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Fuzzy Supervisory Control Strategies to Minimise Energy Use of Airport Terminal Buildings

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Abstract— Airport terminal buildings are among energy most consuming buildings and this presents huge opportunities for implementing energy saving strategies. Achieving satisfactory control of these buildings using classical controllers alone is difficult because they contain components that are complex, non-linear but dynamically related. Therefore, this paper presents and appraises fuzzy control strategies for reducing energy consumptions while simultaneously providing comfort for passengers in an airport terminal building. The inputs into this fuzzy supervisory controller are the time schedule for arrival and departure of passenger planes as well as the expected number of passengers during each flight, zone illuminance and external temperature. The controller outputs optimised temperature, airflow rates and lighting setpoints for the conventional controllers. Simulation studies in MATLAB/SIMULINK confirmed the capacity of this control strategy to provide comfort setpoints for the passengers at reduced energy.

Keywords- Fuzzy Logic Control, Building Energy Management, Airport Terminal, Carbon Emission, Supervisory Control

I. INTRODUCTION

The problem of carbon emission has made the aviation industry and its infrastructure to be reorganised within the idea of low carbon, energy saving and reduced operating cost. One of the most effective ways of saving energy in large buildings generally is efficient control system based on realistic control strategy for that building. A control strategy described how the achievement of some selected objectives could be realised under the constraints imposed by the process itself, the quality of the available information, and the mathematical tools and support available [1].

PID control and other advanced model-based techniques are typical examples of algorithmic-based control. In order to design these controllers, the mathematical model of the system to be controlled must also be modelled. Building environmental systems are known for their non-linear dynamic behaviours, uncertain and time varying parameters; these characteristics make the mathematical modelling of such systems from first principles very difficult or sometimes impossible. Because they are built on the assumption of a linear system, classical controllers of these systems do not respond well to disturbances and modification [2].

Professor Lotfi Zadeh, an expert of Systems Theory at the University of California, Berkeley, theoretically developed fuzzy logic principle during the first half of the 1960s and for the first time used the word "fuzzy" to describe the logic [3]. However, it was Ebrahim Mamdani who first built a fuzzy logic controller during the early 1970’s to control the operation of a steam generator that was difficult to control using the conventional control techniques [4].

Since then, Fuzzy logic theory is now applied to problems in several fields of engineering, business, medical and related health sciences, and the natural sciences.

In line with this development, recently, the use of logic rules in emulating operator thinking, also known as heuristic control based on different techniques has been implemented for the control of building systems and fuzzy logic has featured in many of them. Studies in building artificial intelligence has proved that smart control techniques such as fuzzy control can bring about reduction in energy use while still maintaining comfort [5].

Fuzzy logic control is especially suited for resolving control ambiguity in modelling nonlinear and multi-variable relationships using every day language [6]. Fuzzy modelling has the ability to combine different kinds of information obtained from an experienced operator, measurements and first principle modelling, thus, it employs as much of the available information as needed. Even with vague or imprecise knowledge of those systems, it is still possible for them to be described by an expert in human language, or in nonmathematical terms, using the so-called fuzzy IF-THEN rules [7].

Kolonkotsa et al (2002) used optimisation method based on genetic algorithm to provide optimal comfort settings, which are applied directly on fuzzy logic controllers [8]. Also Dounis et al (2007) developed an intelligent coordinator, which uses fuzzy inference mechanism based on 3D fuzzy sets to produce signal that change setpoints of the primary controllers [9, 10]. Soyguder et al, (2009) applied a self-tuning proportional-integral-derivative (PID)-type fuzzy supervisor to tune the parameters of classical PID controllers with successful results [11]. A more comprehensive literature review on this topic is found in [12].

In most building control applications, a human operator must determine the setpoints for numerous PID controllers and periodically adjust the setpoints to adapt to changing process conditions [13]. Because comfort setpoints changes many times daily, annually and diurnally, updating it manually is a herculean task for operators of large buildings such as the airport terminals. In addition, airport building control operation assumed a 24/7 operations, a study conducted in Manchester airport summarised in another paper [14] found that there are
many hours’ opportunities in the week investigated to operate energy saving setback strategies. Our approach therefore uses high-level fuzzy logic module to perform set point regulation and supervision for the classical controllers in response to variation in passenger occupancy, external temperature and zone illuminance.

The remainder of this paper was organised as follows; supervisory control strategy was first briefly introduced followed by discussions on the structure of the fuzzy controller, determination of the membership function and construction of the fuzzy rules for the supervisory controller. In the last section, a case study simulation results based on some input data from Manchester Airport was presented.

