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Development of miniaturized Wireless Sensor Nodes suitable for building energy management and modelling

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ABSTRACT: Buildings consume 40% of Ireland's total annual energy translating to €3.5 billion (2004). The EPBD directive (effective January 2003) places an onus on all member states to rate the energy performance of all buildings in excess of 50m2. Energy and environmental performance management systems for residential buildings do not exist and consist of an ad-hoc integration of wired building management systems and Monitoring & Targeting systems for non-residential buildings. These systems are unsophisticated and do not easily lend themselves to cost effective retrofit or integration with other enterprise management systems.
It is commonly agreed that a 15-40% reduction of building energy consumption is achievable by efficiently operating buildings when compared with typical practice. Existing research has identified that the level of information available to Building Managers with existing Building Management Systems and Environmental Monitoring Systems (BMS/EMS) is insufficient to perform the required performance based building assessment. The cost of installing additional sensors and meters is extremely high, primarily due to the estimated cost of wiring and the needed labour. From this perspective wireless sensor technology provides the capability to provide reliable sensor data at the required temporal and spatial granularity associated with building energy management. In this paper, a wireless sensor network mote hardware design and implementation is presented for a building energy management application.. Appropriate sensors were selected and interfaced with the developed system based on user requirements to meet both the building monitoring and metering requirements. Beside the sensing capability, actuation and interfacing to external meters/sensors are provided to perform different management control and data recording tasks associated with minimisation of energy consumption in the built environment and the development of appropriate Building information models (BIM)to enable the design and development of energy efficient spaces.

1 INTRODUCTION

Traditionally building automation systems are realized through wired communications. However, wired automation systems require expensive communication cables to be installed and regularly maintained and thus are not suitable for many retro fit applications of sensor technologies [1, 2]. For example, the installation cost of a light switch in a building facility can be as high as 10–30 times the cost of the switch; this estimate does not include the possibility of additional work such as conduit installation and infrastructure work.

In recent years, wireless technologies have become very popular in a wide variety of applications spaces, for fitness and health monitoring, environmental monitoring and other both home and commercial networking applications. In particular, the use of wireless technologies offers distinctive advantages in the field of home and building automation [3-5] as, installation costs are significantly reduced since no cabling is necessary, and neither conduits nor cable trays are required. Wireless technology also allows the placement of sensors where cabling is not appropriate for aesthetic, conservation or reasons of safety [4, 5].

Wireless sensor networks are required to have extended lifetime in deployment, be rugged, reliable robust and be easy to deploy by non technical personnel in the field. The requirement for extended lifetime deployments requires that low power design starts with the obligatory use of energy efficient hardware (e.g., low supply voltages and support for sleep modes in microcontrollers) [6].

A Building Information Model (BIM) consists of two major components: a three dimensional graphical reproduction of the building geometry and a related database in which all data, properties, relations are stored.

The value of BIM created during design and construction phase is well documented and can result in an estimated 30 percent reduction in total construction costs. Throughout the typical Building Life Cycle there are series of discontinuities in the transmission of building data that occur. Transitions from design to construction to operation result in loss of data, added cost to reconstitute the data, and overall reduction in data integrity. The impact, growing at each handover, culminates with the handover to the facility operator and therefore to the energy manager. This paper is focussed on the development and deployment of a miniaturized Wireless Sensor system for building sensing, meter interfacing and actuation and the development of building models with the data sets delivered.

2 WSN NODE DESIGN

2.1 *System Architecture and Functional Units*

The Building Energy Management “mote” is designed in modular mode to enable the additiona and interfacing of additional functionality as required and is based around the Tyndall institutes modular prototyping system for sensor networks. As Figure 1 shows, the system contains four main sections, these are the data processing section, the RF communication section, sensors/meters and actuation section and the power supply management section.

