Development of Intelligent Wireless Sensor Networks for Human Comfort Index Measurement

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Abstract

Conventional wireless home automation networks (WHANs) incorporate embedded wireless sensors and actuators that monitors and control home living environment. WHANs primary goal is to maintain user comfort and efficient home management. Conventional WHAN lacks higher "intelligence" in term of managing compound human comfort where as it deals with multitude of human comfort factors individually instead of collectively.

This paper presents wireless sensor networks (WSN) based Human Comfort Ambient Intelligence (HCAmI) system. The design of a Fuzzy Rule Based System (FRBS) for the measurement of Human Comfort Index (HCI) in a living space is presented. The design of FRBS is described and the system is evaluated and tested by using combined simulated and empirical data. It explores the complex relationship between multiple comfort factors in human comfort provisioning. The comfort factors considered here include thermal comfort, visual comfort, indoor air comfort and acoustical comfort.

Keywords:
Wireless Sensor Network, Ambient Intelligence, Fuzzy Logic

1. Introduction

Wireless Sensor Networks (WSNs) enable fine-grained collection of sensor data about the real world, and promise to revolutionize our understanding of and interaction with our environment. Typically, WSN devices are small, communicate wirelessly, have limited power, are low-cost, and most importantly are embedded in the physical world through their onboard sensors and actuators.

WSN is the key enabling technology for building and surrounding space monitoring system. WSN is capable of providing reliable (robust wireless communications), cost effective (no messy wires, plug and go) and extensible solution (scalable) for existing and new structures. In recent years, with better and cheaper electronics, wireless sensor and actuator networks have gained high momentum, gaining substantial attention from academia, industry and standards development organisations. School of Computer Science and Informatics at UCD Dublin and Centre of Adaptive Wireless Systems at Cork IT starts to explore the tools and techniques we need in order to build 'augmented materials’ which combine sensing, actuation and processing into the fabric of built objects [1].
One of the primary application domains of this emerging technology is building and surrounding space monitoring and automation. Wireless home automation networks (WHANs) facilitate monitoring and control applications for home user comfort and efficient home management. WHAN normally consists of several types of embedded devices that sense the environment, which may be battery powered and are equipped with low power radio frequency (RF) transceivers. The use of RF as means of communication allows flexible installation (additional or removal of devices) and cut down installation cost by eliminating conduits and cable trays needs from the system. On the other hand, RF itself poses significant challenge in its own entirety. The dynamics of radio propagation such as refraction, deflection, signal attenuation, and signal loss challenge the design, deployment and use of WSN in WHAN [1].

Studies shows strong link between comfortable living environment and human productivity. Uncomfortable people are less productive, and in the long run it could be costly from economic point of view. Measuring the environment is easy, but quantifying human comfort is not. Human comfort is notoriously tricky and difficult to measure, hence most system just settled with typical environment measurement and adjustment such as temperature, humidity, light luminosity and air quality. Human comfort is, to some extent, subjective, and there are many comfort factors which influence an individual’s perception of comfort such as thermal comfort, visual comfort, indoor air comfort and acoustical comfort.

To provide a comfortable and healthy place for people to live was the sole reason building was design and constructed. Hence, WHAN primary goal is to monitor and maintain acceptable human comfort for their dwellings, at the same time caters the secondary objective of optimising energy use. For example, most immediate to human comfort is thermal comfort. Is 17.5°C is good enough for a comfortable living? Should the temperature be increased? What is the caveat? How to achieve it? Does the action have any impact on other comfort factors as well?

In our enthusiasm of having ideal cozy homes, complex relations between mentioned comfort factors have to be look into in great detail. The delicate assessment act between those comfort factors were look into and modelled as hybrid fuzzy reasoning expert system that marked as human comfort index. Given a living space, a group of WSN will sense the environment (temperature, humidity, clothing, metabolic rate, wind speed, luminosity, etc), make sense of raw information and by means of fuzzy logic, weighting and integration criteria, measures the Human Comfort Index (HCI).

In this work, WSN is evaluated as an enabling instrument that monitors human comfort of a living space. Furthermore, WSN is examined as technology enabler of Ambient Intelligence (AmI) by means of embedding the intelligent within the WSN itself.

This paper is laid in as follows: Section 2 introduces existing work related to thermal comfort, visual comfort, indoor air comfort and acoustical comfort. Section 3 reviews the current work that is being undertaken is the system design, methodology and setup. Section 4 analyses the results gained and section 5 provides the conclusion and future work.

2. Related Works

A number of separated studies have been conducted in various discipline that focus on specific issues and challenges associated with smart living space, ubiquitous computing, and environmental comfort [2, 3, 4, 5, 6, 7, 8, 9]. These researches were done in their own specific domain needs.

