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Implementation of an integrated indoor environment and energy management system

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Abstract

The aim of this paper is to present the architecture, the algorithms and the performance results of an integrated indoor environment energy management system (IEEMS) for buildings. The buildings' users comfort requirements are fulfilled and regulated using a fuzzy controller. The fuzzy controller's structure is adjusted to the users' requirements that are monitored via a smart card system. The IEEMS is installed in two buildings in Athens and in Crete, both in Greece. The energy conservation achieved by the IEEMS operation is more than 30% compared to the existing control system.

Keywords: Energy management; Indoor environment; Fuzzy controller; Energy efficiency

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1. Introduction and state of the art

Energy and indoor environment management systems targets to preservation of comfort conditions for buildings' occupants and minimization of energy consumption and cost. Standards regarding indoor comfort are defined in international bibliography, stating indoor conditions that satisfy user's requirements for thermal comfort, visual comfort and indoor air quality [1,2,7]. Fuzzy techniques are applied to a significant number of cases in building energy management systems (BEMS) [9,3–5,14,15] demonstrating a significant reduction of total energy consumption compared to a conventional system. Finally, the move towards sustainable development lead building designers towards passive design strategies for maximization of the use of ambient and solar energy. There is evidence however that in reality some of these passive techniques are not robust and occupants reactions are not correctly understood and modeled, thus occupants avoid to use these passive designs that maximize environmental benefits [8,13].

This paper describes an integrated indoor environment and energy management system for buildings with the following features: (a) incorporates all the three aspects of the indoor comfort in a global control strategy for building's zone control; (b) the control strategy maximizes the energy conservation by giving priority to passive techniques to maintain comfort; (c) integrates the occupants' comfort requirements into the control strategy and simultaneously minimizes the energy consumption.

2. The implementation of the indoor environment energy management system

2.1. The implementation hardware

The IEEMS is installed and tested in one building of the Technical University of Crete (TUC) situated in Crete, Greece, and in the secretary office of the Central Institution for Energy Efficiency Education (CIENE) of the National Kapodestrian University of Athens (NKUA) situated in Athens, Greece. The TUC monitored building (24°04′E and 35°59′N) has a floor area of 144 m^2 and is 4.5 m high. The secretary office of CIENE is situated in the University Campus of the NKUA. One office is selected instead of the

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whole building for the following reasons: (i) the office is located in a place with several identical offices and conclusions can be drawn for the overall building arrangement and (ii) the installation cost for the whole building is very high. The office (37°58′N, 22°72′E) is situated at the northern part of the Physics Department Building, with a north-oriented external façade. The IEEMS consists from: (a) smart card kiosk; (b) sensors and actuators; (c) PLC controller; (d) central PC [10]. All the above are interconnected using the local operating network (LON) capabilities.

The smart card kiosk [10] is the man–machine interface of the implemented IEEMS and collects the occupants preferences. The same type of sensors is installed in both buildings. The sensors installed are measuring the following environmental variables: (i) mean radiant temperature; (ii) indoor temperature; (iii) relative humidity; (iv) air velocity using a hotwire anemometer; (v) CO_2 concentration; (vi) indoor illuminance; (vii) outdoor temperature and humidity.

The sensors (i) to (iv) are used for the evaluation of the thermal comfort using the Fanger's predicted mean vote (PMV) [7]. PMV is the mean vote which one would expect to get by averaging the thermal sensation votes of a large group of people in the given environment. PMV is a function of the imbalance in the heat equation of the human body under comfort conditions L (W/m^2), of the metabolic rate M (W/m^2), both being related to the area of the human body. The sensor (v) evaluates the indoor air quality and the sensor (vi) is used for the measurement of the indoor visual comfort. Finally the sensors (vii) evaluate the outdoor conditions. The actuators installed for the control of the thermal comfort are relays for the air conditioning systems in both buildings. The relays for the air conditioning systems operate on a pulse width modulation (PWM) basis [12]. The natural ventilation is performed using window opening/closing motors. The control of shading is performed using opening/closing motors in the existing blinds. The electric lighting system is fluorescent tubes and their control is accomplished using three relays in the TUC building and electronic ballasts for dimming in the NKUA building. The three electric lighting relays operate in a zonal form splitting the TUC building in three zones in relevance with the window positions.

