SENSOR-BASED AWARE ENVIRONMENT

Requirements towards establishing a computational self-configuring sensing system

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Abstract. This paper provides an overview of the requirements for a computational model of a Sensor-Based Aware Environment (SBAE) that integrates sensor technologies with the Building Information Modelling (BIM) in order to sense ambient and physical aspects of the built environment. Wireless sensors sense ambient data of a built environment, process, and communicate these data through an ad-hoc wireless network. The BIM, on the other hand, is based on International Foundation Classes (IFCs) and contains data about the physical infrastructure (i.e. Walls, Windows, doors) and abstract entities (i.e. Spaces, Relationships) and relationships between those entities. Therefore, the proposed computational model could sense real time data that are related to the as-built information model allowing for holistic building state information.

1. Introduction

Low-powered wireless sensors with on-board computing capabilities hold the potential for applications in aware environments. Mahdavi (2004) defines an aware environment as the one that exhibits a sensor-based, dynamic, and self-updating internal representation of its own context. In these aware environments, sensors and artificial intelligence (AI) computation afford peripheral awareness of human activities, ambient environment, and physical infrastructure (Dong et al. 2004). Such an environment could support a range of facilities management applications such as monitoring and evaluation of the building performance and responding to occupant directives and activities. However, extant methods for collecting ambient environment data and building configuration data for existing built environments is time consuming and driven by manual labour. Such labour-intensive methods will not be able to cope with the collection and analysis of such data for efficient facilities management.

Existing monitoring systems are concerned with specific building services rather than whole building context. Continuous data acquisition about building facilities is essential for approaching life cycle information and therefore supporting overall facilities management and decision making tasks. The advancement of wireless sensor technology and wide adaptation of Building Information Modelling (BIM) within the Architectural Engineering Construction (AEC) industries offer a potential solution to this problem. Our thesis is that integrating wireless sensors with the BIM could enable a Sensor-Based Aware Environment (SBAE).

Since little work exists in this specific area, it is useful to begin with a working definition for the concept of SBAE:

It is an environment that is an effect of a self-configuring sensing system. The self-configuring sensing system responds to changes in the ambient environment and built environments in order to achieve ad hoc deployment of wireless sensors and their unattended operation in a changing context.

The concept of a SBAE raises the following issues:

Context: It is important to understand the word context and what it means for this research. The context of a built environment refers generally to two constituents *i)* occupants: who are the people which inhabit, use, and visit the building; and *ii)* components: which include building systems, and physical and digital artefacts (Mahdavi, 2004). The context in this paper refers to the physical constituents of building as a technical artefact (the product called facilities).

Self-Configuring Sensing System: is a system that can modify its set number of finite parameters in response to changes in the environment.

Algorithms are required to enable the sensing system to exhibit self-configuration within the following configurable parameters:

a) Localization of the wireless sensors;

b) Automated discovery of sensible objects for each sensor; and

c) Automated discovery of new or removed sensors and their type.

Integration between wireless sensors and BIM: Wireless sensors can sense data about the ambient environment (i.e. temperature, humidity, and lighting) as well as other technical and operational data such as energy and water consumption, and gas leakage. In contrast, the BIM is based on International Foundation Classes (IFCs) which contains data about tangible entities (i.e. walls, windows, and doors) and abstract entities (i.e. spaces, and relationships) and establish relationships between those entities. The importance of the BIM is that it maintains hierarchical relationships between building components which could be modified to the user's needs.

This paper discusses the requirements for a computational "self-configuring" sensing system that could potentially lead to establishing sensor-based aware built environments. The sensing system self-configures parameters that maintain a representation of sensors and respective sensed objects and their localization. The self-configuring sensing system adapts to changes in the sensor infrastructure and the physical built environment. Ideas for the self-configuring sensing system are based on concepts of machine awareness, pervasive computing systems (wireless sensor networks, embedded computing) and object repositories of building data.

The use of a self-configuring sensing system in the building context could have several implications: *i)* minimise human intervention in acquiring facility state data; *ii)* support the autonomous process of collecting, updating and visualizing the data of the context; *iii)* allow ad hoc deployment of the sensors into an existing facility.

2. Related Work

Developments in related research areas are summarized and their relevance discussed in the context of SBAE introduced above. The research comprises two theoretical areas a) intelligent buildings; and b) aware machines, and two technologies c) BIM, and d) wireless sensors. The theoretical areas and the wireless sensor technology will be discussed towards highlighting the requirements of self-configuring sensing system.

