Adaptive energy consumption optimization using IoT-based wireless sensor networks and structural health monitoring systems

Adaptive Energy Consumption Optimization Using IoT-based Wireless Sensor Networks and Structural Health Monitoring Systems

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Abstract

Recent developments in combining sensors, communication systems, and other fields like cloud computing and Big Data analysis have provided perfect tools for researchers, developers, and industries to develop cutting edge systems for improving energy efficiency and consumption. Smart homes, smart sensors, and Internet of Things (IoT) are just few examples of these technologies that will lead to more sustainable and resilient energy systems. This paper presents a new system based on a network of wearable devices, customized structural monitoring systems, and other sensors which has been developed to make energy consumption optimization more intelligent, adaptive, and efficient. Current industrial solutions for improving energy efficiency and energy consumption in residential and industrial buildings, especially large ones, do not provide a proper level of comfort for people and ideal energy efficiency. In the present work, users' location, body temperature, and feedback and data from other energy monitoring sensors are processed to minimize energy consumption based on the current status of the system.

1. INTRODUCTION

Industrial and residential buildings consume a lot of energy and emit great amount of CO_2, sulfur dioxide, and nitrogen oxide. Based on the report of the United States Environmental Protection Agency (EPA) [1], buildings in the USA consume 65% of the electricity that is produced and use 36% of the whole country energy annually. Moreover, they produce 30% of the carbon dioxide found in the air which is the main greenhouse gas related to the climate change. Considering the fact that non-renewable resources of fossil fuels are the main source of current energy production, and due to the negative effects of greenhouse gases produced from these resources, it is crucial to investigate and exploit new methods in order to use more renewable fuel resources, reduce energy loads, and increase efficiency. Based on [2], in order to achieve an optimized energy consumption, buildings and facilities must have a comprehensive perspective during their design and development phase for the new ones and reuse, renovation or repair phase for the existing ones. Some of these perspectives/processes are:

- Reducing heating, cooling, and lighting loads;
- Using efficient HVAC and lighting systems;
- Monitoring building performance through metering, annual reporting, and etc;
- Optimizing building performance by means of energy modeling and control strategies using occupancy sensors, air quality sensors, and so on.

In order to find energy solutions that improve efficiency, building energy management systems (BEMS) must be used. Based on [3,4], by using BEMS it is possible to obtain higher energy efficiency and lower power consumption and costs. Moreover, there are simulation tools like Building Energy Optimization

(BEopt) [5] which has been developed by the National Renewable Energy Laboratory (NREL) to identify most efficient designs for new and existing building at the lowest possible cost. This and similar simulation-based software, are used to design optimization based on specific building characteristics, like size, architecture, occupancy, and so on. Although the mentioned tools and methods provide solution for energy efficiency in buildings, there still issues that should be solved. Some of these tools have not been effective and efficient enough always. For example, current solutions that deal with energy consumption optimization and energy efficiency in residential buildings do not consider the inhabitant's role and their level of comfort effectively. For instance, an automatic heating system in a building maintains the internal temperature between a certain range, while its set point can be changed based on different parameters like inhabitants' location, body temperature and humidity, and etc. As an example, the temperature set point can be decreased when nobody is inside the building or when people feel hot.

2. SYSTEM DESCRIPTION

In this project a comprehensive solution for obtaining higher energy efficiency and lower power consumption has been developed. This system includes wearable nodes which collect data of people and SHM nodes that are used to both assess the building health (vibration, displacement, and so on) and also create the network of sensors. The system is capable of measuring people's location through real-time indoor localization using specific on-board radio frequency modules. Location data beside other data like users' feeling temperature (near skin temperature/body temperature) are used to develop control strategies which are dynamic and adaptive. Data are processed locally or in cloud based servers and the results are used to modify the current energy consumption profile. Lighting system and temperature set point for cooling and heating systems will be modified according to the people's distribution, feeling, and other parameters which cause high level of comfort for inhabitants. Figure 1 represents the overall concept ot the developed system. As it is show in Figure 1, the wearable nodes are in connection with

