Study and Implementation of a Fuzzy PD Thermal Comfort Controller for Embedded Fieldbus Systems Applications

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Abstract: - The aim of this paper is to present the design and evaluation process of a Fuzzy PD controller for an experimental platform for buildings based on a fieldbus system. The experimental platform consists of interconnected nodes (sensors and actuators), using the European Installation Bus (EIB) fieldbus network infrastructure. A “smart node” consisted of a personal computer, containing custom control software, is attached to the above installation and executes the control process program. The controlled parameter is the indoor thermal comfort of the installation zone expressed by the Predicted Mean Vote (PMV) function. The software deployed on the “smart node” makes use of the measurements collected from the sensors and gives the appropriate output values to the actuators using various fuzzy logic algorithms. By application of past studies results, a minimal Fuzzy PD thermal comfort controller is implemented and evaluated. This controller is designed taking into account the easiness of future deployment onto embedded systems with limited memory and processing power capabilities.

Key-Words: - Fuzzy Logic, Embedded Systems, Thermal Comfort, Predicted Mean Vote, Fieldbus Systems

1 Introduction

During the last few years, there has been rapid convergence of the technologies of Informatics, Microelectronics and Control Systems leading to novel approaches and solutions to important scientific problems. The complexity of systems deployed on modern buildings has created the need of their optimal control. Successful control of building installations yields to an increase in comfort [1] and security of the residents, which has a vital impact on their productivity. Moreover, enhanced management of the available resources leads to the reduction of energy consumption, providing significant aid for the struggle against the greenhouse effect and the decrease of the conventional fuels capacity. Last but not least, energy preservation reduces the operational cost of a building.

Fieldbus systems [2] present an extremely effective way of using modern techniques and technologies to satisfy the above goals. These systems offer the essential infrastructure to create “smart” electromechanical installations. Such installations incorporate microprocessor or microcontroller based systems which execute programs whose algorithms use the environmental values of the building, gathered by deployed sensors, and the accumulated human expertise to provide specific outputs to the actuators. Furthermore, fieldbus systems provide a unified approach to both sensors and actuators, which are all treated as equal nodes identified by a unique network address. This approach makes the scaling procedure for such installations simple and rather straightforward. The same applies to the addition or the removal of a network node. Moreover, the total system stability is improved as it doesn’t depend on a specific device whose failure would make the whole installation non-operational. Finally, fieldbus systems offer great flexibility on the selection of transmission means taking into consideration the buildings’ requirements. All transmission means demonstrate increased tolerance to electromagnetic noise and interference.

The research area of deployment of fieldbus technology to building energy management systems has received extensive attention. Galata et al proposed an adaptive approach (EDIFICIO) [3] using neural networks to fine tune fuzzy controllers for indoor comfort preservation and simultaneous energy saving. Mozer and Vidmar [4] proposed a similar approach which utilizes a combination of feed-forward back-propagation neural networks and lookup tables from past measurements of sensors to dynamically derive optimal rules for a fuzzy controller. Nebenfuhr and Schildt [5] employed a distributed algorithmic approach for network of microcontrollers. These microcontrollers execute a local copy of the neural-fuzzy controller software and intercommunicate in order to exchange information of the sensors and actuators. Moreover, Xelhuantzi et al. [6] proposed a client / server system for controlling different autonomous zones through a central controller (Dome) based on Fuzzy Logic. Furthermore, Oseli et al. [7], Salapura [8] and Eichfeld et al. [9] demonstrated hardware implementations of fuzzy controllers for embedded solutions.

This paper contributes to the study of the design considerations and quantitative analysis of a fuzzy PD controller. The controller is designed and tuned for easy implementation into embedded systems like microcontrollers or ASICs where computational costs and needs in storage and memory are of outmost importance. Moreover, on the contrary to existing building energy management systems (BEMS), which mainly provide monitoring facilities, the resulting system regulates the indoor thermal conditions so as to preserve thermal comfort and energy saving simultaneously.