The PLC controller and/or the LON devices perform the following actions: (a) reads the sensors data through its analogue input channels, (b) run the fuzzy control algorithm for the adjustment of indoor thermal-visual comfort and air quality levels, (c) drive the actuators through its digital and analogue outputs, (d) communicate with the smart card unit using an RS485 connection and (e) communicate with the PC via an RS232 port through an LON device. The implementation in the two buildings is carried out in two phases: during the 1st phase the sensors and the smart card system is installed in order to monitor the environmental parameters of each building and the users' preferences. The 1st phase is divided into three monitoring periods in winter, summer and spring of 15 days each. During the 2nd phase the installation of the actuators and PLC is completed.

2.2. The implementation software

A fuzzy controller is developed and tested with main task to maintain indoor comfort at the building by giving priority to passive techniques thus minimizing the energy consumption. Passive cooling is endorsed through window openings to reach the thermal comfort levels using natural ventilation techniques during transitional seasons. During winter and summer, windows are kept closed to avoid thermal losses. The sun penetration is controlled to allow the passive heating during winter and reduction of solar gains during summer. Various scenarios are modeled and tested which lead to the selection of the fuzzy controller that is described below. A fuzzy P, a fuzzy PID, a fuzzy PD, an adaptive fuzzy PD and an on–off controller [11] are compared. The comparison and selection criteria are the regulation of indoor comfort and the minimization of energy consumption. The performance of the fuzzy controller is more satisfactory compared to the other feedback schemes. The selected fuzzy controller is developed by taking into account the outcomes of the users' preferences and indoor climatic conditions monitoring phase. The fuzzy controller has five inputs and four outputs as tabulated in Table 1 [12]. The input–output universe of discourse is covered using triangular and trapezoidal membership functions whose type and position is selected based on the users' preferences.

3. Experimental results

3.1. The experimental results of TUC and NKUA buildings

The full IEEMS installation, including the controller and the actuators, in the TUC building is monitored for the period 20 February 2001 to 31 August 2001 including winter, spring and summer period. Indicatively, the measured PMV index and the heating actuator for 1 winter day are illustrated in Fig. 1. The response of the indoor illuminance, the CO_2 concentration and the window motor signal, for 1 winter day are depicted in Figs. 2 and 3.

During daytime the indoor illuminance is kept between 450 and 500 lux. The peak that occurs on 16:00 is due to the direct sunlight that falls on the sensor. The electric lighting

Table 1
The fuzzy controller input and output parameters

Fuzzy controller inputs	PMV	Outdoor temperature	CO_2 concentration	The rate of change of CO_2 concentration	Indoor illuminance
Fuzzy controller outputs	Heating/cooling		Window opening	Shading	Electric lighting

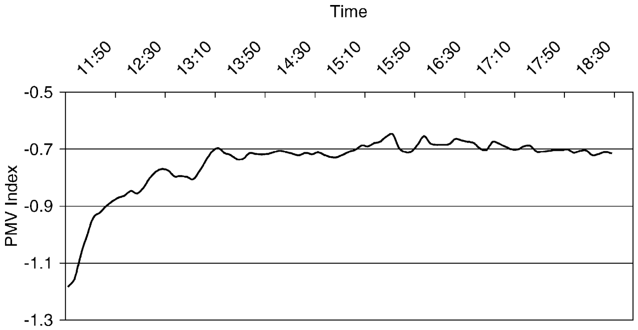

Fig. 1. The PMV index *t* measured in the TUC Laboratory on 28 February 2001.