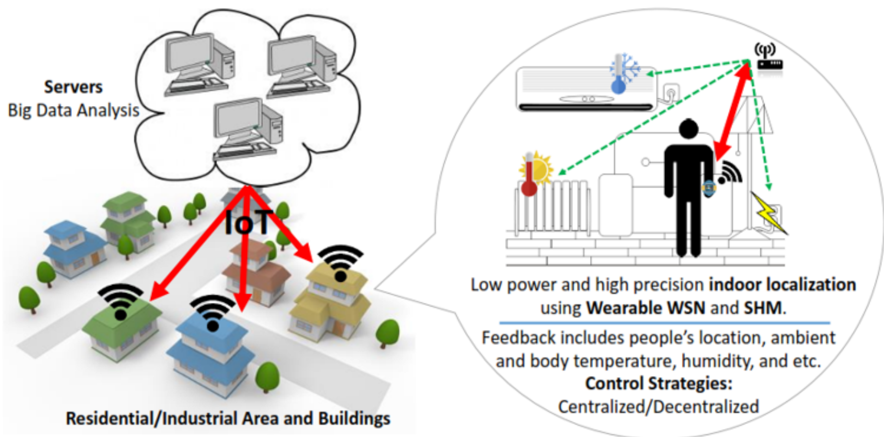

Figure 1 : The overall system concept.

SHM nodes. Users' precise location, body temperature, human activity level (heart rate), and their online feedback are sent to the SHM nodes. Processed data are added to the system states which change energy consumption control strategies. SHM node send control data to the IoT-based thermostats and lighting control units in order to modify the set point temperatures, light intensity, and so on. Figure 2 shows the system schematic.

2.1 Hardware

The system hardware includes two different hardware that have been developed for the wearable nodes and SHM nodes.

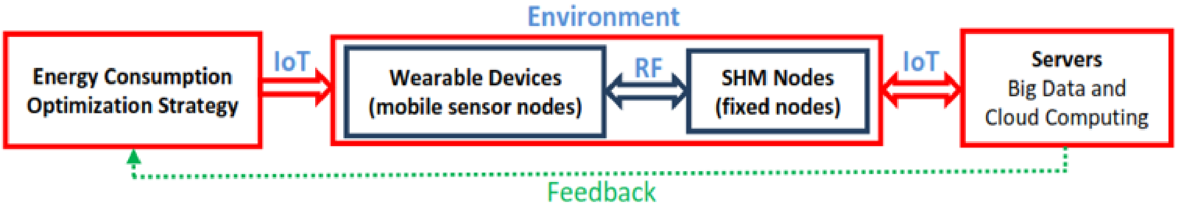

Figure 2 : The overall system schematic.

2.1.1 SHM nodes

These customized SHM nodes have been used for general structural health monitoring and also provide a platform for constructing the wireless sensor network including wearable nodes and other energy meters and monitoring sensors (e.g. light, heat, electricity, and so on). SHM nodes can measure vibration, displacement, ambient humidity and temperature as their general features for SHM nodes. They also have been equipped with a ultra-wideband (UWB) radio frequency module that has been used for real-time indoor localization and transferring data between the wearable nodes and the SHM nodes. As a part of an IoT-based device, SHM nodes have Wi-Fi modules in order to transfer data through the Internet. For situations where Wi-Fi connection is not available, SHM nodes can send and receive data through the on-board quad band GSM/GPRS data. Table 1 lists the main sensors and modules that have been used in the SHM nodes. In addition, Figure 3 shows the SHM node schematic and its subsections.

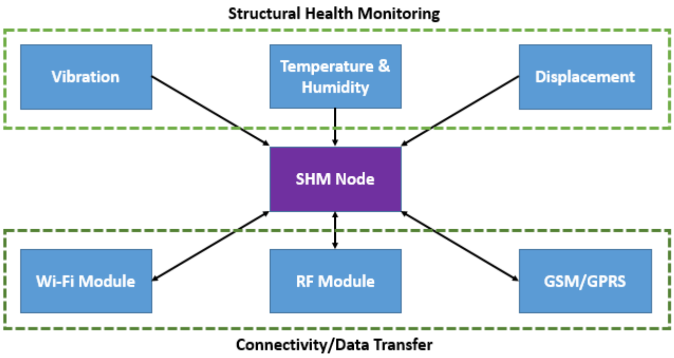

Figure 3 : SHM node schematic.

