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Multi-sensorial network placement for building performance analysis and evaluation and facility management

S. Zikos[1], A. Tryferidis[1], S. Krinidis[1], D. Ioannidis[1,2], D. Tzovaras[1] & S. Likothanassis[2]
[1]*Centre for Research and Technology Hellas, Information Technologies Institute, Greece*
[2]*Pattern Recognition Laboratory, Computer Engineering and Informatics, University of Patras, Greece*

Abstract

The paper presents the process of placing a multi-sensorial network comprised of a large number of heterogeneous sensors, able to provide accurate information about energy consumption, occupancy, comfort conditions and environmental quality. The proper selection of the sensors' type and location is very important for the accurate representation of the building information in order that the building's real conditions are represented properly. The multi-sensorial network consists of multiple heterogeneous sensors, such as depth sensors, PIR motion, door counters, acoustic sensors, RFID, luminance, temperature, CO_2, humidity sensors, actuators, etc. and is able to provide in real-time an all-inclusive perspective of the real-life conditions of the building under interest. The selected building information is combined and analysed in order to evaluate and assess its performance related to energy consumption as well as occupants' comfort and satisfaction. To this end, visual analytics techniques are utilized, which are able to visualize the building information in a comprehensive way, closer to human perception. The building information is visualized in the spatio-temporal domain assisting the analyst to detect patterns that are difficult to be detected otherwise. All this information can be used for the analysis of building's current performance, and decision making about an operational scenario which can be applied by utilizing the actuators of the multi-sensorial network. Finally, the overall system has been installed and evaluated in real-life conditions at a

building comprised of offices, multi-purposed spaces (e.g. kitchen, conference room, etc.) and corridors.
Keywords: sensors, energy consumption, occupancy, building monitoring, visualization.

1 Introduction

Monitoring and performance measurements through sensors, energy consumption analysis and control, and data management and visualization constitute some of the applied or developing BIM functionalities for existing buildings [1]. There is a motivation towards developing new solutions that combine information from intelligent smart sensor networks, aiming at analyzing the performance and improving the energy efficiency of buildings. In most cases, the interfaces among heterogeneous sensors and devices are not clear and interoperability with additional smart sensors is not guaranteed. Furthermore, usage of separate and disconnected tools results in information fragmentation and redundancy, posing problems for well-informed decision making [2]. An ontology definition is usually required due to the existence of different entities in a building. Ontology contributes to the conversion of human knowledge into a well-defined format, which is machine understandable. Several studies, such as [3], focus on ontology development process for real-time building monitoring. The measurements provided by the installed sensors have to be accurate in order to represent the actual building's conditions. The most appropriate sensor types must be selected prior to installation. Proper placement of the selected sensors plays a crucial role in the accuracy of the output values, as various environmental parameters can potentially affect the readings. The optimal organization and presentation of the available information is another topic of interest which is important and challenging. Appropriate and sufficient visualisation tools can allow facility managers to effortlessly review the building's performance, evaluate it, and identify potential sources of high energy consumption. They also provide facility managers with the necessary functionalities to better and in real-time analyze the acquired data facilitating their decision making process, and allowing them to apply control actions in real-time when necessary. Additionally, in case an automated facility management system is employed in controlling devices, its actions have to be clearly presented to the facility manager for reviewing.

The present paper presents the architecture and installation of a multi-sensorial network at a research institute, which provides information about different parameters, and the proper presentation of this information to the facility manager in order to evaluate the building's performance, detect potential issues, and reduce the energy consumption by controlling devices via the actuators of the multi-sensorial network. Due to the large number of sensors, devices, and monitored spaces, ontology for mapping the sensors and the devices to building spaces is utilized. The system presents various aspects of the building's state in the spatio-temporal domain such as the status and power consumption of devices (HVACs, lights, etc.), environmental conditions such as temperature, humidity and luminance, and real-time occupancy information. The latter, provided by the occupancy extraction system, allows the facility manager to correlate energy consumption with occupancy, both at building level and as low as space/room level. For example, when an HVAC is operating in an unoccupied office, the status and consumption is reported and the facility manager can easily switch it off increasing the energy savings. Furthermore, in case a space is occupied, the facility manager can look up the environmental conditions, provided by the installed temperature, humidity, CO_2 and luminance sensors, and adapt the energy profile for optimal balance regarding energy consumption and occupants' comfort.