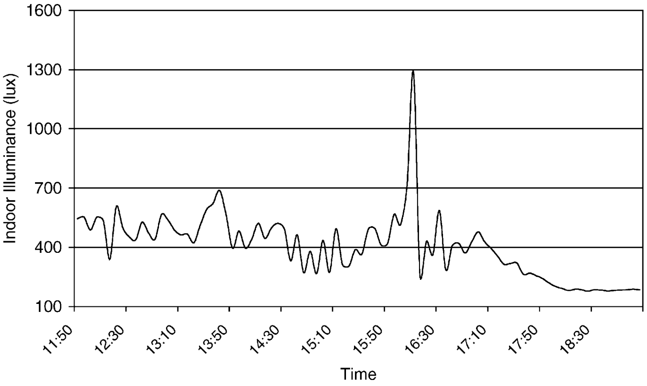

Fig. 2. The indoor illuminance of the TUC Laboratory on 28 February 2001.

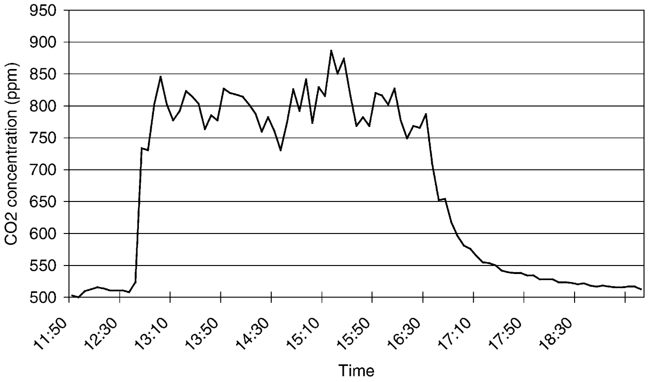

Fig. 3. The CO_2 concentration of the TUC Laboratory on 28 February 2001.

and shading coefficients' oscillations are attributed mainly to the external daylight fluctuations. The CO_2 concentration is kept in 800 ppm between 12:00 and 16:00 where there are 40 students in the laboratory.

For NKUA building the full system installation was monitored for the period 24 April 2001 to 15 July 2001. Figs. 4–6 represent some characteristic measured parameters for a specific day of the experimental period (2 June 2001) in order to demonstrate the operation of the control system. Fig. 4 illustrates the measured PMV index and the operation of the cooling system actuator. The NKUA office was equipped with a split air conditioning unit and for that reason the control operation was on/off (variation of the controller signal between 0 and 100%). The PMV remains between 0.1 and 0.35 the whole period of the presented day.

The operation of the lighting system and the window opening motor together with the related measured parameters (indoor illuminance, CO_2 concentration) are presented in Figs. 5 and 6. For the indoor illuminance the controller turns on and off the artificial lighting system (on/off dimming operation) in order to achieve a value between 400 and 500 lux. During the early morning for this specific office, even the full operation of the artificial lighting system is not enough to reach the required illuminance levels (it is north oriented), but after 11:00 the controller achieves to reach the target illuminance. Concerning the time variation of CO_2 concentration, this parameter remains into acceptable.

3.2. The IEEMS evaluation

3.2.1. The IEEMS energy consumption evaluation

The evaluation of IEEMS's energy conservation is based on the following methodology:

- The environmental parameters selected during the 1st monitoring phase form a data set for each building.
- A theoretical model has been developed for the each building using the Building Simulation Tool SIBIL 1.02, which has been developed within the BUILTECH project [6]. The model consists from the following sub-models: (a) thermal (alone air temperature) model, (b) natural ventilation model, (c) PMV index model, (d) CO_2 concentration model, (e) relative humidity model, (f) luminance-glare model and (g) outdoor environment model including solar radiation and temperature.
- Each theoretical developed building model using SIBIL is validated against the data set from the 1st phase monitoring period in order to confirm that the theoretical model describes accurately the energy/thermal behavior of the building.
- The calibrated/validated building model is used in order to simulate the performance of the building with and without the controller using Test Reference Year (TRY) climatic data.
- The energy consumption and therefore the energy conservation due to the operation of the IEEMS is estimated.

The evaluation procedure is quite accurate as the modeled behavior of the thermal properties and lighting characteristics follows the experimental behavior of the buildings (see Figs. 7 and 8). The values compared are (a) the temperature, which is related to the heating/cooling consumption and (b) the indoor illuminance, which is related to electric lighting consumption.