2.1 INTELLIGENT BUILDINGS

In architectural design, an aware environment has also been called intelligent buildings, intelligent rooms, and sentient spaces. There are many available definitions of intelligent buildings as in Sherbini (2004) that refer to criteria such as automation, responsiveness, and effectiveness in order for the building to 'be' intelligent. We consider an aware environment as a different sort of intelligent building. An aware environment is:

A type of machine which possesses a self-aware model of itself and of its environment and exhibits aspects of intelligence such as knowledge representation, learning and reasoning.

Regardless of the definition of an intelligent building, there are two generally regarded principles for intelligent buildings: context-awareness and intelligent agents. According to Pascoe (1999), context-awareness, the ability of a device or a program to sense, react or adapt to its environment, is a key technology in ubiquitous computing. That is, an intelligent building should be able to adapt to changes by acquiring data from the context that can be used as informational basis for context awareness. Second, an essential part of the computing components of an intelligent building are intelligent agents. There are many definitions of intelligent agents in the literature. However, the definition by Russell (1995) that "*An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors*" is the appropriate for intelligent rooms. Intelligent agents are pieces of software that are embedded into a system in order to take decisions and actions. The principal components of an intelligent system based on intelligent agents are according to Russell (1995): *1)* the ability to perceive the context; *2)* the ability to maintain a representation of the context; *3)* the ability to reason; *4)* the ability to learn. Learning and reasoning, however, are dependent on the agent's ability to perceive and maintain a representation of the context. Multi-agent systems appear to be the dominant approach for creating intelligent rooms.

Intelligent buildings are typically consisting of a large number of autonomous/self-directed agents (Ranganathan, 2003). Multi-agent systems such as the ScatterBrain system cited by Coen (1997) are already found in operational implementations of intelligent rooms. Because agents are simple entities, agent based systems relinquish the need for complex centralized control (Coen, 1998). These agents work together to transform built spaces into intelligent buildings by coordinating sensors and effectors to achieve desired behaviours.

2.2 AWARE MACHINES

The development of aware environments is founded upon fundamental ideas of machine awareness from the field of artificial intelligence. One of the main criteria for intelligent systems is their ability to perceive their world and to respond to this world. In aware environments, the perception of the world would be enabled through sensors. The sensors in an aware environment need to be able to calibrate automatically and adapt to the environment as needed by establishing a communication network. All the sensors in an environment need to communicate their state and their coverage area to each other and develop a model of the context (Essa, 2000). Therefore, the integration of awareness of itself and the context are mandatory components of an aware machine and therefore, an aware built environment. The integration of sensor systems with the digital building representation is one potential way to create an intelligent building that is an aware machine.

2.3 WIRELESS SENSOR NETWORKS

Wireless sensor networks with the BIM are basic technologies required to establish the SBAE. An aware environment requires information about its surroundings as well as about its internal context. In order to develop a real-world data acquisition method, pervasive computing systems (i.e. wireless sensor networks and embedded computing) are required. Therefore, it is important to understand how these pervasive systems function. We have chosen to deploy the wireless sensor "motes" commercially developed by Crossbow. There are three components of a Crossbow wireless sensor network as: *1)* sensor and data acquisition boards; *2)* mote processor radio platform; and *3)* gateways and network interfaces.

2.3.1 Sensor and Data Acquisition Boards

Zhao (2004) defines a sensor as: "*a transducer that converts a physical phenomenon such as heat, light, sound, or motion into electrical or other signals that may be further manipulated by other apparatus*." A sensor converts the quantity to be sensed into a detectable signal that can be directly measured and processed. Examples of sensor and data acquisition boards from Crossbow (http://www.xbow.com) are shown in Figure 1.

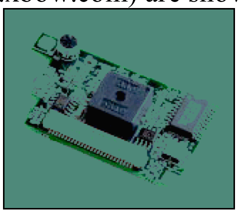

Figure 1. Example of sensor board "MICA"

2.3.2 Mote Processor Radio Platform ("Motes")

A sensor board can only send data through the wireless network when it is affixed on a radio platform called Mote. The combined package of sensor board and mote processor is known as a Sensor Node (Figure 2).