The present paper describes the use of a fieldbus system installation, along with custom control software, in order to fulfill the goals set previously. The next section includes a brief introduction to the EIB system followed by a presentation of the experimental installation where the topology, and the network devices used are stated. Finally, the experimental results are discussed.

2 Description of the EIB

The European Installation Bus (EIB) [10] is a de facto building networking standard which was proposed by a number of companies, academic institutions and universities, which established the independent EIB Association (EIBA) in 1990. At present, EIB is a subset of the KONNEX standard which is the first certified European standard for electrical installation networking by CENELEC. EIB standard is very frequently used in small and middle-sized building installations keeping the largest share of the respective market, especially in central Europe.

EIB is a decentralized protocol of networking. All compatible nodes embed processing power using a custom microcontroller. The EIB installation is a network of such peer nodes. EIB provides a versatile approach to the selection of the transmission medium making available, every possible combination of twisted pair cable, power line and radio transmission, in the same installation. EIB demonstrates tolerance in noisy environments and at the same time guarantees the delivery of information on time. Data transmission rates can reach 9600 bps yielding a packet delivery interval of 25ms.

Every node has a unique physical address (similar to a MAC address on computer network interfaces) and one or more logical or group addresses. Physical addressing is used to distinguish the nodes. On the contrary, logical addresses are tied to every function of the node providing a communication interface between nodes. For example, a two-button rocker has a single unique physical address and two logical ones, which are tied to the upper and lower button respectively. The logical addresses of the rocker are shared by the respective functions of a relay switch (e.g. ON and OFF). Logical addresses can be shared by more than two nodes functions, thus, implementing complex functions.

The EIB standard [11] utilizes a tree topology. The simplest installation contains a *line* which can hold up to 64 nodes. A more extended network is an *area* which consists of 12 *lines* yielding a total of 768 network nodes. Lines are interconnected using special devices which are called area couplers and can handle the routing of the transmitted information packets. Similarly, 15 *areas* can be connected using area couplers (similar to line couplers) to create a full scale EIB installation containing 11520 nodes. The concept of the area in an EIB installation is illustrated in Fig.1.

In order to avoid collisions from the concurrent transmission of information packets from two nodes, EIB uses CSMA/CA, a method similar to CSMA/CD used in IEEE 802.3 (Ethernet) in computer networks. According to CSMA/CA, when a collision takes place, the participating nodes wait for a random interval before retransmitting. The window of this time interval increases in an exponential way proportional to the rate of collisions in the bus.

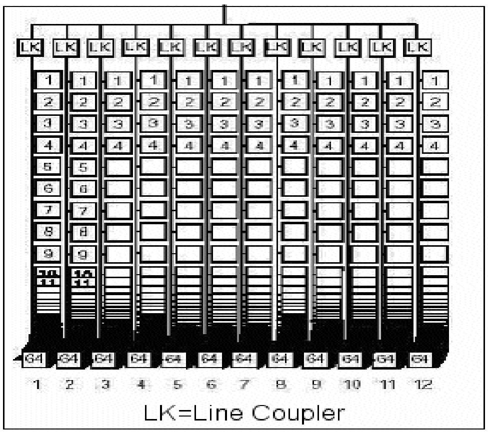

Fig. 1, Illustration of the Topology of an Area

There is a large set of software solutions for the design of EIB installations. Moreover, 32-bit libraries for the Windows platform are used to access the bus, thus, enabling the production of applications which can utilize its features. Moreover, more than 100 hardware manufacturers provide a great collection of compatible devices for all the types of control applications.

3 Description of the Installation

The proposed experimental installation consists of a typical EIB installation incorporating sensors and actuators attached or embedded to network nodes, and a personal computer which communicates with the installation using a serial (EIA-232) to EIB interface.

