant. A more appropriate indicator of thermal comfort is the predicted mean vote (PMV). Using the PMV indicator (with thirteen fuzzy sets) as the input to a fuzzy logic environmental control system results indirectly in the regulation of the environmental variables, Dounis et al (1995). The controller can have PMV and outdoor temperature as its inputs, its outputs can be auxiliary heating, auxiliary cooling and ventilation window opening. In order to minimise the number of rules which are adopted for a prototype rule base for control of all three environmental categories, the number of fuzzy sets describing the PMV has been reduced to seven, resulting in a set of 35 rules for the control of thermal comfort.

The rule set consisting of thirty five rules for thermal comfort control takes the following form:

If (pmv is VN) and (tamb is L) then (ah is VB)(ac is OFF)(window is closed)
If (pmv is N) and (tamb is L) then (ah is PB)(ac is OFF)(window is closed)

. . . . . .

If (pmv is P) and (tamb is VB) then (ah is OFF)(ac is PM)(window is closed)
If (pmv is VP) and (tamb is VB) then (ah is OFF)(ac is ON)(window is closed)

Similarly, the illuminance levels and the daylight glare index have been proposed as controlled parameters in order to build visual comfort control with fuzzy reasoning, with outputs the window shading and the artificial lighting, Dounis et al (1992b). The fuzzy logic controller aims to maintain the illumination level within the desirable limits, which have been set by the user, whilst at the same time, glare must be controlled to fall within acceptable levels. A rule set consisting of twenty four rules for visual comfort control takes the following form:

If (dill is n) and (dgi is imp) then (shading is unshaded)(al is on)
If (dill is n) and (dgi is acc) then (shading is unshaded)(al is on)

. . . . . .

If (dill is vl) and (dgi is unc) then (shading is fullyshaded)(al is off)
If (dill is vl) and (dgi is unb) then (shading is fullyshaded)(al is off)

SIMULATION RESULTS

A series of simulations for both the heating and cooling season have been performed using a model of single building zone model with a south facing opening. The fuzzy controller attempts to maintain the PMV between –0.5 to 0.5 (the comfort zone) via regulation of auxiliary heating, cooling and window opening, whilst simultaneously controlling the lighting levels to 300 lux and the daylight glare index to 22 glare index units through regulation of the shading and artificial lighting. At the same time, the controller adjusts the window opening for control of CO_2 concentration levels by natural ventilation. The results of the simulations for the heating season are shown for three consecutive days in the Figure 4. The use of shading to control visual comfort, in particular glare, results in a reduction of the solar gains and the controller is unable to maintain thermal comfort, since the rule set for thermal comfort is based on the utilisation of thermal gains for minimisation of energy consumption and the heating system is sized accordingly. The CO_2 levels are adequately maintained close to the desired level of 800ppm.

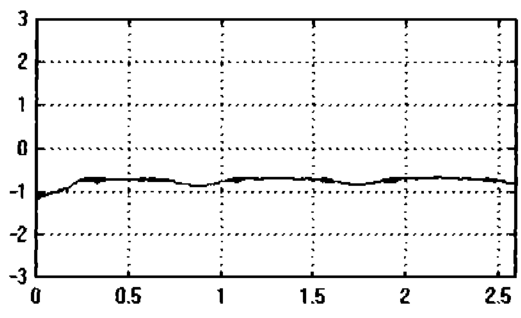

Fig.3a : PMV index vs time (x 10^4s)

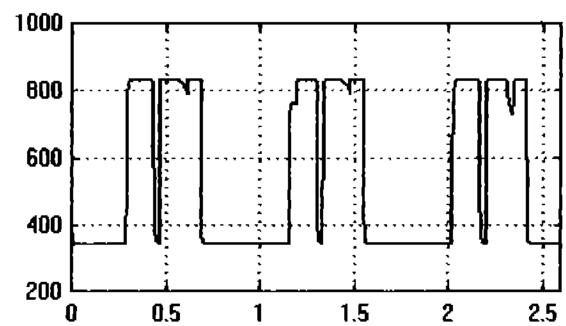

Fig.3b : CO_2 concentration (ppm) vs time (x 10^4s)

CONCLUSIONS

The simulations demonstrate the potential of the fuzzy controller to maintain indoor air quality close to the desired set point (800ppm) whilst simultaneously attempting to maintain thermal and visual comfort. Allowing for adjustment of the rule set to accommodate for the negative effects of the conflicts between the control requirements of the three indoor environmental parameters, it can be seen that a fuzzy rule-based controller is capable of maintaining the three global parameters close to there desired levels. The specific rule base has been developed to allow a maximum use of solar gains, but this is in conflict with the glare controller which imposes very high shading co-efficients. The result is that the PMV remains close to its lower desirable limit. The adoption of the rate of change of the PMV indicator as an input to the fuzzy controller is also proposed, since otherwise the indicator must be outwith the comfort zone before a control action is taken, Egilegor et al (1997). This is not necessarily the case for lighting control, since the natural variations in daylighting are more rapid than those of the thermal response of buildings, and this could lead to instability in the control. Further study of the controller performance with the proposed inputs, together with a combined building and plant model (in order to allow for plant response) is necessary in order to arrive at a final prototype controller for control of visual comfort, thermal comfort and indoor air quality. The case of a full rule base should also be studied.

Furthermore, intelligent control techniques offer the possibility of meeting the required levels of indoor air quality through selective exploitation of the potential for natural ventilation and the use of mechanical ventilation. The rule base should be further developed in order to study the performance of the controller with respect to the selective control of combined natural and mechanical ventilation.

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