Environmental quality in living space refers to the provision of visual comfort, acoustical comfort, thermal comfort, and acceptable indoor air quality for its occupant [10]. Hence the evaluation of human comfort in a living space may be broken down into relevant comfort factors. These comfort factors may be relevant to achieve the desired comfortable level of living.

2.1. WSN and Thermal Comfort

Orosa et al [11] scrutinise in great detail various thermal comfort model based on ISO 7730 standards and ASRAE Standards. Coupled with scientific research, they present both deterministic and empirical models for application related to building design and environmental engineering. On the other hand, Feng et al [6] proposed a network infrastructure by integrating TCP/IP network with ZigBee network in respect to thermal comfort activity for ubiquitous smart living space application. They provide a WSN based algorithm to coordinate smart-skin equipment and air conditioners in order to improve thermal comfort. Network optimisation is achieved by means of clustering huge
network into smaller chunks. Then, from WSN hardware context, Lee et al [12] proposed a light powered sensor networks that were able to gather indoor thermal comfort information. The information then is use in air conditioning systems by implementing a comfort-optimal control strategy. The sensing node integrates an IC-based temperature sensor, a radiation thermometer, a relative humidity sensor, a micro machined flow sensor and a microprocessor for Predicted Mean Vote (PMV) calculation. The 935 MHz band RF module was employed for the wireless data communication with a specific protocol based on a special energy beacon enabled mode capable of achieving zero power consumption during the inactive periods of the nodes. A 5W spotlight, with a dual axis tilt platform, can power the distributed nodes over a distance of up to 5 meters. A special algorithm, the maximum entropy method, was developed to estimate the sensing quantity of climate parameters if the communication module did not receive any response from the distributed nodes within a certain time limit. Recently, Rawi et al [13] proposed Predicted Mean Vote (PMV) engine for WSN where WSN is embedded with sensing engine and PMV engine to determine thermal comfort of a living space.

2.2. Real Time HVAC Engine (Thermal Comfort, Indoor Air Quality and Energy)

Atthajariyakul et al [8] proposed an alternative methodology dealing with real time determination of optimal indoor air condition for Heating, Ventilation and Air Conditioning (HVAC) system in order to achieve overall requirements of the system. PMV, CO₂ and cooling/heating load are the input parameters that indicate the thermal comfort, indoor air quality and energy consumption respectively. Real time gradient-based technique is used in order to yield optimal indoor air condition for HVAC system. The performance index of the HVAC system is defined by summation of square errors between each parameter indices and the desired ones.

2.3. Thermal Comfort, Visual Comfort and Fuzzy Logic

Gouda et al [14] proposed a PMV-based fuzzy logic controller to evaluate the PMV level and uses a linguistic description of the thermal comfort sensation for ease of use. The controller uses Mamdani’s minimum operator method for inference engine. The controller shows better performance and gives better control tracking and robustness compared to traditional PID-based comfort controller. Meanwhile Naadimuthu et al [7] and Chen et al [15] deals with fuzzy adaptive network (FAN) to model the thermal comfort system based on real world experiment. Finally, Lah et al [16] works with fuzzy control for thermal and visual comfort. The work combines two comfort parameters to strike the right balance towards harmonising the thermal and optical behaviour of a building with regulated energy flows through the space. Different control strategies for different season were proposed and tested.

3. HCAmI System

Figure 1 illustrates the building block of Human Comfort System Manager from software point of view. Human Comfort Index (HCI) sub system will give the indicator of a living space comfort index based upon Thermal Comfort (TC), Visual Comfort (CV), Indoor Air Comfort (IAC) and Acoustical Comfort (AC) values.

Each of comfort sub system serves as human comfort knowledge components where each of them will work out respective comfort values from sense parameters such as air temperature, mean radiant temperature, relative humidity, air velocity, clothing, metabolic rate, luminance level, shading level, CO₂ concentration and sound level. Due to modular comfort model, each comfort factor can be calculated within the group itself even though the sense value might come from different node as shown in Figure 2.