Moreover, the personal computer executes custom software which embodies the thermal comfort fuzzy logic control algorithm. This software carries out the communication within the bus nodes, visualizes and logs the sensor measurements and the controller output values.

3.1 Hardware Description of the Installation

The experimental platform is installed on the Electric Circuits and Renewable Energy Sources Laboratory of the ECE Department of Technical University of Crete. The bus nodes are placed on a common DIN type rail for electrical installations. The transmission medium used in this network is shielded twisted pair cable. It is selected because of its low cost, its high immunity to noise and the ability of very long cabling without the need of repeaters.

All network devices draw power from the bus transmission line where data is transmitted over a DC 24 V voltage. This voltage is provided by a specific EIB power supply which incorporates a choke so as to filter out, 50Hz and harmonic frequencies, noise from the 220V power network, from the transmission line. As previously mentioned, the installation consists of sensors and actuators as illustrated in Fig.2. Most of the sensors used are attached to analog input interfaces as they were not available as network devices at the time of installation. All sensors are linear and have a 0-10 Volt output.

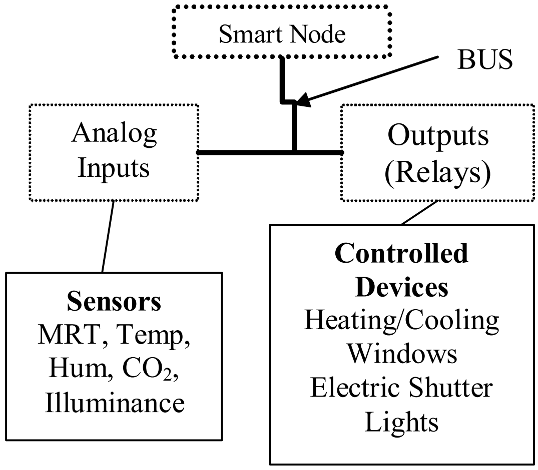

Fig. 2, Block Diagram of the Installation

The following sensors are used: MRT (Mean Radiant Temperature), Indoor Temperature, Relative Humidity, Airflow, Carbon Dioxide (CO_2) and Indoor Illuminance. The analog input interfaces used feature 10-bit ADC resolution, adequate for this application.

The actuators are EIB compatible binary outputs (Relays), which could handle loads up to 20A. Connected to these outputs are: the heating/cooling modules, two electric shutters, two electric windows and three rows of eight fluorescent lights each.

3.2 Description of “smart node” software

A vital part of the experimental installation is the software executed at the “smart node”. It is coded using Rapid Application Development (RAD) tools taking into account the simplicity of code and the ease of updating and maintenance during its life cycle. Moreover, a modular form of design is adopted. The graphical user interface, bus communication, logging and main loop tasks are coded in Visual Basic 6.0 using the eteC Falcon EIB API libraries. The main algorithm which is called from the main application, (e.g. the Fuzzy PD thermal comfort controller) is coded in Visual C++ and compiled as a DLL library. The modularity of the main algorithm enables the programmer to effortlessly replace the algorithm, experimenting with other ones since their programming interface remains the same.

The developed software executes, sequentially, several tasks in a main program loop. During its initialization phase, it establishes a connection to the bus. If the connection is successful, it enters the main loop and retrieves the values from the sensors of the installation displaying them on the screen later. The next step is to feed these values to a fuzzy logic controller and retrieve the fuzzy output values. Then, it processes, converts and sends them to the respective actuators. Eventually, it displays the output values and logs, both measurements and actuation values to a text file for offline processing.

The period of this system loop is set to 3 minutes except for the heating/cooling subsystem which is being activated in a 30 minutes cycle. The 3 minutes interval is chosen so as to acquire both dense measurements and prompt response to changes in the lab (e.g. open doors, smokers etc.). The diverse period for the heating/cooling module is selected bearing in mind the stress of its mechanical parts and the amount of time it needs to provide adequate amount of heat or cooling.