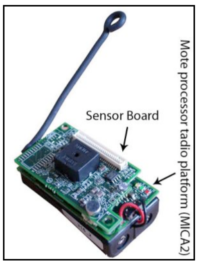

Figure 2. Sensor node with MICA2 and sensor board (photo by the author)

2.3.3 Gateway and Network Interface

A base station called a “Gateway” allows the aggregation of sensor network data onto a PC or other computer platform (Figure 3). MICA and MICA2DOT sensor boards can also be affixed onto the MIB510 gateway to be programmed to do certain tasks

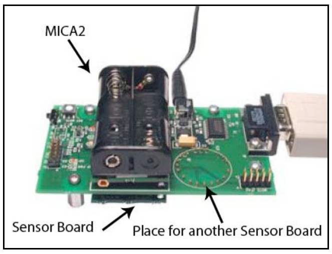

Figure 3. Example of a gateway (MIB510) with MICA2 and sensor board by Crossbow

2.3.4 Ad hoc Networks

One of the special features about the motes is the idea of using large numbers of motes that communicate with each other and form ad hoc networks without human intervention. The ad hoc network allows data from each mote to be passed from one mote to another toward the gateway. The range of communication between wireless sensor nodes is between 10m and 30m. The ad hoc network is formed by hundreds or thousands of motes that communicate and pass data along from one to another. (Figure 4) illustrates an example of an ad hoc network.

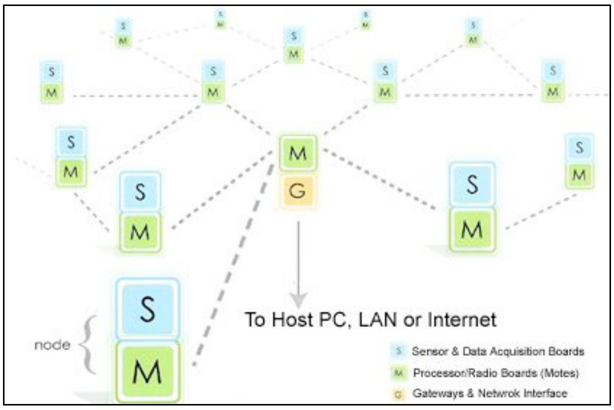

Figure 4. Illustration of the wireless sensor network that forms an ad hoc mesh network. “S”: sensor board, “M”: mote, and “G”: gateway

2.3.5 Wireless RFID Motes

Radio Frequency ID (RFID) is a wireless communication technology with advanced features ideal for scanning other RFID tags attached to anything that needs a memory or an ID number (Skyetek, 2005). RFID Readers can read from and write to RFID tags without contact, even through walls.

For the self-configuring sensing system, the wireless RFID mote is called an Anchor Node ("aN") as in (Figure 5). Each of the anchor nodes acts as a beacon which periodically scans its neighbourhood for sensor nodes. Each of the sensor nodes has an RFID tag. The anchor node consists of two components; 1) RFID reader; and 2) radio transmission board for communication within the wireless sensor network.

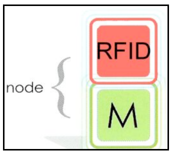

Figure 5. Anchor Node ("aN") for this research consists of: RFID reader/writer (RFID), and mote (M)

3. Self-Configuring Sensing System

Towards establishing a computational self-configuring sensing system that potentially results in an aware environment, the system therefore consists of:

I. **Components:**
   1) Sensor technology to perceive the context;
   2) BIM technology to perceive the building attributes; and
   3) A large number of autonomous/self-directed artificial agents.

II. **Behaviour:**
   1) Maintain a representation of the context;
   2) Autonomously update itself over time; and
   3) Process and analyse context information.

III. **Parameters:**
   1) Localization of the wireless sensors;
   2) Automated discovery of sensible objects for each sensor; and
   3) Automated discovery of new or removed sensors and their type.

IV. **Function:**
   1) Integrate data from sensors with the BIM.

Figure 6 shows the computational framework for the self-configuring sensing system. According to Russell and Norvig (1995), wireless sensors could act as agents that perceive the external environment. Sensor and BIM agents are inventory software that communicates with the sensing system to exhibit self-configuration for the above mentioned parameters. The out put of the sensing system could potentially lead to establish the proposed environment that is aware of changes in the ambient environment, and physical infrastructure of the built environment.

