# Autonomous embedded fuzzy logic based wireless sensor network for indoor energy management

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## ABSTRACT

The 2008 Climate Change Act requires a reduction in carbon emissions by 80% on 1990 levels by 2050. With the building sector contributing to 40 - 45% of all CO2 emissions in the UK, it is vital to address home and building energy management by making them more energy efficient, and ensure that new buildings are designed and built with high levels of energy efficiency (Government 2013). Wireless Sensor Networks (WSN), due to their low cost and energy consumption, and robust communications, present a promising solution for retro-fitting to existing buildings for optimal building energy consumption control.
This paper discusses the main challenges in creating an autonomous WSN and proposes a solution using WSN technology, Fuzzy logic techniques and Agent Software system.

**Keywords**
Wireless sensor network (WSN), building energy management system (BEMS), ambient intelligence, multi-agent system (MAS), fuzzy logic.

## 1. Introduction

Nowadays it is not surprising to see automated lighting and heating working along with sensors. Current smart meter systems do not only measure energy consumption or provide grid protection, but they also support monitoring and enable interaction with the consumers using graphical displays. The number of features they provide keeps increasing but the information about the systems and control advancements still stays very close to human control and decision making.

The list of possible connected components of a smart home network is rapidly growing. This rapid expansion of energy monitoring and management systems is not surprising seeing the statistics of building energy consumption as seen in figure 1 (Murphy 2012). Because of projected improvements in buildings and appliances efficiency, the Energy Information Administration's 2012 Annual Energy Outlook forecast a 13% increase from 2009 to 2035 (D&R International 2012).

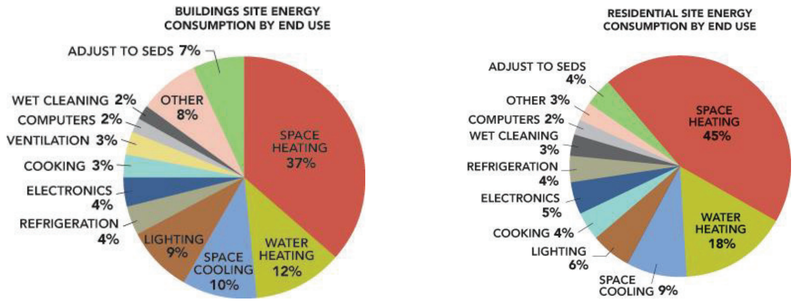



Figure 1 - Building and Residential energy footprint

Despite an extensive research into managing building interior energy, comfort and control, many issues remain opened and new ways of controlling, sensing and managing events continue to motivate researchers. The development of intelligent control systems has improved the efficiency of control systems for the management of indoor environment including user preferences (Dounis and Caraiscos 2009).

Based on our research, we are proposing an autonomous building control for indoor energy management systems by deploying a WSN which, by cooperation and reasoning, enables an intelligent energy management system. This system integrates artificial intelligence techniques, such as fuzzy logic and agent technology at a software level and smart sensors in hardware design. In our research we adopted some of the results from current research.

***Related work***

Continuously sensing the environment and gathering data are necessary for optimizing building's energy consumption. The overall system performance is related to the volume of data provided as well as the meaning of the data collected. A collaborative and efficient effort is key as demonstrated in (Ploennigs, Hensel et al. 2010) where a virtual comfort sensor was designed using a wireless sensor network. An intelligent occupancy monitoring system is demonstrated in (Akhlaghinia, Lotfi et al. 2009) using PIR motion detection door contact sensors. Working along with physiological, microphones or infrared sensors a fuzzy logic controlled alarm and localization were designed for elderly people in (Farella, Falavigna et al. 2009; Medjahed, Istrate et al. 2009), improving their quality of life as well as identifying dangerous events.

The integration of local processing and storage allows sensor nodes to perform complex filtering and triggering functions, as well as applying application-specific or sensor-specific data preprocessing algorithms (Polastre, Szewczyk et al. 2004).

Application of fuzzy logic for energy management has been developed in (Hagras, Callaghan et al. 2004), called I-Dorm project the system used IP network, and could learn and predict the user's needs, adjusting the agent controller automatically. In (Rutishauser, Joller et al. 2005) a commercial building is equipped with a wired network of sensors and actuators using fuzzy rules. Another real environment project, aimed to identify different scenarios for thermal and illumination response (Lah, Zupančič et al. 2005). The project was based on an automation system (roller blind) in a test chamber and a fuzzy system was able to manage the roller blind to provide the visual and thermal comfort depending on the two inputs.