The rest of the paper is organised as follows: Section 2 presents the different sensor types that are utilized and installation issues. Section 3 provides an overview of the system architecture and section 4 presents the high level visualization components. In section 5, experimental results of the system evaluation are demonstrated. Finally, section 6 summarizes the conclusions and introduces topics for future work.

2 Multi-sensorial network

2.1 Sensor types

The installed multi-sensorial network includes a large variety of heterogeneous sensors in order to cover many different aspects of the building's state such as the energy consumption, occupancy and environmental state (table 1).

Door counter sensors are used in order to count occupants passing by the doorway of a closed space, by extracting direction. To this end, we use double-beam sensors, Pressure mats or both combined, due to their low cost as compared to specialized people counter sensors. Low-cost analog acoustic sensors are used for ambient noise detection in spaces such as a meeting room and a kitchen. Acoustic events are sent periodically. When movement is detected an activation event is sent by the PIR motion sensor. A deactivation event is sent after a 3-sec period of no movement detection. Magnetic contacts are installed at some main doors and windows. A change in the state implies occupant activity, while the binary value alone can show the state, e.g. open window. Carbon Dioxide (CO_2) sensors return the concentration of carbon dioxide in ppm (parts-per-million), which is an air quality measure along with an occupancy density measure. An event is sent when a change of at least 5% is detected. Temperature sensors output the temperature in ^{o}C degrees, while humidity sensors output the relative humidity percentage. In some spaces, combined temperature, humidity and CO_2 sensors (3in1) are used. The luminance sensors that are installed provide information about the luminance in a space by sending an event when a change of at least 15 Lux is detected (fig. 1). The installed SmartPlugs report the current power consumption every 1 minute and the status of the plugged device if changed. A SmartPlug can operate as a switch and allows controlling (switch on-off) the connected device. Different types of devices are connected to SmartPlugs such as PC monitors, printers, water coolers, microwave ovens, a vending machine, a coffee machine, etc. A sensor/actuator for the building's first

Table 1: Types of sensors.

Sensor type	Usage	Output	Connection interface
PIR motion	Occupancy	Binary state	Via alarm system
Magnetic contact	Occupancy	Binary state	Via alarm system
Double-beam/ Pressure mats	Occupancy	Entry / exit	Arduino with Wi-Fi or Ethernet
Acoustic	Occupancy	Sound activity every 4 seconds	Arduino with Wi-Fi or Ethernet
RFID antennas	Occupancy	RFID tag detection	Ethernet PC
Depth cameras	Occupancy	Number of detected occupants	Ethernet PC
CO_2	Occupancy/ Environmental	Concentration in PPM	EnOcean (wireless)
Temperature	Environmental	ºC	EnOcean (wireless)
Humidity	Environmental	Relative percentage	EnOcean (wireless)
Luminance	Environmental	Lux	EnOcean (wireless)
SmartPlugs	Energy cons./ Control	Power cons., device status	ZigBee
Water heater sensor/actuator	Energy cons./ Control	Power cons., water temperature	Arduino with Ethernet
Actuators	Control	N/A	EnOcean or OPC server


(a)


(b)

Figure 1: (a) CO_2, Temp., Hum. sensor; (b) Luminance sensor.

floor water heater was developed, by utilizing a temperature sensor, a CT sensor and a relay. It reports the power consumption and the water temperature. The multi-sensorial network also includes the actuators for controlling the lights and HVAC systems. For controlling lights, two types of actuators are utilized: dimmer actuators and on/off switch actuators.

Occupancy sensors are utilized by the occupancy extraction system, which supports both group-based (occupancy per space) and individual location extraction (location per occupant). For group-based occupancy extraction two systems were developed and utilized, one that uses depth cameras and one that uses multiple low-cost sensor types. The occupancy extraction system that uses depth cameras [4, 5] detects human targets in real-time and outputs the exact number of occupants in the monitored space. The system yields an average accuracy about 95%. An alternative occupancy extraction system utilizes multiple low-cost sensor types such as PIR motion, acoustic, and door counters. The method uses sensor fusion by combining data of different sensor types and it is based on probabilistic Conditional Random Fields (CRF) models [6], where features are derived from the sensor data and the produced estimations can be one of presence/absence, occupancy density or exact number of occupants. A training phase is required in order to create the model. Individual occupancy extraction refers to the mapping of an occupant to a location in the building. The extracted data in the temporal domain can provide information about the flow of occupants in the building. Data are accessed and processed based on a tag ID (and not an occupant's name, in order to preserve privacy). An RFID antenna is installed over an entrance in order to detect semi-passive tags, which are carried by specific occupants. The tag identification upon detection is combined with information from the installed door counter sensor in order to extract direction (entry or exit). Then, based on the entrance id number, the respective current location is extracted and stored.