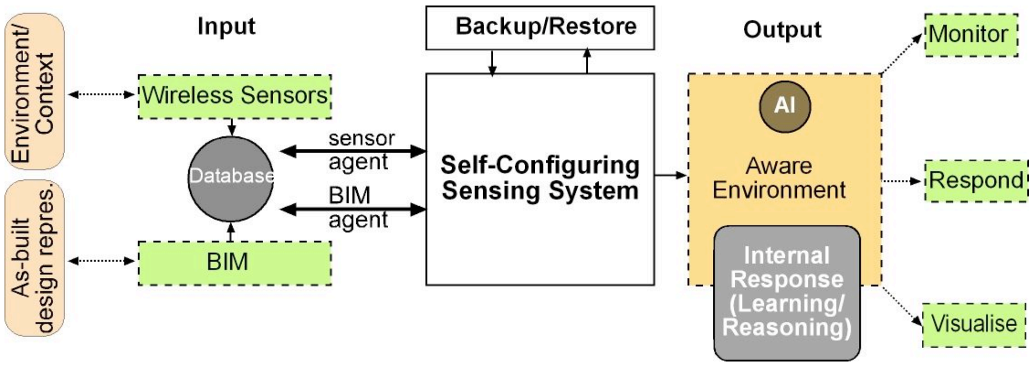

Figure 6. Proposed system framework for this research

3.1 INFRASTRUCTURE COMPONENTS

The proposed sensing system consists of the following components:

- **Object Nodes ("oN"):** are physical and infrastructural components of the building such as (light fixtures, doors, windows, and columns). In another word, they are all effectors inside the built environment that can be sensed by wireless sensors. Object Node representation with relation to location is derived from the BIM using IFC models.
- **Anchor Nodes ("aN"): "***usually known by beacons*" are nodes that are pre-programmed by the user into the system according to their locations inside the building. The anchor nodes periodically scan the location of their neighbourhood for any sensor node that has a RFID tag.
- **Sensor Nodes ("sN"):** are nodes that consist of: 1) sensor board; 2) mote; and 3) RFID tag (Figure 7).

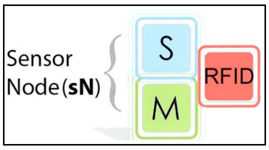

Figure 7. The sensor node design components to be used in this research. “S”: sensor board, “M”: MOTE and RFID tag

3.2 LOCALIZATION

One of the important significance of the SBAE system is the ability to accurately locate sources of sensor data inside the building. This is the problem of localization. This is because the wireless sensors should be deployable in arbitrary locations. The following simplified scenario describes the self-configuring localization parameter mentioned earlier.

3.2.1 Localization of Anchor Nodes and Object Nodes

Prior to placing wireless sensors (sN) in different locations inside a built environment, two relationships need to be stored in a database; *a)* relationship between object nodes (oN) and their locations in the built environment (“reln_oN_location”), and *b)* relationship between anchor nodes (aN) and their locations (“reln_aN_location”).

a) reln_oN_location: object entities called Object Nodes (“oN”) are stored in database and related to locations in the built environment which is basically derived from the BIM. The BIM contains information about architectural and building components including object’s serial number (“oN_serial”), object’s description (“oN_description”), object’s type (“oN_type”), and object’s location (“location_ID”). Thus, all information about Object Nodes that are affixed inside a building will be stored in the system (table 1).

TABLE 1. “reln_oN_location” The BIM representation of relationship between object nodes and location_ID

oN_serial	**oN_description**	**oN_type**	**location_ID**
00001	Light fixture	light	274
00002	window	temperatur e	113
…n	xxx	xxxxx	xxx

b) reln_aN_location: beacons or wireless Anchor Nodes (“aN”) are assumed to be placed in specified locations inside the building such as offices, corridors, and plant rooms. Every Anchor Node has a unique RFID represented in the database as ("aN_RFID"). Every aN_RFID will be related to a specific location_ID into the database as shown in table 2 ("reln_aN_location"). In practice, this is done by scanning the RFID tag of the aN to an RFID reader and then typing in the intended location of the aN inside the building. The Anchor Nodes are then ready to be manually affixed in the specified locations.

TABLE 2. "reln_aN_location" The relationship between aN_RFID and location_ID

aN_RFID	location_ID
51151	274
46637	113
…n	xxx

3.2.2 Localization of Sensor Nodes

The user selects the type of sensors such as (light, temperature, and humidity) to be placed in one location. Each location could have more than one Sensor Node ("sN") but may only have one Anchor Node aN. Every sN has an ID ("sN_ID") pre-programmed by the user onto sensor board, RFID tag ("sN_RFID"), and one or more sensing capabilities. The process of sensor deployment and sensor node localization is as follows:

a) Anchor node scanning: After the user selects wireless sensor nodes for deployment, s/he needs to walk into the target location and deploy the sensor where it can sense the ambient environment. The periodic scanning for the sensor nodes by anchor node triggers the self-configuring localization of the sensor nodes.