3.1. HCAmI Setup

Figure 2 depicts an example of a typical living space where sensor nodes placement points shown. Every node may consist of one or more sensors and may share their sensor reading with other sensor that requires them. For instance, node N1 may sense shading level and luminance level, therefore responsible for Visual Comfort calculation. Node N2 is responsible for sensing CO₂ concentration and responsible for Indoor Air Comfort computation. Where as N3 nodes collaborate among themselves to sense air temperature, mean radiant temperature, relative humidity, air velocity, clothing and metabolic rate that determine the Thermal Comfort’s Predicted Mean Vote (PMV) value [13]. Node N4 equipped with microphone that listens the living space’s ambient sound. It is responsible for figuring the Acoustical Comfort value. SN is the sink node that finalise the Human Comfort Index calculation and acts as gateway to outside world.
3.2. HCAmI Fuzzy Engine

A variety of techniques have been developed to implement intelligence into sensors. Different kind of artificial intelligence system can be used such as artificial neural networks, fuzzy logic, and hybrid fuzzy-neural network system. In WSNs, different embedded artificial intelligence model have been used and researched. However, small attention has been focussed on integrating Fuzzy Rule Based System (FRBS) into WSNs. In this work, each sensor node on the network can carry out small FRBS execution individually or collectively (data source). Each node comprises of a knowledge base (KB) in the form of IF-THEN fuzzy rules, fuzzyfication and defuzzyfication interface and fuzzy inference engine as show in Figure 3. The system is based on basic structure of Mandani fuzzy rule base engine with minor modification to suit Sun SPOT’s embedded Java. It consists of scalable input \( (i_1 \ldots i_n) \) and output \( (o_1 \ldots o_n) \) functions, fuzzyfication and defuzzyfication interfaces, knowledge based (KB) and inference engine.

The KB consist of data, rules based, variable definition for each comfort factors and defined fuzzy sets for each variable and rules. All of these properties can be defined over the air via Over The Air Configuration (OTA-Conf) function to appropriate node as needed.

Since traditional centralised approach of FRBS can not be implemented within one node only, due to limited node resources such as processing power, memory and battery, this work proposed a distributed FRBS adapted to the sensors. Specific node (N1, N2, N3 and N4) will be equipped with stripped down FRBS with specific adaptation to appropriate comfort factor as shown in Figure 4. This is done to reduce the computational burden of each node where each node only execute a small but complete FRBS adapted to them. Further customisation was done to reduce the battery consumption, hence prolonging the battery life by putting all nodes in deep sleep. All nodes will wake up every 10 min (time sync) to sense the environment, share the sense value to any node that requires them, process the data and finally transmit the comfort values to sink node. Sink node will finalise the process by calculating the Human Comfort Index.
3.2.1. Thermal Comfort

Thermal Comfort FRBS was adapted from [13] where Predicted Mean Value (PMV) was calculated. PMV value then is used as the input for Thermal Comfort FRBS as shown in Figure 4a). The input membership function of Thermal Comfort is illustrated in Figure 5a). The value of membership function was fine tune according to [17]. The output of Thermal Comfort FRBS is the Thermal Comfort (TC) value (Poor - Good - Excellent) and Environment Control request such as Fan Speed, Air Condition and Heating that will be relayed to Actuator Control via HC Manager.

3.2.2. Visual Comfort

The input membership function of Visual Comfort FRBS is illustrated in Figure 5b). Visual comfort is determined by the luminance level from light sensor, measured in lux. The output is Visual Comfort (VC) value (Poor - Good - Excellent) and Environment Control request such as Artificial Light and Dimmer value to be relayed to Actuator Control via HC Manager.

3.2.3. Indoor Air Comfort

Indoor Air Comfort FRBS input membership function is illustrated in Figure 5c). Indoor air quality that is mainly influenced by the concentration of pollutants in the living space where CO₂ concentration (measured in ppm) is se-
lected as it represents the presence of users as well as various sources of pollutants in the living space [18]. The output is Indoor Air Comfort (IAC) value (Poor - Good - Excellent) and Environment Control request such as Ventilator and Fan Speed to relayed to Actuator Control via HC Manager.

3.2.4. Acoustical Comfort

Finally, Acoustical Comfort FRBS input membership function as illustrated in Figure 5d). Sound level from attached microphone is used to determine Acoustical Comfort (AC) value (Poor - Good - Excellent).

3.3. Human Comfort Index

The output membership function as shown in Figure 6 is similar for all TC, VC, IAC and AC. Three membership functions are used per comfort output (Poor - Good - Excellent) than can have numerical value of 0 to 100. A total of 17 rules were needed to compute the individual comfort value where 7 rules for Thermal Comfort, 3 rules for Visual Comfort, 4 rules for Indoor Air Comfort and 3 rules for Acoustical Comfort were distributed among FRBS Comfort Nodes.