II. SUPERVISORY CONTROL STRATEGY

This control strategy was developed for zones that are exclusive to the passengers and staff of the airport; such that the occupancy flow pattern can be mapped directly to flight schedules. Airport buildings are often zoned such that the landside areas accessible to the public is separated from the airside areas that are accessible to only passengers and staff with relevant entry documents. The usual practice for transit passengers in many airports is that they are allowed in the general areas such as the shops or other leisure area not covered in this strategy until few hours before their departure when they can move to a particular gate, which is covered in the strategy. This differentiation is necessary in order to capture areas within the terminal in which occupancy varies strictly with arriving and departing planes. In general, terminal arrival process is less complicated as passengers are mostly interested in picking their baggage and checking-out quickly to attend to their travel purpose. The departing process takes longer time. International Civil Aviation Organisation (ICAO) recommends forty-five minutes for international arrival passenger processing from disembarkation to completion of the last clearance process and one hour for the departing passenger from clearance to embarkation [15]. To account for delays in the environmental systems, we are assumed that arriving and departing passenger processing takes one hour each. The additional fifteen minutes to the arrival processing is the time taken to bring the building to the new comfort-setting regime before occupation and this was about the time taken between landing of aircraft and passengers entering airport building.

This fuzzy controller is supervision on top of the conventional control system and its main goal is to increase the operating availability of the process under control based on the functionality of the control space (fig. 1). To achieve this, the controller coordinates the actions of the distributed controllers according to the evolution of the passenger flows and external conditions. The heuristic tools in this strategy are based on operator knowledge obtained from building operation and in-situ measurements of control variable carried in the building.

This supervisory controller is schematically modelled after Yokogawa Electric’s temperature controller [13] where the fuzzy supervisory module leads the PID controller along a temperature trajectory that can quickly reach the actual setpoints without overshoot. The difference is that Yokogawa controller is a close-loop system while the one described here is an open-loop system.

Contributions to improve the overall performance of the supervised systems is achieved mainly from mapping availability of operating setpoints for identified zones and coordination and management of local control based on passenger flows and variation in external condition. The overall architecture of this control strategy for a zone in the airport building is shown in fig. 1 above.

The controller designed using SIMULINK [16] and Fuzzy Logic Tool box [17] (fig. 2) in MATLAB [18] was fed with information on when a plane is to land/take-up and the number of people on board estimated form the aircraft type. This information can be acquired from the passengers’ information desk up-to a week before the actual flight. The controller also receives as input the real-time external temperature and zone illuminance data from the outside temperature sensors and inside lighting sensors respectively. The controller will then provide the required thermal, lighting and indoor air-quality comfort setpoints to the identified zones in the terminal where the passengers will be transiting. These setpoints are available at the landing time of the aircraft allowing the systems to raise or lower the indoor conditions as the case may be to the required comfort range before occupation about fifteen minutes later.

III. STRUCTURE OF FUZZY CONTROLLER

Fuzzy logic provides a convenient way to map an input space to an output space. Specifically, a fuzzy inference system
interprets the values in the input vector and, based on some set of rules, assigns values to the output vector. The mapping then provides a basis from which decisions are made, or patterns discerned [20].

In general fuzzy controller comprises the fuzzifier which determines the membership degrees of the controller crisps input values in the antecedent fuzzy sets, the inference mechanism which combines this information with the knowledge stored in the rules and determines what the output of the rule-based system should be. The output is a fuzzy set but for control purposes, a crisp control signal is required. The defuzzifier calculates the value of this crisp signal from the fuzzy controller outputs [19].

**IV. DETERMINATION OF MEMBERSHIP FUNCTIONS**

The controller takes Outdoor Temperature (OT), Zone Illuminance (ZI), Passenger Numbers (PN) at a given flight time as inputs and outputs indoor Lighting Levels (LL), Temperature Setpoint (TS) and Airflow Rates (AR) for the zones. The varying range of OT, ZI, PN, LL, TS and AR are described using linguistic terms. The discourse domains in the fuzzy set are between (-10 to 35) degree Celsius for OT, (0 to 500) lux for ZI, (0 to 30) degree Celsius for TS, (0 to 400) litres per second for AR. Fuzzification was done using the triangular membership function. Defuzzification was achieved using the centroid of area method.

**V. CONSTRUCTION OF FUZZY RULES**

The heuristic rules mapping inputs to outputs was defined using linguistic terms (Table 1) such as if *Outside Temperature* is Cold, *Zone Illuminance* is Dark and the *Passenger Number* is Many then provide *Winter* temperature setpoint; lighting is Bright and *Airflow Rates* is Many. An in-occupancy scenario might read if *Outside Temperature* is Cold, *Passenger Number* is None and *Zone Illuminance* is Dark then provide Winter-un-occupied temperature setpoint, *Light Levels* is Off and *Airflow Rate* is Un-occupied.

The thirty-six fuzzy rules for this controller were defined using Mamdani [20] Fuzzy Modeling. That is, the antecedent and the consequent proposition were expressed linguistically.