Other projects focused their work on prediction analysis such as (Akhlaghinia, Lotfi et al. 2008) or pattern extraction in an inhabitant intelligent environment (Mahmoud, Lotfi et al. 2013).

However, most of the work described in the previous paragraphs is deployed on expensive stand-alone workstation.

In this paper, a WSN is proposed using low-cost cost embedded system devices and agent technology for temperature and light control management leading to more efficient use of indoor energy. Integration of Fuzzy logic and agent algorithms will perform decision making and contribute to create a smart home system with intelligent house monitoring and controlling. We consider the motivation and challenge for autonomous systems in indoor energy management in section 2. A summary of intelligent agent and fuzzy logic implementation is reported in section 3. Section 4 describes the proposed system architecture. The fuzzy agent design is detailed in section 5 along with the experimental results, followed by the conclusion and further work remarks in section 6.

## 2. Autonomous systems for indoor energy management

An Intelligent building is one that utilises computer technology to autonomously govern and adapt the building environment so as to optimize user comfort, energy consumption, safety and work efficiency (Hagras, Callaghan et al. 2003). Building energy management research efforts rely on a set of technologies that enhance energy-efficiency and user comfort as well as improving the monitoring

and safety of the buildings. Technologies include new, efficient building materials as well as information and communication technologies.
Sensor networks can be deployed to enable smart building applications and significantly contribute to energy reduction. Siemens estimate the energy savings due to more precise climate, air quality and occupancy sensors at 30% compared to traditional automation technology (OECD 2009).

Lighting, heating, ventilation, and air conditioning (HVAC) energy management systems provide a rich habitat for the development of sensor-driven solutions that regulate energy flow in buildings. One controller can offer simultaneous wired and wireless control for both lighting and HVAC applications. For example, a self-powered wireless occupancy sensor can provide data that controls both climate and lighting (O'Callaghan 2012).

***The wireless sensor network solution***

Wireless sensor networks are ideally suited for enabling building's energy reduction as they allow an easy installation without constructional changes (Menzel, Pesch et al. 2008).

Connected in a wireless network, autonomous nodes or agents should be able to self-mange themselves and cooperate in order to achieve the goals of energy optimisation for individual home appliances or manage household energy more efficiently in an autonomous and intelligent way. The main benefit of such systems resides in its awareness of the environmental conditions and ability to act without manual guidance from users.

There is a need to deploy independent autonomous system instead of user-driven control but autonomous systems should not compromise occupants' perception of having some degree of control of their indoor environment. Humans are the best available sensors and they are highly subjective and should not be overruled by control routines (Toftum 2010).

## 3. Ambient intelligence

To realise the ambient-intelligence vision, people must be able to seamlessly and unobtrusively use and configure the computer-based artefacts and systems in their ubiquitous-computing environments without being cognitively overloaded (K. Ducatel et al. 2001).

Most of the existing work in WSNs assumes a data sink where the sensor data from the network is sent. The base station is used to centralise data gathering and network control. Clustering uses another approach for framework and is a popular and new way to support self-organisation and enable smart sensor networking.

A smart home system requires automation as well as sensing abilities to be aware of the environment and its needs. The decision making process links those two requirements and guides the reasoning based on AI techniques. IA techniques such as fuzzy logic, Bayesian reasoning or Markov models are known to provide designers powerful decision making capabilities.

***Fuzzy logic benefits and implementation***

Fuzzy systems, especially in the area of control, offer engineers a powerful and efficient tool for dealing with imprecision in measurement (Luger and Stubblefield 1998). Fuzzy logic is flexible, tolerant of imprecise data, it simplifies the decision process when dealing with non-linearity or uncertainty in systems. Because it is based on natural language, it is suitable for human environment.

Fully controlled fuzzy logic by microcontroller examples are still difficult to find as computing systems already offer built-in fuzzy algorithm, such as Matlab or LabVIEW (Saeed and Mehrdadi 2012). These systems come with user friendly graphical interfaces along with analysing, debugging and simulating functions. Although very powerful, these tools don't offer much portability. On the other hand embedded fuzzy inference engine provides the designer more opportunity to customise or optimise the system.