2.2 Selecting types of sensors

Regarding occupancy extraction per space, various possible combinations of sensors can be utilized. For selecting an optimal sensor combination, different parameters have to be considered such as the desired occupancy extraction accuracy, the desired response to occupancy changes, the total cost, and the special characteristics of the space. The occupancy extraction component supports different granularities of occupancy extraction, such as presence detection, occupancy density (5 levels) and estimation of the exact number of occupants. The selected occupancy extraction type defines the potential sensor types that can be used. Generally, accuracy increases with increasing number of different sensor types, however, total cost increases too. In the case low response time is required, for instance in a space that is frequently occupied for relatively short time periods (e.g. short meetings in a meeting room), a door counter sensor can be preferred as opposed to a CO_2 sensor, and the use of an acoustic sensor can be considered. Furthermore, as each space is utilized differently, its characteristics have to be taken into account when deciding the set of sensors. The use of depth cameras could raise privacy concerns in working environments. On the contrary, in case a room can be divided into zones and occupancy extraction per each zone is of interest, the installation of multiple depth cameras would allow it.

2.3 Placement of sensors

The proper placement of the sensors in the building is of great importance for the accurate representation of the building information. While high measurement performance is the top priority, other secondary yet important parameters have to be considered. Each sensor type has its own installation requirements, based on its operation. Some examples are presented next.

CO_2 sensors for occupancy sensing are installed in the breathing zone, at a height about 1.20–1.80m above floor level. In our setup, for the CO_2 sensors installed in meeting room and in kitchen, wherein occupants are usually seated most of the time, the installation height was set to the lower bound 1.20m. Thus, the sensor is closer to the source of carbon dioxide emission, and as a result the response of the sensor to the changes is improved. Double-beam sensors, which are used for counting occupants, are installed at a height about 1.20m, in order to minimize the probability of double-counts due to arm movement [7]. For the PIR motion sensors, make sure there are no uncovered critical areas in space. For example, in a multi occupant office, a PIR motion must be in such position so that it can detect each occupant when he/she enters or exits the office. The location of space's openings such as windows/doors should be taken into account when deciding the placement of most sensors types because their output is affected. When measuring indoor conditions, most sensor types, such as CO_2, humidity, acoustic are not installed near windows in order to reduce the impact of the external environment's condition. The installed temperature sensors (indoor or outdoor) are shielded from solar radiation, being under shade provided by a reflective low-thermal mass material, such as plastic. Plants are not appropriate to provide shade in this case as they tend to cool the ambient temperature due to transpiration. Thermal gradient, the rate of temperature change with distance, should be considered when placing a temperature sensor. As the thermal gradient is more intense near ground level, the sensor has to be at least 1.25m from the ground, preferably around 1.50m [8]. Optimal indoor humidity level heavily contributes to occupant comfort. Although the recommendations for indoor relative humidity vary from country to country, the human comfort zone is around 25–60% relative humidity [9]. Nearby heat and moisture sources affect the output of humidity sensors. They must also be placed away from windows and not close to cooling/heating coils. In outdoor installations, a humidity sensor must be protected from solar radiation in order for water vapour process not to be affected. A luminance sensor must not be exposed to direct light, either daylight or artificial light. We have installed the luminance sensors on the ceilings, at locations that are not directly lit by the lamps or by daylight during the day. To achieve this, we can observe the shadows produced by the lamps at night and the shadows created by sunlight at daytime. Besides performance, other parameters that have been considered are: unobtrusive installation, protection and connectivity. For sensors such as depth cameras and door counters the selected installation location minimizes the required cable length. Furthermore, cable management contributed to the limitation of the cables' visible parts. The Arduino nodes were concealed from optical sight by using case boxes that host them in a more protected environment (fig. 2).