b) Establishing relationship between aN and sN: When the aN sensor scans a sensor nodes in its vicinity, the aN sends a message to the system formatted as (aN_RFID, sN_RFID). If sN_RFID is already stored in the database then the system goes to the next message. If the sN_RFID is not stored in the database, it means that the sensor node is a new node found in location and therefore, the system establishes a relationship between the new sN and aN. This is done by storing the relation into a new table (Table 3) ("reln_aN_sN") and recording the new relation. Following is a pseudocode for establishing relationship phase:

Pseudocode 1: localization of sensor node

1: pre-define aN to location_ID in the BIM and write into database (table "reln_aN_location")
2: deploy aN into specified location
3: deploy a sN

```
aN frequently scans the location for any sN
aN sends message to system upon scanning the room with a relation msg (aN_RFID, sN_RFIDs)
    for each msg received from aN_RFID, compare the associated sN_RFIDs in msg with existing sN_RFIDs in database
        if sN_RFID in msg == sN_RFID in database, then this sN_RFID is active
        else if sN_RFID is not in database, then this sN_RFID is new and should be stored in database
        else if sN_RFID in database has received no match from msg, then this sN_RFID is inactive or removed from aN_RFID location and should be deleted
    end if
  end for
end
```

TABLE 3. "reln_aN_sN" The relationship between aN_RFID and sN_RFID

aN_RFID	sN_RFID
51151	83332
46637	28783
…n	…n

3.2.3 Self-configuration of Sensible Objects:

The wireless sensor network works as a monitoring system of the ambient environment. Each wireless Sensor Node sends raw data through the network to the sensor board or sensor network Gateway. The raw data requires an interpreter to display information about the sensor which could include sensor ID ("sN_ID"), data stream value ("sN_value"), sensor type ("sN_type") engineering units of data ("sN_unit"), and time of reading ("time") (see table 4). These data could be stored in a database which will be accessed by the self-configuring sensing system for the final integration step.

TABLE 4. An example of the sensor information that could be stored in a database after being interpreted

sN_ID	**sN_value**	**sN_type**	**sN_unit**	**time**
14	420	light	lux	07/10/2005 11:35:54
23	42	humidity	percent	07/10/2005 11:42:20
27	25	temperature	deg C	07/10/2005 12:44:07

Self-configuration of the sensible objects is completed when the system finds a match in type between sN and oN from table 1 and 4. The system then establishes relationships between the two nodes in the same way as before (see pseudocode 1). The system then stores new relationships in a new table. Thus, for every location inside the building, the user identifies where Sensor Nodes are placed, but the system automatically determines sensible objects as Object Nodes.

Pseudocode 2: final integration

```
begin
LOCALISATION PHASE
 for i = 1 to locations
    read every location (i)
    check what object (m) is in location (i)
    check what sensor (n) is in location (i)
      for j = 1 to m
         read all object (j)
         check what is object_type (j)
         for k=1 to n
            read all sensor (k)
            check what is sensor_type (k)
               if sensor_type (k) == object_type (j) store new relationship in
               final table
          end if
       end for
    end for
  end for
end
```

4. Future Directions

We plan to develop a prototype of the self-configuring sensing system according to the scenarios and specifications described above to test its workability. The notion of the aware environment as an effect of the sensing system will be then developed to exhibit aspects of artificial intelligence, learning and reasoning.

4.1 CONCLUSION

The paper introduced the concept of self-configuring sensing system towards sensor-based aware environments (SBAE). We believe that such computational models could benefit several domains such as facilities management in that real-time visualising and updating of the ambient and physical infrastructural information about the facilities could be possible. This information could be used in different applications when it is fed back to the system for analysis of the current status, predicting the future through simulations, and responding more effectively to the occupants and building needs. With such computational models that automatically update themselves to reflect changes in the built environment, the human intervention, which currently limits the process of collecting and visualising data, could be overcome or at least significantly reduced. Dynamic monitoring of changes in a facility, when systematically collected in real-time though wireless sensors and the BIM could provide valuable information and feedback to a number of building professionals, not the least to building designers, who currently know very little about the long-term behaviour of their designs.

Acknowledgements

The author would like to acknowledge the Key Centre of Design Computing and Cognition (KCDCC) at the University of Sydney for its support of the research and for providing the wireless sensor technology needed for this research. Also the gratitude extends to the reviewers for their valuable comments.

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