# 4. System Architecture

Human based environments are different from machine ones, as people's comfort needs to be considered. An individual's comfort may vary from one to another, and finding the right balance between energy reduction and comfort becomes a tricky process. In order to achieve this goal we have designed and implemented a system consisting of a number of sensors and actuators to reduce energy wastage and gain efficiency in its usage, and added a user based parameter in each scenario. Connected wirelessly the system is able to regulate the temperature and light autonomously while taking user preferences into account. The system takes any manual changes into consideration to adjust the outcome. The reasoning algorithm and agent is discussed in the following section.

A major constraint in the WSN is the amount of energy available for each node and the ability to maintain the wireless network working with a limited storage capacity. Transceivers are the most power hungry devices in a WSN. Hence, for our system we have used Zigbee modules and protocol since it offers the best solution concerning power consumption and security. Because the transceivers have a high energy consumption they are turned off most of the time (Beeby and White 2010). Low power microcontrollers, used in this project, allow various mode of operation with different features to reduce energy consumption. The ratio between sleep and active times of the nodes needs to be as high as possible, more than 95% of the time in sleep mode (Arms, Townsend et al. 2005).
To demonstrate features of wireless sensor agent system we have adopted two possible scenarios where autonomous action of the system would contribute to the reduction in energy consumption: temperature and light control.

***Autonomous temperature and light controls***

Temperature control inputs

Input Delta: $\Delta = Temp\,℃ - (Temp - 1)℃$
Input Error: $\mathcal{E} = Temp\,℃ - setpoint\,℃$

Light control inputs

Input Presence: Time counting input (seconds), reset to 0 on every motion, sound or pressure detection.
Input Economy: adjustable variable used to determine the degree of energy consumption by the LED lighting
Input Brightness: Room brightness level measurement

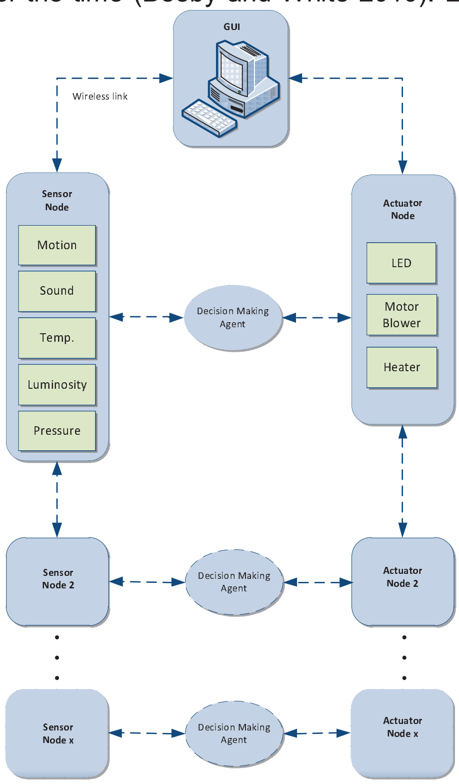



Figure 2 - node's architecture

The system architecture is shown in figure 2; a mesh network topology has been deployed where sensors and actuators can share information and status between themselves. As mentioned before, the decision making agent is embedded. It uses fuzzy logic reasoning implemented on low power PIC microcontrollers to control the actuators using pulse width modulation which can be seen as a percentage of the maximum power consumption.

This Agent system uses sensor data from the environment to make autonomous decisions and control the environment. Being fully aware of the lit environment also allows optimisation that extends beyond energy savings. The combination of proximity/motion and light sensing provides an abundance of data concerning the interior environment (Ghoshal 2013).
Those two inputs combined with a user feedback (economy parameter), provide to the decision

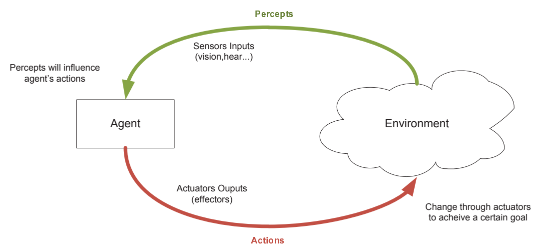



Figure 3 - Agent and environment

making agent all the necessary data to create an autonomous light control.