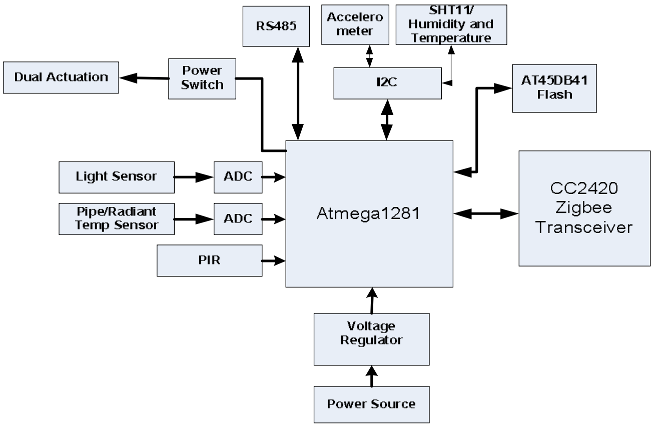

Figure 1: Block diagram of the WSN mote

The multi-sensor layer was designed to interface with number of selected sensors as well as incorporating additional capability for use within the Building environment. This includes dual actuation capabilities for any AC/DC system using an external high power relay based system for devices which consume up to 280 V and 25 A (to turn on and off appliances) as well as an onboard low power switch to enable the actuation facility. The on-board sensors are either digital communicating with the microcontroller through serial bus interface like I2C or analogue connected with any of the ADC channels.

The two external sensors/meters interfaces are dedicated to any meter using MODBUS protocol [7] and variable resistance temperature sensors. The MODBUS meter is exchanging data/commands through RS485 serial communications.

This interface layer was also designed to incorporate external flash memory (Atmel AT45DB041). The layer features a 4-Mbit serial flash for storing data, measurements, and remote re-programming. An image of the modular sensing system developed for BEM deployment is shown in Figure 2.

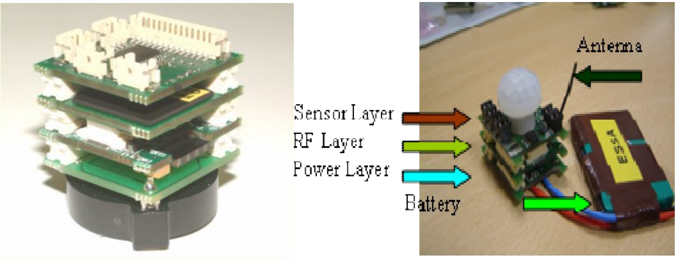

Figure 2: Modular Sensing System developed for BEM deployment

3 SENSORS SELECTION

Based on the user requirements as regards data sets which were needed to develop the Building information models for the buildings under investigation, a variety of sensors were selected and appropriate interfaces developed for deployment in the wireless sensor network. The data sets from these sensor then were used to augment the data sets from standard wired Building management systems.

3.1 *Occupation Sensor (Passive infrared PIR)*

Detecting occupancy parameters of the rooms in the building was identified as being essential in the development of energy consumption rates and trends. A PIR sensor module - the Panasonic AMN44122 [8] was selected for this purpose since it provides a small form factor, low power consumption solution. The module provides a digital detection output that can be used to trigger an interrupt on the processor when activity registers on the sensor. The detection limits of the sensor in deployment are as in Table 1.

Table.1: The comparison of the AMN44122 PIR sensor with reference to date sheet

Items	**Data Sheet**	**Lab test**
Detection Limits	10m (32.808ft)	9m (29.528ft)
Horizontal	110°	90°
Vertical	93°	90°

3.2 *Humidity/Temperature/Light Sensor*

Relative humidity (RH) is an important indicator of air quality in buildings. Extremely low or high humidity levels (the comfort range is 30 - 70% RH) can cause discomfort to workers as well as increasing its overall energy consumption levels. The Temperature and Humidity sensor SHT11 [9] was used on the sensor board which integrates signal processing, tiny foot print and provide a fully calibrated digital output. It uses I2C serial interface to communicate with the microcontroller and provide either the humidity or temperature data based on the received commands.