**TABLE 1. LINGUISTIC TERMS FOR INPUT AND OUTPUT VARIABLES**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Type</th>
<th>Linguistic Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>OT</td>
<td>Input</td>
<td>Cold, Medium and Hot</td>
</tr>
<tr>
<td>ZI</td>
<td>Input</td>
<td>Dark, Dim and Adequate</td>
</tr>
<tr>
<td>PN</td>
<td>Input</td>
<td>None, Few, Average and Many</td>
</tr>
<tr>
<td>TS</td>
<td>Output</td>
<td>Winter-Unoccupied, Winter, Medium, Summer and Summer-Unoccupied</td>
</tr>
<tr>
<td>LL</td>
<td>Output</td>
<td>Off, Dim and Bright</td>
</tr>
<tr>
<td>AR</td>
<td>Output</td>
<td>Unoccupied, Few, Average and Many</td>
</tr>
</tbody>
</table>

**VI. CASE STUDY OF MANCHESTER AIRPORT BUILDING**

Terminal 2 is a jet only terminal with Low Cost, Charter and Long Haul carriers. Smallest regular aircraft type is the B737-300 with 148 seats. Largest is Virgin's B747-400 with 456 seats. This information was used to estimates the passenger number per giving flight time. The flight arrival and departure data was collected from Airport information desk. The external temperature data was retrieved from the British Atmospheric Data Centre (BADC). The airport building has extensive use of glass window and wall façade making several places suitable candidate for Daylighting. Available illumination for the period of October 26th to November 2\textsuperscript{nd} was estimated from global and diffuse horizontal illumination variation based on ten years of measurements by the Building Research Establishment (BRE) [21].

**VII. SIMULATION RESULTS AND DISCUSSION**

Fig 4 shows how temperature setpoints changes in relation to passenger numbers and external temperature. For example; when the zone was un-occupied, (passenger number was zero) and external temperature was less 10\textdegree C as could be the case in
Winter or over 20\(^\circ\)C as may be the case in Summer; the controller relapses the setpoint to its setback temperature of about 10\(^\circ\)C or above 23\(^\circ\)C for Winter and Summer unoccupied scenario respectively. However, when the place becomes occupied the controller provides comfort setpoints commensurate with the comfort requirement for that zone based on whether outside condition is winter, midseason or summer. Therefore, temperature setpoints are varied due to occupancy and change in external condition.

During period of inoccupancy, up to 1000 litres per second is still provided to support non-passenger activities.

![Figure 5. Surface view results of mapping between inputs and outputs for Air Flow rates as in figure 5](image)

Air Flow rates as in figure 5 on the other hand varies directly with the estimated arriving or departing passengers at a giving time. This explained the rise in airflow rates as the passenger numbers increases. Ten litres per second per person was provided for each passenger being the minimum fresh air requirement recommended by CIBSE [22] for such place.

![Figure 6. Surface view results of mapping between inputs and outputs for Arrival hall](image)

Lighting setpoints of 200 lux was provided when occupancy was predicted to occur and it is off when the zone was unoccupied as shown in figure 6. This was because according to CIBSE Guide A [22] 200 lux is recommended for most indoor spaces within the terminal except offices and shop areas. Daylighting control was also included as the lights are dimed or switched-off depending on the adequacy of the daylight illuminance within the zone. This lighting control does not include security and a task light that may be used by the staff if higher illuminance values are required at the desk for passenger processing.

![Figure 7. Temperature Setpoint output from the controller](image)
One-week simulation results for winter using Manchester Airport external weather data, flight arrival time for T2 and estimated available zone illuminance from 26 October to 2nd November 2011 shown in figure 7, 8 and 9. These figures clearly showed that the comfort setpoint based on CIBSE recommendations for arrival area of the airport in winter is being provided and they vary with passengers’ occupancy schedule. Fig. 7 shows a temperature setpoint of about 19°C during occupancy and less than 12°C during period of inoccupancy. Fig. 8 shows that about a 1000 litres per second minimum fresh air was provided during inoccupancy while the ventilation rates during occupancy varies with the number of passengers. Fig. 9 shows that about 200 lux setpoint of artificial lighting was provided for the zone during occupancy and when available natural daylight was inadequate while the artificial lighting remained switched-off during inoccupancy and when there is adequate daylight within the zone.

VIII. SUMMARY & CONCLUSION

This paper shows that fuzzy rule systems do not require any process model and that heuristic rules could be used to model a controller. Fuzzy supervisory controller strategy and design process was presented. Also, using 3D surface view and output results from the fuzzy supervisory control system, the controller performance was analysed. This paper has demonstrated the capacity of the designed system to optimise indoor thermal, visual and air flow setpoints for airport terminal buildings, which will lead to reduction in energy use. Another contribution of the paper is that thermal and visual comfort and indoor air quality setpoints were derived from fuzzy controller rather than from operator’s manipulations.
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