3.3 Description of the Fuzzy PD thermal comfort controller

Fuzzy Logic is an elegant and effective approach to control systems in cases where classical methods of control need complex models with high computational cost. Extended use of the human expertise and past experience have been deployed in the present research field where there have been many successful approaches to control the environmental parameters of a building, using such controllers. In this paper the design of a simple yet effective controller is demonstrated. The resulting system is illustrated in Fig. 3. The mathematical analysis of a Fuzzy PD controller has been extensively described in the scientific literature. See [12,14-16].

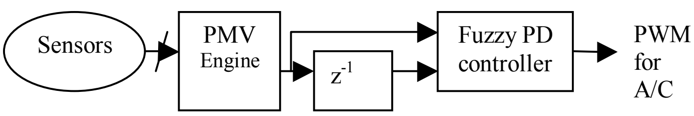

Fig. 3, Block diagram of the resulting system

The controlled value is the output of the PMV function [13] according to the ISO 7730 standard. The PMV function is a statistical measure of the thermal comfort between humans. The weights of its function equation are derived from statistical methods of processing. Optimal values of this function vary depending on the season of the year, yielding a set of [-0.5, 0] for winter and [0, 0.5] for summer.

The proposed Fuzzy controller emulates the behavior of the classic analog PD controller which is proven to be very stable for a variety of diverse systems. It contains two inputs (PMV, dPMV/dt) and one universal output for both heating and cooling (negative output values for cooling, positive values for heating). Each fuzzy input consists of three membership functions which are depicted in Figs. 4 and 5 respectively. The fuzzy output consists of five membership functions, illustrated in Fig. 6. Nine activation rules are used, presented in tabular form in Table 1. It is clear that this controller is designed bearing in mind the constraints imposed by the candidate target architectures. The selection and the placement of the membership functions used both in inputs and output is made using the accumulated experience from other more complex fuzzy logic controller approaches.

The absolute value of the controller output is used to set the period of operation for the heating / cooling module. Thus, the heater (or cooler) is operated for a time interval which corresponds to the 0 to 100% of a 30 minutes duty cycle. This decision was made due to the lack of an inverting circuit in those modules.

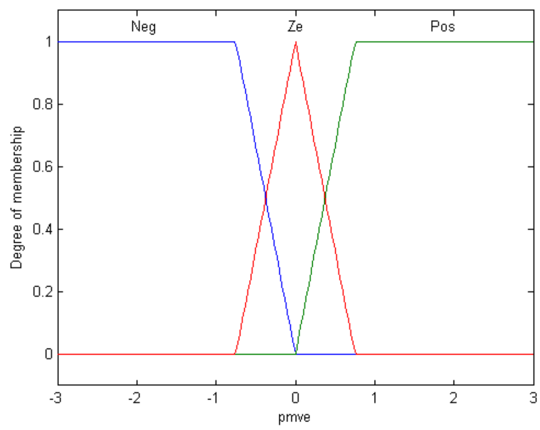

Fig. 4, Membership functions for PMV input

4 Experimental Results and Discussion

In order to verify the functionality and evaluate the behavior of the resulting system, a series of tests are performed. The testing phase takes place during summer so the controller outputs are set for cooling operation. Initially, the region of optimal PMV values is chosen to be [0, 0.75] in order to avoid system stressing.

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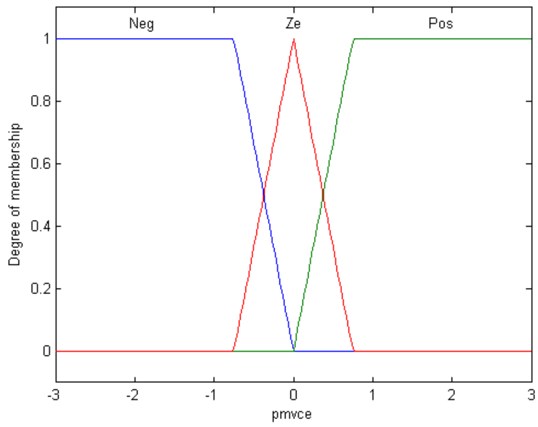