After the evaluation phase the intelligent controller performance is compared with the performance of the pre-IEEMS installation situation. The comparison results for the TUC

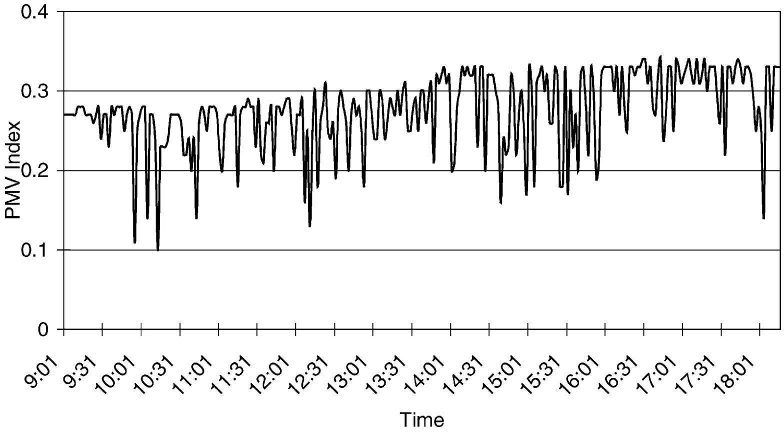

Fig. 4. The PMV index measured in the NKUA office on the 2 June 2001.

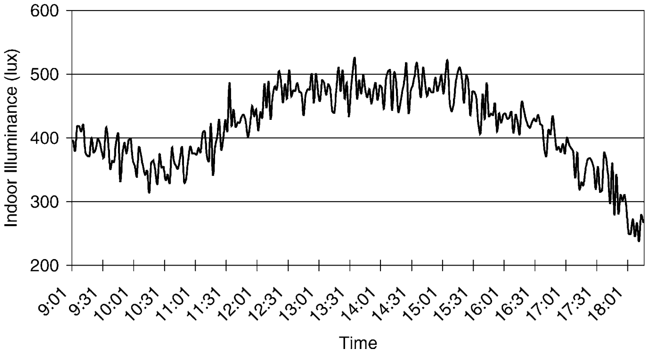

Fig. 5. The indoor illuminance of the NKUA office on 2 June 2001.

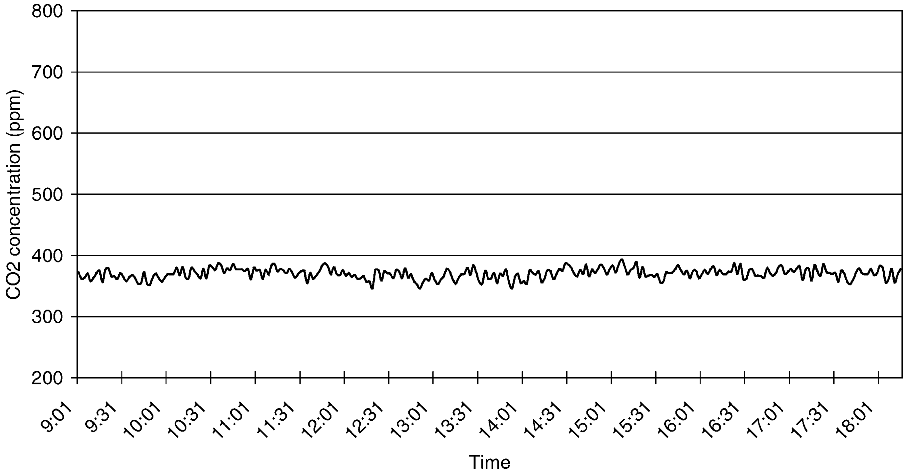

Fig. 6. The CO_2 concentration of the NKUA office on 2 June 2001.