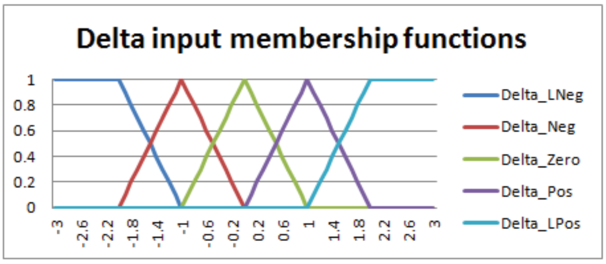
## 5. Decision making agent

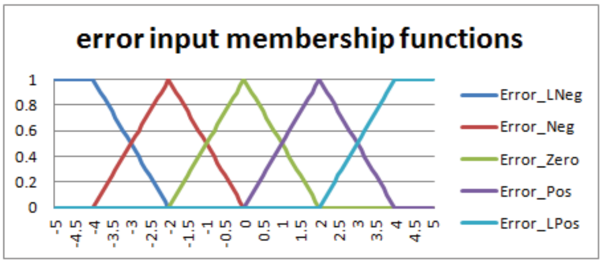
In order to implement the fuzzy engine as part of the agent design, the program must define the following settings: system inputs, input membership functions, antecedent values, rules, rule output weights, output membership functions and system outputs. The following chapter describes the temperature control process.

Fixed number of rules resulting of inputs and their membership function fuzzy sets (MFFS) total:

$$Rules = nput\ 1\ MFFS\ total * \ Input\ 2\ MFFS\ total * \ldots * \ Input\ x\ \ MFFS\ total$$

Temperature control rules: $5 * 5 = 25$




Defining rules is a crucial part of designing a fuzzy logic based controller, often referred as fuzzy inference system or engine. We have designed fuzzy rules in order to govern the system's actions and reactions according to its inputs. Figure 4 displays the matrix representing the temperature rules. Temperature control manages two outputs (Heater & Fan) with one Membership function of nine fuzzy sets: heat maximum, heat high, heat moderate, heat low, off, fan low, fan moderate, fan high and fan maximum.

Too Cold — Too Hot

Getting Cooler — Getting Hotter

| Δ \ ε | L_Neg | Neg | Zero | Pos | L_Pos |
|---|---|---|---|---|---|
| L_Neg | {0}H_max | {1}H_max | {2}H_mod | {3}F_low | {4}F_mod |
| Neg | {5}H_max | {6}H_max | {7}H_low | {8}F_mod | {9}F_high |
| Zero | {10}H_max | {11}H_high | {12}Off | {13}F_high | {14}F_max |
| Pos | {15}H_high | {16}H_mod | {17}F_low | {18}F_max | {19}F_max |
| L_Pos | {20}H_mod | {21}H_low | {22}F_mod | {23}F_max | {24}F_max |

Figure 3 - Temperature control rule matrix

The inferencing process combine or infer each rules before going to the defuzzification stage.

*e.g. IF (delta is Zero AND error is L_Neg) THEN {rule [10] = Delta_Zero & Error_LNeg}*
*⇨ MIN (Truth(Delta_Zero), Truth(Error_LNeg))*

In this case rule ten's outcome is the minimum value of ―Delta_Zero” and ―Error_LNeg” degree of membership. Max-Min inferencing may be the most common and simple method but in the case of multiple input (more than two) rules, the logical product may not reflect the reel degree of membership of the rule and risk mostly to be influenced by that one minimum or maximum value. For the light control the averaging method offers better result, indeed for more sophisticated rules and a single output fuzzy system this approach produces a continuous output function.

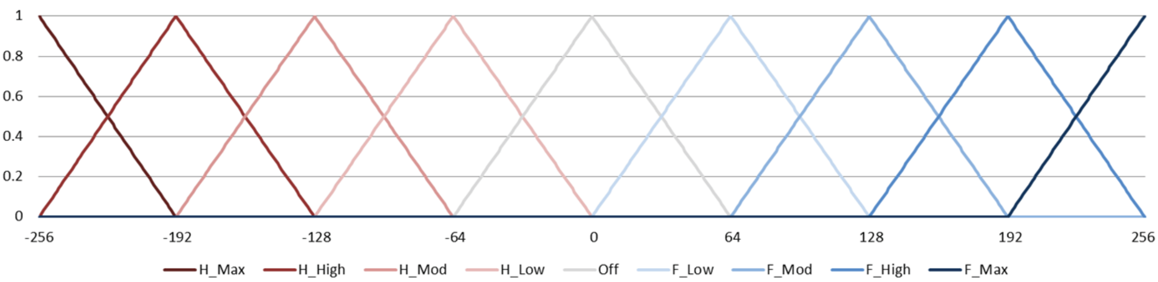



Figure 4 - Temperature Output Membership Functions

Centroid defuzzification is applied to get a final crisp output value:

$$\text{Output } = \frac{\sum_{i=0}^{n} \mu_i x_i}{\sum_{i=0}^{n} \mu_i} \; ; \qquad \mu \text{ is the weighted result or strength of the output MF and } x \text{ its center.}$$