Table 1 : List of the main components (sensors/modules) of the SHM nodes.

Item	Description
Temperature	Measuring ambient temperature for structural health monitoring.
Humidity	Measuring humidity for structural health monitoring.
IMU	Measuring vibration for structural health monitoring.
Displacement	Measuring displacement for structural health monitoring.
RF Module	Communicating with other SHM or wearable nodes / Indoor localization.
Wi-Fi module	Transferring data through Internet.
GSM/GPRS module	Connecting to Internet through the GPRS.

2.1.2 Wearable nodes

The wearable devices that have been designed and developed in this project, are equipped with RF modules for indoor localization and transferring data between wearable and SHM nodes, body and ambient temperature and humidity sensor, Bluetooth module for transferring data between wearable device and mobile app, and heart rate sensor for human activity measurement. Figure 4 represents the overall schematic of the wearable nodes. In addition, Table 2 shows the list of components that have been used in the wearable device.

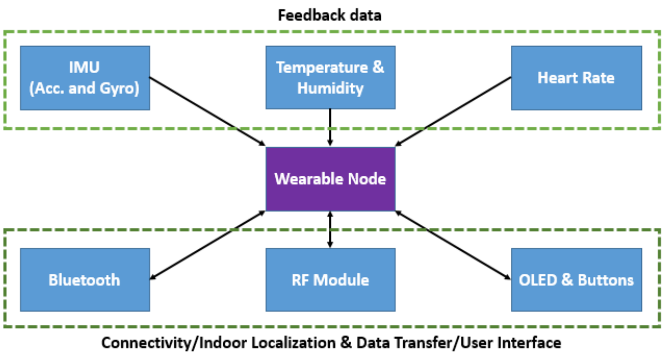

Figure 4 : Wearable node schematic.

Table 2 : List of the main components (sensors/modules) of the wearable nodes.

Item	Description
RF Module	Communicating with SHM nodes / Indoor localization.
Temperature	Measuring ambient/body temperature as a human-based feedback.
Humidity	Measuring ambient humidity.
IMU	Motion detection / Indoor localization error compensation.
Bluetooth module	Connecting to the mobile phone and the developed application.
Heart rate	Measuring heart rate and body activity level.
OLED Display	User Interface / Displaying useful information.
User buttons	User Interface

Figure 5 shows the 3D model of the wearable node and the actual hardware without the 3D printed cover. The overall size of the wearable node is 45x35x10 mm.

2.2 Methodology

Using the proposed system, data have been collected in order to obtain the following items.

1. Real-time localization of people inside building in order to:
    - Change the lighting status and heating/cooling set points based on the distribution of people;
    - Modify the energy load based on the presence/absence of people in different areas.
2. Collecting data like near body temperature, humidity, and heart rate in order to:
    - Modify the set points based on the body temperature and body activity level.

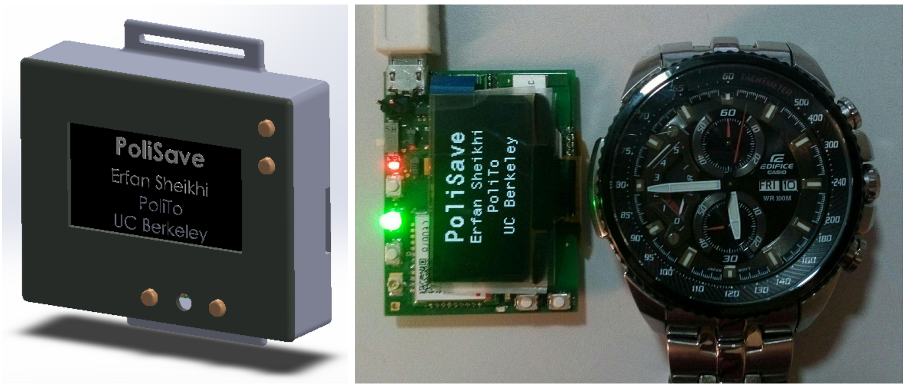

Figure 5 : 3D model and actual hardware of the wearable node.