Laboratory and NKUA secretary office are presented in Table 2. The main points are:

- The NKUA secretary office has very low cooling load due to (a) the office's north orientation and (b) to the reduced casual gains (PCs, number of persons, etc.) compared to the TUC building where there are large openings in all facades. As expected, the heating load of the NKUA secretary office is considerable high compared to its cooling load.
- 20% reduction of the energy consumption for heating and cooling is achieved for both buildings on annual basis.
- The energy conservation for lighting is correlated with the sun's altitude and the respective energy reduction for each month is estimated [5]. Thus, the energy savings with the fuzzy controller on an annual basis

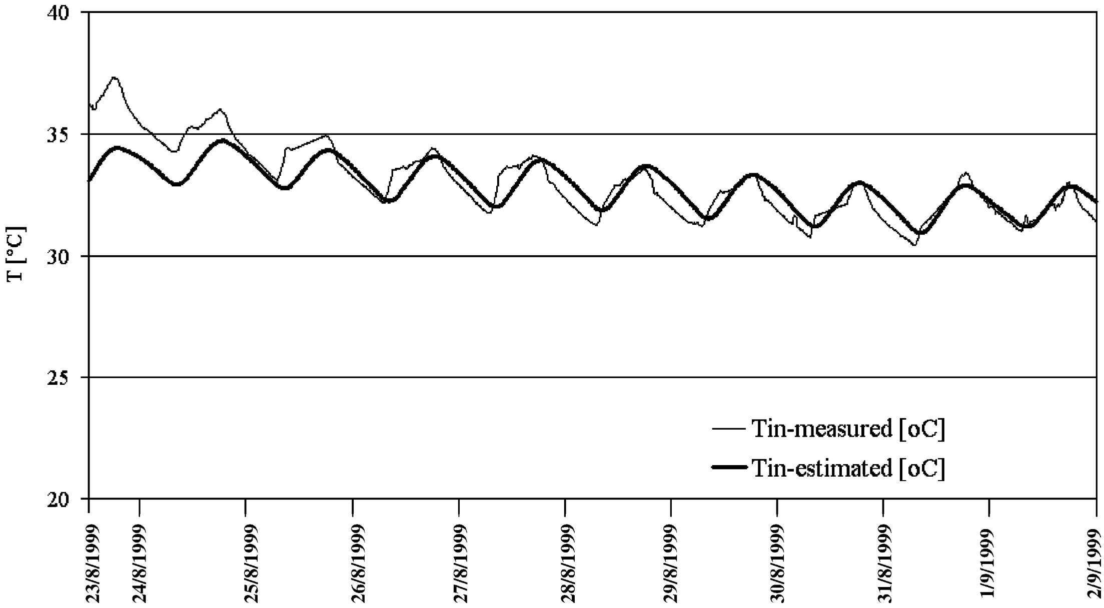

Fig. 7. Measured and estimated temperatures for the period from 23 August 1999 to 1 August 1999 for the TUC building.

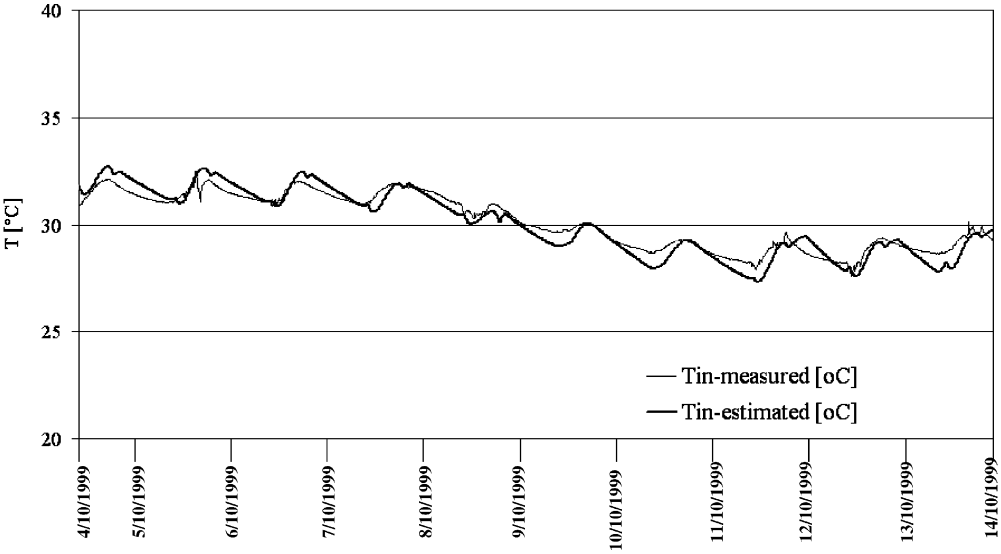

Fig. 8. Measured and estimated temperatures for the period from 4 September 1999 to 13 October 1999 for the NKUA building.

are estimated for each building. The results show that the reduction of the energy consumption for artificial lighting, when intelligent systems are implemented, is considerable.