A miniaturized photo diode with output current proportional to ambient light level conditions was used to measure the amount light LUX levels present in the building.

3.3 *Windows/Doors status monitoring*

The detection of the windows/doors status was one of the building parameters required to be monitored by the WSN node. A 3-axis accelerometer was selected for this application since it can provide useful angle information which helps to know how wide door/window is opened or closed. The LIS302DL is an ultra compact low-power three axes linear accelerometer was integrated in the node design [10].

The main design challenge with using the accelerometer is that the microcontroller has to be continuously active to record sensor data which means high current consumption and short batter life time. In order to overcome this problem, a mechanical vibration sensor with very small package was used in this design to provide an external interrupt to the Atmel microcontroller when there is any kind of motion as presented by Figure 3.

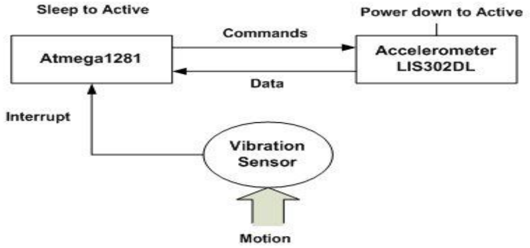

Figure 3: Functional block diagram of the motion sensor design

3.4 *Water flow metering in heating circuits*

It is required to get the flow rate measurements from different locations inside the building where pipes made from different materials and have wide scale diameter size to evaluate the thermal efficiencies of the heating system in place. An ultrasonic based system was developed for this purpose over a standard industrial MODBUS protocol [11] interfaced to the sensor node. The STUF-300EB flow meter from Shenitech [11] was used for this application. It provides excellent capabilities for accurate liquid flow measurement from outside of a pipe. Figure 4 shows the water flow readings obtained from running the meter for almost 4 days. Where flow activity can be clearly seen.

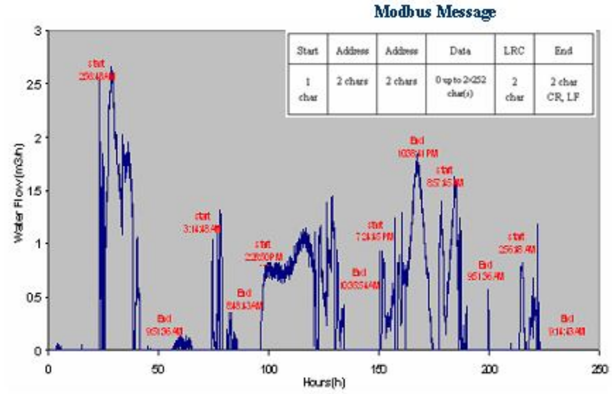

Figure 4: Water flow rate measurements

The monitoring of the water temperature passing in the building pipes was also needed and as a temperature sensor from SIEMENS [12] was selected for this application as non-introductive units and can be mounted directly on a pipe inlet to sense the temperature of water passing through.

4 ACTUATION CAPABILITY

The wireless control of different types of AC loads in the building was incorporated in to the network architecture in addition to its data collection capabilities to be proactive in the the reduction of energy consumption in its deployment environment for which the Muilding information models are being developed. Based on the data sets gathered in real time from the different types of sensors commands are sent to some of designated nodes to perform actuation such as the switching on/off light, heat pumps, water valves or radiators. The sensor node design implemented provides two options to enable this actuation capability; the first for the control of small current devices, up to 2 Amps, e.g a PC, using an on-board PHOTOMOS relay which is an opto-electronic device which drives a power MOSFET switch[13]. The Second option provides the ability to connect an external relay that derives higher current loads through one of the on-board connectors.

To evaluate the actuation capability of the node and develop the necessary control algorithims, a demonstration was setup to control the operation of heater radiators as shown in Figure 5 based on selected data sets. The network monitored the room temperature/humidity and the appropriate command to the actuator to either switch off or on the radiator autonomously.