Figure 2: Arduino acoustic sensor in a case box.

When selecting an installation location for a sensor, it has to be confirmed that it will be protected both from occupants and interference. Regarding occupants' activities, precautionary measures were taken to assure that a sensor cannot be accidentally unplugged, moved, or covered by any activity caused by the occupants. Interference can be caused by nearby electrical equipment, such as a power cable parallel to a sensor's cable. In this case, the output of the sensor can be affected. An issue regarding the sound sensor that is installed in the meeting room, which is set at high sensitivity, has been noted. In two cases, after meetings, the sound sensor was reporting periodical minimal sound activity, when the room was unoccupied, resulting in erroneous occupancy estimation. The problem was due to interference with the conference phone that is located on the table. The issue was solved after the redeployment of the conference phone.

3 System architecture

The system incorporates various different components, apart from the low-level heterogeneous sensors. Due to sensor heterogeneity, different connection interfaces are utilized and therefore intermediate components are used, each corresponding to a specific set of sensors. The hardware and software intermediate components manage the connections to sensors, receive their data and store the events into the central database, where all data are finally stored.

Higher level components interact with the data stored in the database: These are the occupancy extraction component, the SpaceUI component and the facility manager's visualization and control component. The occupancy extraction component receives as input real-time raw sensor data from occupancy sensors and extracts the occupancy per each occupancy zone defined, and the current location per each RFID tag for the individual extraction case. An event is created and stored when occupancy changes. The user-oriented SpaceUI component retrieves and visualizes data about the current condition of the selected space, regarding power consumption, occupancy and environmental conditions. The facility manager's visualization and control component can present real-time and historical information. It also offers the facility manager the ability to control devices via the actuators. The overall architecture is shown in fig. 3.

4 Information visualization and facility management

The SpaceUI application (fig. 4) presents current state information for a particular space in a single view, such as the status of lights and HVAC system, total power consumption, environmental conditions (temperature, humidity, CO_2) and occupancy. The information is available to all occupants via a monitor placed in the space of interest. The occupants can inspect how their presence and their actions affect the environment and the power consumption in the specific space, which can contribute to adopt a more energy efficient behavior.

New data, generated by multiple sources (raw sensor data, occupancy data, energy consumption data) are produced continuously at a high rate. These data have to be processed, be properly organized and presented in order to be

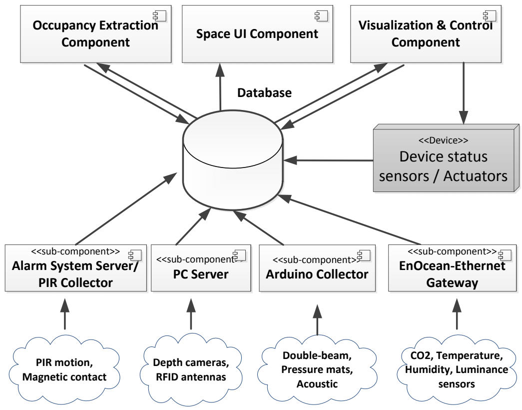

Figure 3: System architecture.

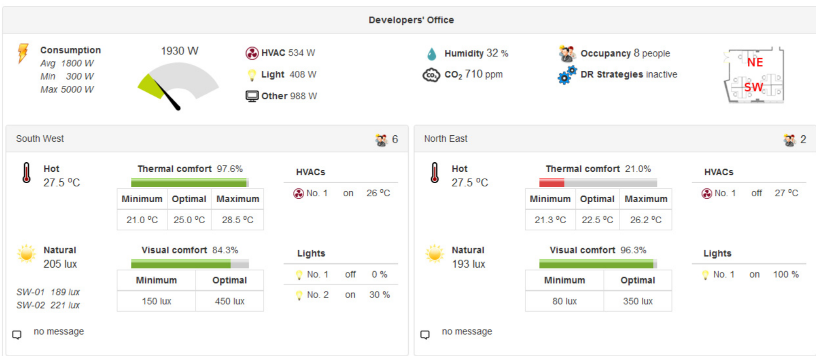

Figure 4: SpaceUI.

valuable for the facility manager. Thus, the presentation must be clear and easily configurable, in order to allow the facility manager to perceive compound relations among the different measured variables. To this end, the facility manager's visualization and control component exploits characteristics of the field of Visual Analytics. Visual Analytics is the science of analytical reasoning supported by interactive visual interfaces and it can be seen as an integral approach combining visualization, human factors, and data analysis [10]. Using advanced visual interfaces, which are highly configurable, a facility manager can have access to human readable visualized information, allowing him/her to make the best possible decisions and perform the most appropriate actions.