Fig. 5, Membership functions for dPMV/dt input

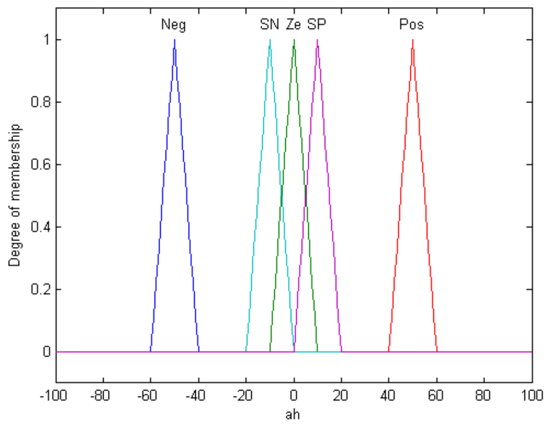

Fig. 6, Membership functions for heating / cooling output

Table 1, Activation Rules of the Fuzzy PD Controller

PMV / dPMV/dt	Neg	Zeq	Pos
Neg	Ah ⇦ Pos	Ah ⇦ SP	Ah ⇦ SN
Zeq	Ah ⇦ Pos	Ah ⇦ Z	Ah ⇦ Neg
Pos	Ah ⇦ SP	Ah ⇦ SN	Ah ⇦ Neg

As illustrated in Figs. 7 and 8 the has system operated as expected. PMV values are smaller than 0.5 for the largest part of the observations, yielding a mean value of 0.2945 for the [0, 0.75] set and 0.2446 for the [0, 0.5] set. Moreover, the system responds rapidly to external changes in environmental parameters. Strictly speaking, the controller responded promptly to sudden temperature rises or drops (the corresponding peaks or dips on both charts) by setting the appropriate output values to the cooling module. The total system response (output to cooling module), compared to PMV and environmental parameters (external,-internal temperature and Mean Radiant Temperature), are depicted in Figs. 9 and 10 for the [0, 0.75] and [0, 0.5] cases respectively.