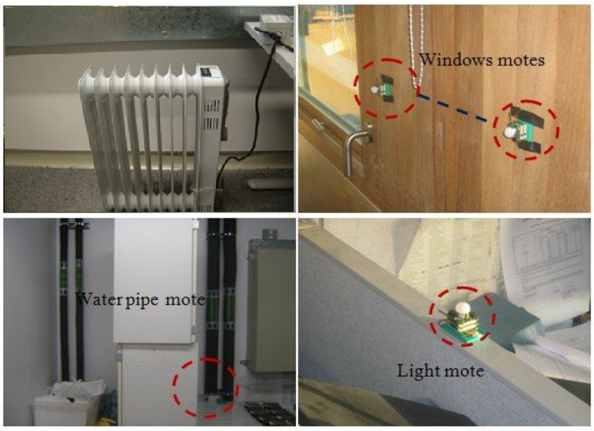

Figure 5: Number of Deployment Sites: on radiators, Windows, Light and Water pipe monitors

5 WIRELESS SENSOR NETWORK ARCHITECTURE

The adopted WSN architecture is based on recently released IETF IPv6 over Low power WPAN (6LoWPAN) (RFC 4944) open standard for IP communication over low-power radio devices – IEEE 802.15.4 represents one such link. WSN LoWPAN networks are connected to other IP networks through one or more border routers forwarding packets between different media including Ethernet, Wi-Fi or GPRS as shown in as shown in Figure 6 [14]. The IETF 6LoWPAN standard extends the same communication capabilities to low-power devices whose battery power must last for months or even years. The 6LoWPAN utilizes a pay-only-for-what-you-use header-compression scheme. Through direct integration with IP routers, it can take advantage of advanced network security schemes rather than depending on those provided by ad hoc gateways.

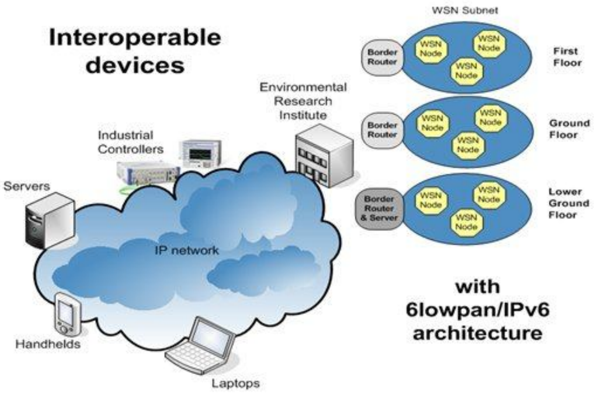

Figure 6: WSN in the broader view

This implementation offers possibilities for widespread commercial adoption and broad interoperability due to its attributes such as openness, flexibility, scalability and manageability. Many industrial standards, including BACNet, LonTalk, CIP and SCADA, introduced an IP using either TCP/IP or UDP/IP over Ethernet [14].

6 DATA STORAGE AND REPRESENTATION

The Environmental Research Institute (ERI) building, located at University College Cork (UCC), Ireland was designed as a green flagship building and a low energy research facility [14]. Its building function includes a combination of both laboratory and office spaces requirements distributed in three floors. This building was chosen as the test bench for our large scale deployment because it is the most densely measured building on the UCC campus. However numerous required measurement streams are missing. When combined these reasons offer an ideal test bed for evaluation of scenario modelling using wired measurements and wireless measurements as obtained from a wireless sensor network

To provide sensed data to the end user (or other software components) for the purpose of building performance monitoring (BPM), there are a number of conceptual and practical challenges that need to be overcome. The conceptual challenges can be the definition of BPM to different stakeholders of a building [15]. Practical challenges include data quality, availability and consistency, and benchmarking. A Data Warehouse (DW) implementation was created to store large data sets of data provided by the data streams of the WSN in ERI.