![Figure 6: Comfort Output Membership Function](image)

With multiple comfort factors involved, there’s an imperative need for a quantitative measurement of overall comfort, hence we introduce Human Comfort Index (HCI) that serve as a human comfort pointer or indicator of the sensed environment. HCI is based on weighted average of comfort factor values (C) for the sense environment during a given interval of time as shown in Equation 1. Based on work by [19], the weight (W) given to TC, VC, IAC and AC are 0.5, 0.3, 0.1 and 0.1 respectively.

\[
\text{HCI} = \frac{\sum_{i=1}^{n} C_i W_i}{W_i} = \frac{(C_1 W_1 + \ldots + C_n W_n)}{(W_1 + \ldots + W_n)} = \frac{C_{TC} W_{TC} + C_{VC} W_{VC} + C_{IAC} W_{IAC} + C_{AC} W_{AC}}{W_{TC} + W_{VC} + W_{IAC} + W_{AC}}
\]

(1)

3.4. HCAmI Hardware and Simulation Operation

The proposed system has been designed and tested based on Sun SPOT WSN platform [20]. The Sun SPOT uses 180MHz 32-bit ARM920T core processor with 512K RAM and 4M Flash and it is programmed almost entirely in Java. SunSPOT comes with 2.4GHz radio with an integrated antenna on the board. The radio is a TI CC2420 (formerly ChipCon) and is IEEE 802.15.4 compliant.

The test bed composed of 2 physical Sun SPOTs and 2 virtual Sun SPOTs that runs on Sun SPOT Simulator in Solarium (an application for discovering and managing Sun SPOT). One physical Sun SPOT with SHT17 temperature and humidity sensor from Sensirion AG manages Thermal Comfort and one physical Sun SPOT manages Visual Comfort via it’s built in light sensor. Two virtual Sun SPOT manages Indoor Air Comfort and Acoustical Comfort that was feed with generated value of CO2 and Sound Level respectively. Each of these nodes computes respective comfort factor and transmit the result to sink node (SN) where SN will do the final HCI calculation. The environment sensing scenario was simulated based real Thermal Comfort and Visual Comfort data collected from 08:00 25/08/2010 to 11:40 26/08/2010 in SeNSe lab. It was a typical gloomy late winter day in Auckland with indoor air temperature varies from 21°C to 27°C and indoor relative humidity varies from 37.2% to 46.7%.
4. Results

In this section, the work results are shown. Firstly, we look the performance of a Sun SPOT node when it carry out the work of sensing the environment, execute FRBS and transmitting the result to sink node; and secondly, the simulation results are shown.

As for Sun SPOT performance, the node that was chosen is the one that handles Thermal Comfort due to Thermal Comfort being the most complicated compared to other comfort factor. It is presume that if the node can manage the most complicated task, then it would be more than sufficient to handle other less complicated task. TC node was implemented with 7 IF-THEN fuzzy rules, 7 environmental sensor input that produce 1 input fuzzy variable (PMV) with 7 membership functions and 1 output fuzzy variable with 3 membership functions. On average, Sun SPOT spends about 250ms in active mode for sensing, calculate PMV value, compute TC fuzzy task, compose a datagram and transmit the datagram to sink node. In making sense of Human Comfort Index, the environment is scanned every 10 minutes, so the reaction time is more than enough.

As for the simulation results, the whole HCI architecture has been modelled and tested. The model represents the working scenario based on real Thermal Comfort and Visual Comfort data collected from 08:00 25/08/2010 to 11:40 26/08/2010 in SeNSE lab. The comfort inputs are shown in Figure 7. Figure 7a shows the PVM value varies between -1 (Slight Cool) to 1 (Slight Warm). It dipped during night time due to lab heater being switch off and climbed up again after 6am the next morning. Figure 7b illustrate the light level in the lab. It fluctuates from 0 to 650, representing typical gloomy late winter sunlight. During the daytime, it hovers below 400 (dim). Figure 7c and Figure 7d displays simulated Indoor Air Comfort and Acoustical Comfort level where CO2 remains constant through out the day and sound level drops after 7:30pm due to less activity in the lab.

Figure 8 shows Comfort Outputs from FRBS engines. As can be observed in Figure 8a to Figure 8d, it varies based on sensed environment from Poor to Good to Excellent; matching the Comfort Input values.

Finally, Figure 9 reveal the Human Comfort Index of SeNSE Lab. It hovers between 40 and 60. The results indicate that the lab can be considered a good living space at that particular sensed time.
5. Conclusion & Future Works

In this paper, we have presented distributed FRBS WSN for measuring Human Comfort Index. FRBS inference engine were distributed among the nodes based on comfort group they belongs to. The architecture allows the addition and removal of any comfort factor as needed. Results have shown that WSN is capable to handle FRBS computational need.

The work is being tested in a real WSN testbed which is composed of minimal sensors and nodes. In this condition, it shows great potential for a full blown sensor and node deployment. Out future work will be focused on testing the architecture with bigger real WSN in order to compare the simulated and real results, hence giving some insight on optimisation activity that needed. Besides, it eventually will be applied to multiple living space as well.

6. References