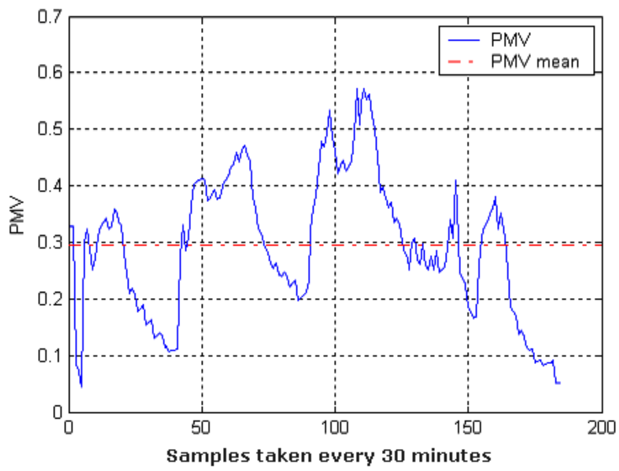

Fig. 7, PMV values for the [0, 0.75] set

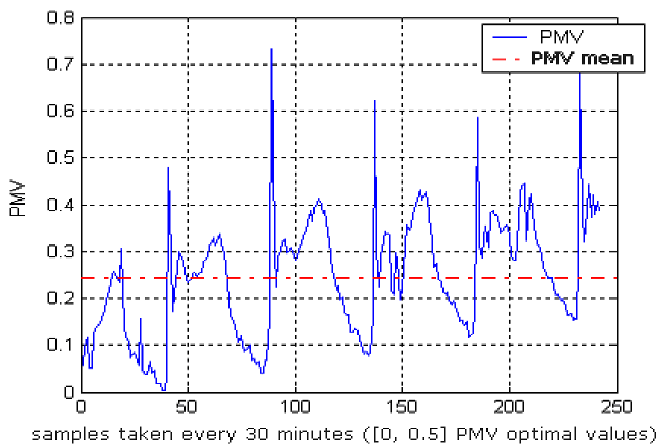

Fig. 8, PMV values for the [0, 0.5] set

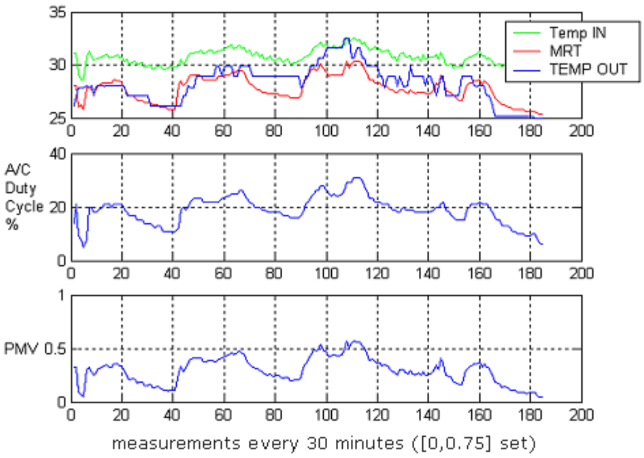

Fig. 9, Environmental measurements versus cooling duty cycle and PMV values for the [0, 0.75] set

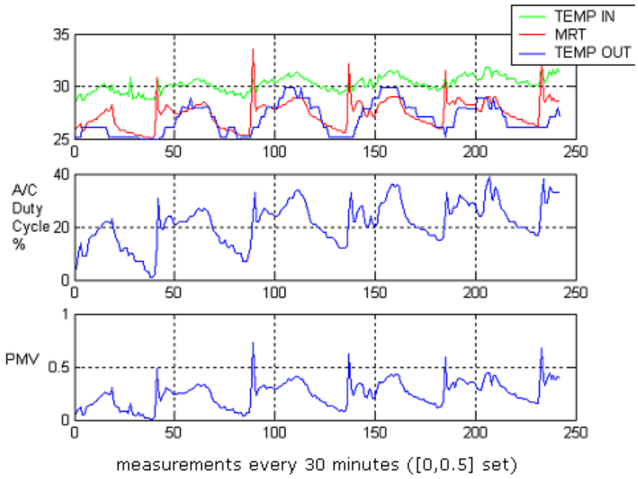

Fig. 10, Environmental measurements versus cooling duty cycle and PMV values for the [0, 0.5] set

The differences between the values of external and internal temperature occur because of the building's structure which, during summer tends to accumulate heat due to its glass roof. Both approaches, as shown, respond smoothly to sun rise and sun set transients (sudden peaks after long dips in PMV curve and opposite) without oscillatory behavior or significant overshoot. A more conservative set of input membership functions, i.e. a wider triangle - [0, 0.75] case, tend to dissipate less energy on PMV transients without stressing the modules' mechanism.

It is obvious that more conservative membership functions have negative impact on the mean value of PMV compared to a more radical approach. Eventually, the statistical processing results of the measurements for the two fuzzy PD implementations are presented in Table 2.

Table 2, Comparison of statistical measures between two fuzzy PD implementations

	Fuzzy PD [0,0.75]	Fuzzy PD [0,0.5]
Mean PMV	0.2945	0.2446
Cooler Mean Duty Cycle	18.86%	21.57%
Mean Internal Temperature	30.707 ˚C	30.22 ˚C
Mean MRT	27.79 ˚C	27.42 ˚C
Mean External Temperature	28.25 ˚C	26.94 ˚C

It can be noted that the [0, 0.5] scenario presents 17.25% less PMV compared to [0, 0.75] conservative approach, while consuming 14.36% more energy.

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