- The reduction of the energy consumption on annual basis is equal to 38% for both buildings. This considerable reduction can also play a significant role in the reduction of greenhouse gas emissions.

3.2.2. The IEEMS users' preferences evaluation

The users' satisfaction is evaluated during the installation of the IEEMS using questionnaire. The users asked to rate the indoor comfort levels for thermal, visual comfort and indoor air quality from 1 to 7, e.g.:

How would you categorize your working space in respect to the thermal conditions?
Very uncomfortable 1 2 3 4 5 6 7 Comfortable

The analysis of the questionnaires showed the following:

- The level for the thermal and visual comfort is satisfactory during the experimental period for both buildings.
- Some problems are revealed concerning the noise levels of the actuators (especially for the window and the shading device actuators). Also, some times it was quite uncomfortable for the NKUA's occupants the dimming of the artificial lighting system, especially when it was necessary to adjust the lighting levels in every time step

Table 2
Evaluation of the energy conservation for the TUC and NKUA buildings

TUC		NKUA	
Summer period – cooling			
Fuzzy controller	On–off controller	Fuzzy controller	On–off controller
4580 kW h	5324 kW h	75 kW h	123 kW h
31.8 kW h/m^2	37 kW h/m^2	1.3 kW h/m^2	2.2 kW h/m^2
Estimated energy saving 14%		Estimated energy saving 38%	
Winter period – heating			
Fuzzy controller	On–off controller	Fuzzy controller	On–off controller
3786 kW h	5151 kW h	1866 kW h	2351 kW h
26.3 kW h/m^2	35.8 kW h/m^2	33.2 kW h/m^2	41.8 kW h/m^2
Estimated energy saving 26.5%		Estimated energy saving: 20.6%	
Annual period – cooling and heating			
Fuzzy controller	On–off controller	Fuzzy controller	On–off controller
8367 kW h	10475 kW h	1941 kW h	2474 kW h
58.1 kW h/m^2	72.7 kW h/m^2	34.5 kW h/m^2	44.0 kW h/m^2
Estimated energy saving: 20.1%		Estimated energy saving: 21.5%	
Annual period – lighting			
Fuzzy controller	No control	Fuzzy controller	No control
1045.6 kW h	4419.4 kW h	3175 kW h	5639 kW h
7.3 kW h/m^2	30.7 kW h/m^2	56.4 kW h/m^2	100.2 kW h/m^2
Estimated energy saving 76.3%		Estimated energy saving: 43.7%	
Annual period – total energy consumption			
Fuzzy controller	On–off controller	Fuzzy controller	On–off controller
9412.6 kW h	14894.4 kW h	5116 kW h	8113 kW h
65.4 kW h/m^2	103.4 kW h/m^2	91 kW h/m^2	144.2 kW h/m^2
Estimated energy saving: 36.8%		Estimated energy saving: 36.9%	

of the fuzzy algorithm due to the intermittent cloud cover. It is important to underline that the dimming of the florescent lamps was continuous from 0 to 100% (electronic ballasts were used). The TUC's users did not mention any dimming problems as the electric lighting adjustment is zonal.

4. Conclusions

The developed IEEMS integrates, in an open architecture, a fuzzy controller that incorporates thermal comfort, visual comfort and indoor air quality aspects and simultaneously performs reduction of energy consumption. The fuzzy controller satisfies the indoor comfort requirements giving priority to passive techniques for heating, cooling and lighting, thus minimizing the energy use. Generally, it can be concluded that the energy conservation amounts to almost 38% without compromising indoor comfort.

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