Temperature control output:

$$TCO = \frac{-255 * H_{Max} - 192 * H_{High} - 128 * H_{Mod} - 64 * H_{Low} + 64 * F_{Low} + 128 * F_{Mod} + 192 * F_{High} + 255 * F_{Max}}{H_{Max} + H_{High} + H_{Mod} + H_{Low} + Off + F_{Low} + F_{Mod} + F_{High} + F_{Max}}$$

Light control output:

$$LCO = \frac{255 * L_{Max} + 192 * L_{High} + 128 * L_{Mod} + 64 * L_{Low} + L_{Min}}{L_{Min} + L_{Low} + L_{Mod} + L_{High} + L_{Max} + Off}$$

***Results***

A small scale test shows the behavior of the room heating system when temperature set point is fixed at 22.5°C with an initial ambient temperature around 21.5°C. Here a power resistor and a calibrated thermistor served as actuator and sensor.

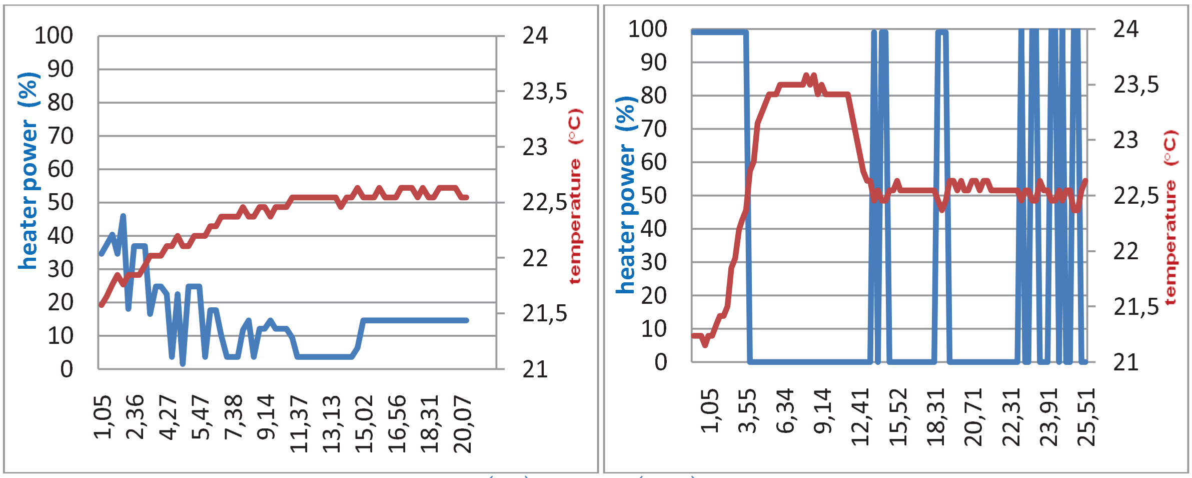


Figure 5 - Fuzzy logic (left) and crisp (right) space heating control

Using approximately the same condition, we can compare the fuzzy control to a simple on/off one (close to manual control). Where the fuzzy logic heating process consumed on average 15% of heater power, the crisp control consumed around 30 % and also took more time to stabilise room temperature to the pre-selected setting.

This type of control system offers better processing of uncertainty in human centered environments. This statement is verified with light control where three inputs have been used, two of them being related to human intervention (one directly and one indirectly).

## 6. Conclusion and Future work

In this paper we have presented the results of our research in autonomous intelligent WSN system for energy management in a building environment. The system is built around a low power PIC microcontroller, sensors and actuators. We have designed an autonomous agent system, using fuzzy logic techniques. The relationship of WSN and the environment defines how intelligent the system is. Agents are often used in a reactive way meaning that their range of action is fixed - ruled based agents; their actions are predetermined and part of a responsive system. Current implementation of our system uses this approach. The test results show that the potential of embedded systems energy management in buildings is promising due to the low cost and ease of deployment. Our future work will extend the rule-based agent system with learning and planning agents. In this way, rules base learning can evolve into a decision making agent by reducing the number of rules and creating a hierarchical system based on rule importance/usage. Furthermore, we will implement the reinforcement learning where the system will try to redefine more accurately actuators values and minimizes the difference between goal and user action/preference over a larger period of usage.

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