The system provides a general view of all spaces to the facility manager that summarizes the current condition of the monitored building areas, such as occupancy and total consumption. It also allows the facility manager to select a particular monitored space in order to receive a more detailed view, such as the status of each monitored device and the environmental conditions. The facility manager can also verify the functionality of the occupancy extraction sensors by

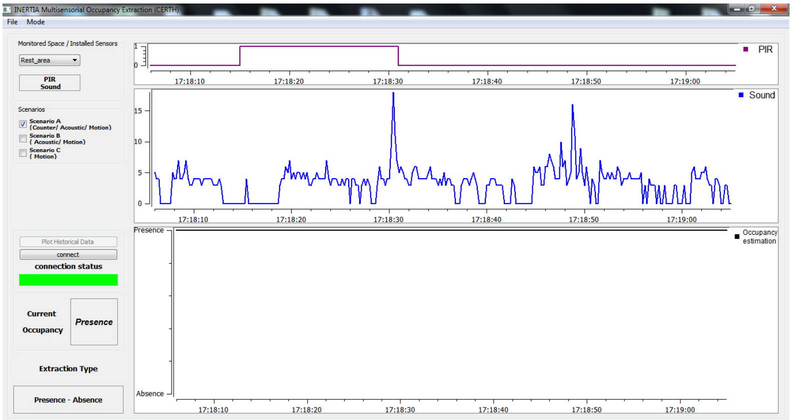

Figure 5: Real-time activity of PIR, acoustic sensors in an open-space area.

examining the real-time graphs which show the current value of each sensor installed along with the estimated occupancy (fig. 5).

In the historical data mode, past data are presented to the facility manager. The latter can discover patterns in past time periods that will help him/her to adapt the applied strategies and increase their efficiency. Furthermore, different operational scenarios can be evaluated and compared. The manager can select the entities and the metrics of interest, for example the total building's power consumption, the power consumption of a particular HVAC, the temperature of a particular space, etc. The defined time interval can be from several days to minutes, and the time step resolution of the presented data can be also configured. For instance, fig. 6 presents the occupied intervals and the HVAC status of the main corridor for two consecutive weekdays. It can be easily observed that in this case the particular HVAC was operating overnight.

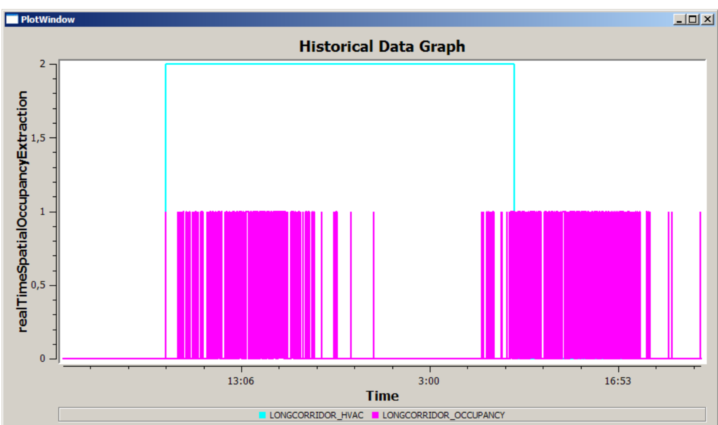

Figure 6: Historical data of two consecutive weekdays.