Figure 7: SOA for WSN to DW and DW to GUI

To extract the environment information from the WSN deployment in the ERI, a Service Orientated Architecture (SOA) was used [16]. For the ERI deployment, data is gathered from the first and ground floor and sent through the wireless backbone to the embedded PC (gateway) in the basement of the building. From embedded PC, a SOA connection is maintained to a data warehouse (DW). Figure 7 shows the architecture used to gather data from the sensors and present data through a graphical user interface (GUI) to the end user.

A sample of the obtained results using a building operator GUI are displayed in Figure 8 showing one days data from light (immunology lab), radiant (immunology lab), door (seminar room) and occupancy (seminar room). Figure 7 shows samples of the selected deployment sites. In total (60) nodes were deployed in the selected three main zones within the ERI building to perform various functions of sensing and monitoring.

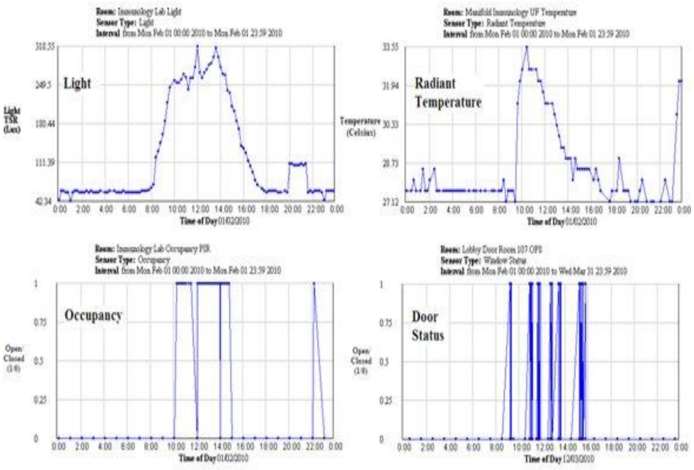

Figure 8: Sample of data recorded (a) light, (b) radiant temperature, (C) occupancy and (D) Door status

This building performance data is to be used to support decision making for facility manager and building operators to optimise maintenance activities and assist in fault detection and diagnosis, as well as the development of Building Information Models (BIM)

7 BUILDING INFORMATION MODEL BASED PERFORMANCE ANALYSIS

One of the goals of this work is the development of a technology platform able to support holistic environmental and energy management in buildings [17] by leveraging cutting edge technologies and in particular formal performance frameworks. The methodology uses BIM technology [18] to define and store performance related information that are associated to specific building geometry objects (e.g. building, floor, zone, wall…) or to specific HVAC system objects (e.g. pipe, air duct, pump, AHU…) and their relative metrics. Based on the data sets from deployed sensors/meters which are are also instantiated and defined in the BIM [3]. All these information are stored through the use of a tool named "Performance Framework Tool (PFT) [20]. The performances are structured in performance objects, objectives, metrics, aspects and scenarios (Figure 9).

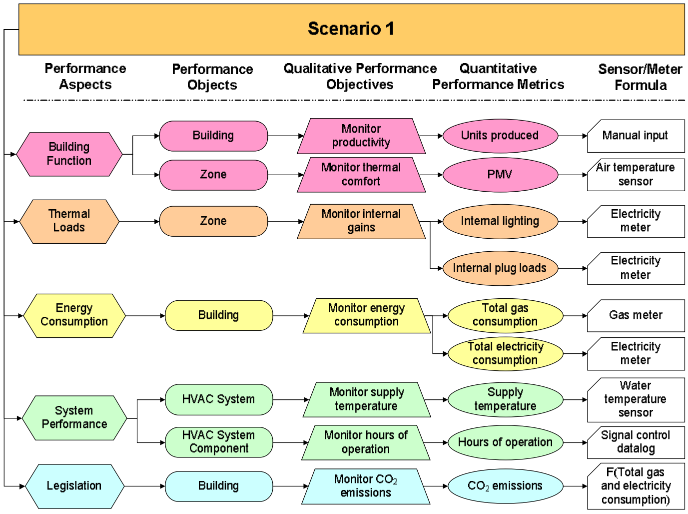

Figure 9 –BIM based performance definition

A performance objective can be thought of as a qualitative objective that may be assigned to a particular performance object (building object). The easiest example of performance objective is "monitor" a parameter, but more complex performance objectives include qualifiers such as "maintain"; in this case a benchmark value has to be defined accordingly. For example, a building manager may wish to maintain the temperature within a particular zone, within a building. This objective can be quantified by associating it with a performance metric, while the zone itself may be considered a performance object.