5 Experimental results

The overall experiment has been carried out over a year. More than 10 different spaces, mostly offices, and other multi-purposed spaces such as a kitchen, a meeting room and corridors are monitored via the multi-sensorial network. Apart from the real-time on site evaluation of the monitoring process, which was performed in each space, historical data provided by different sources were compared and checked for consistency, in order to evaluate the received sensor readings and system integration. For example, fig. 7 shows the estimated occupancy density (Double-beam, PIR motion occupancy sensors) with regard to HVAC state in a multi-occupant office which accommodates 9 employees. Fig. 8 depicts the temperature versus the HVAC operational status in a single-occupant office for a particular weekday. We observe that the temperature decreased and

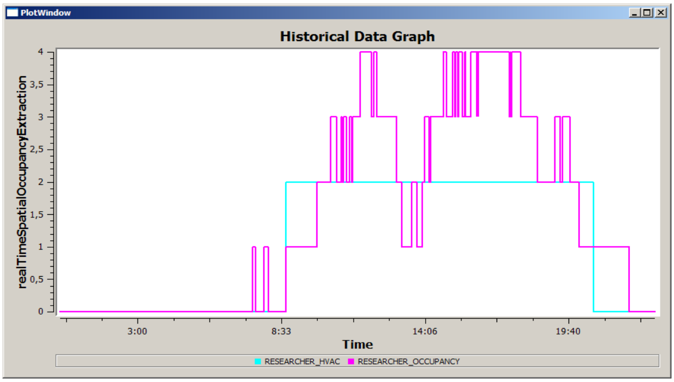

Figure 7: Occupancy density versus HVAC status.

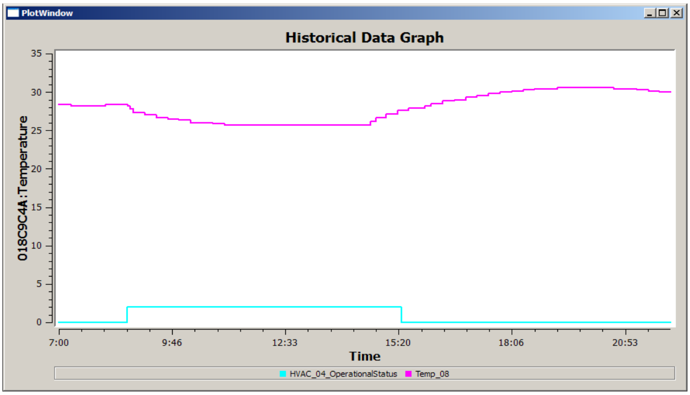

Figure 8: Temperature versus HVAC status.

stabilized while the HVAC was operating. Information about the energy consumption is also available. Fig. 9 presents the total energy consumption that is computed by the power consumption of all monitored electrical devices, from 10:00 until 21:00, which is about 209 KWh for the whole time period.

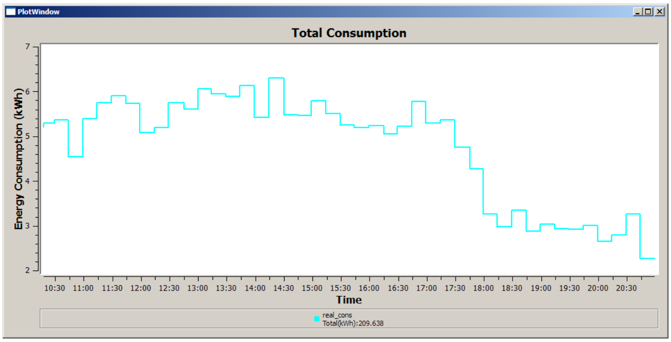

Figure 9: Total energy consumption.

Corrective actions are generated by the occupants as a response to facility management control actions. For example, in the case the manager decides to switch off the lights in an office while an occupant is still present, it is expected that the occupant will turn the lights on shortly after. The corrective actions can be monitored through the sensor network. The number of the corrective actions that are generated shortly after the actions of the facility manager is an indicator that can reveal inefficient management decisions and discomfort on behalf of the occupants.

6 Conclusions and future work

This paper presented a building monitoring system for performance analysis and facility management. The installed multi-sensorial network, comprising of heterogeneous sensors, provides rich information about the state of the monitored building areas, such as power consumption, environmental state and occupancy. Proper selection and placement of sensors ensured the validity of the raw data. Moreover, the system involves visualization tools that allow the efficient review of the building's state in the spatio-temporal domain and the control of monitored devices, such as HVACs and lights. Evaluation tests showed that: a) relative measures derived by different sources coincide and b) the provided information helped the facility manager to apply correct decisions. As a future work, we plan to evaluate an automated facility management system, which takes decisions based on all the monitored parameters.

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