A building may have hundreds of performance objectives, so it makes sense to categorise them under particular performance aspects. In this way, similar performance objectives can be viewed together, in order to provide a clearer picture for the building manager. The five defined performance aspects are: building function, thermal loads, energy consumption, system performance and legislation. A scenario is a collection of associated performance objectives, concerned with a particular aspect of the building operation.

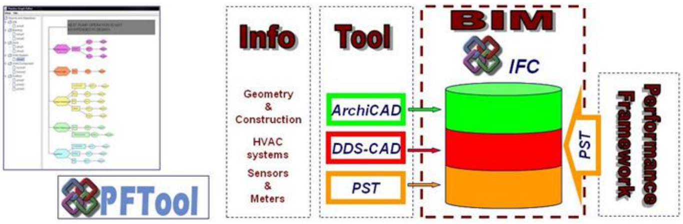

Figure 10. PFT Tool implementation

Concerning the current technical implementation, using data harvested from the WSN system described above, the PFT tool, Figure 10, takes an Industry Foundation Class (IFC) file as its input, defines and appends scenario definitions, and exports the file in IFC format again. The output of this process is a formal description of the building and system measurement framework available and the associated measured data required to monitor the prescribed performance. The measured data can be stored in a standard manually implemented data base or in an automatically implemented data warehouse that is IFC compatible. The data warehousing technology is a more powerful way to structure the data that allows the user to elaborate, pre-process and display them in different fashions [21], figure 11.

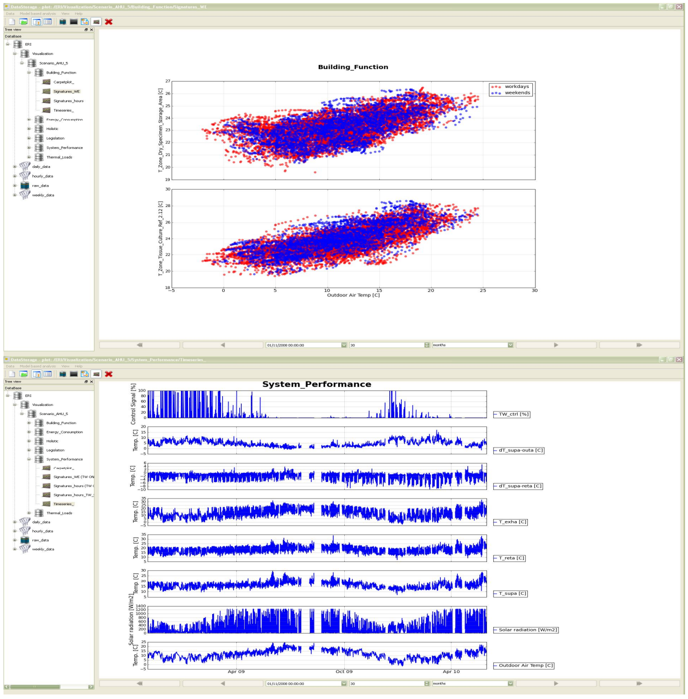

Figure11. Graphical representation of BMS Data (wired and wireless)

8 CONCLUSIONS

This paper presents the design and development of a miniaturized WSN mote based on Zigbee technology for building monitoring, exploring its system control management and technology characters and its useage as an input tool the the development of Building Information Models (BIM). The Tyndall modular WSN prototyping tool was used to develop the appropriate WSN infrastructure for building monitoring, modelling and control to minimise energy consumption in the built environment.

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