- Provide the highest level of convenient for the habitants.

3. Obtaining user feedback in order to:
   - Modify the control strategies based on the people's preferences.
   - Increase the level of comfort.

These collected data will lead to an adaptive and intelligent energy consumption optimization which works beside the current existing optimization tools.

2.2.1 Indoor localization

Each device (SHM and wearable) has been equipped with an on-board UWB radio frequency module that gives the system the possibility to measure the distance between two modules in real-time with a precision less than 100 cm. Using the measured distance between three SHM nodes and trilateration technique, position of each wearable node will be obtained. In order to increase the accuracy, data from the IMU modules has also been used to minimize and compensate noise in measurements. As it is shown in the Figure 6, each person has been localized. Due to the accuracy of localization and also the

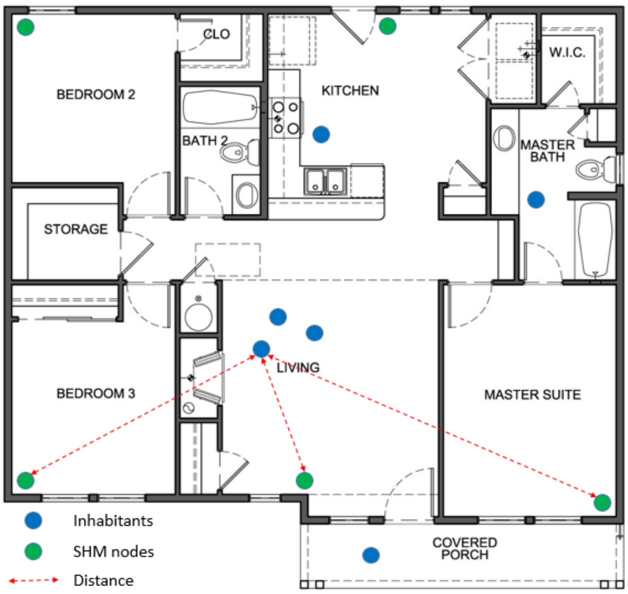

Figure 6 : Localizing inhabitants through high precision and real-time indoor localization.

possibility to measure the quantity of people, this localization system has many benefits with respect to occupancy sensors which are currently being used in building for controlling the lighting system. Based on the Figure 6, Bedroom 2 and Bedroom 3 are empty. Hence the temperature set points for these unused areas can be modified leading to lower energy load. In order to do so, SHM nodes send data to the servers and modify the IoT-based thermostats and lighting system. Thanks to the indoor localization, each area has its own dynamic set point for cooling/heating system. Moreover, different room and space types can have different control ideas based on their usage patterns which are obtained and updated in real-time.

2.2.2 Environmental data collection

Apart from the SHM nodes and thermostats and other possible energy meters which monitor environmental data, each wearable device measures near body temperature and humidity and heart rate and sends them to the servers through the SHM nodes. These data help to exploit dynamic and adaptive control strategies that not only consider the ambient temperature, but also human body temperature. Hence, this can provide higher level of comfort for people with respect to the static control ideas. Figure 7 shows the hardware during environmental data collection.

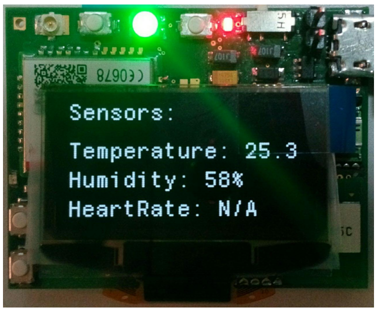

Figure 7 : Environmental data collection using the wearable device.

2.2.3 Collecting users' feedback

In order to increase the level of convenient, it is possible to collect feedback from people through the wearable devices and modify control strategies based on those feedbacks. Figure 8 illustrates two different situations while the system is collecting feedback of the user and adapt the system and control strategies accordingly.

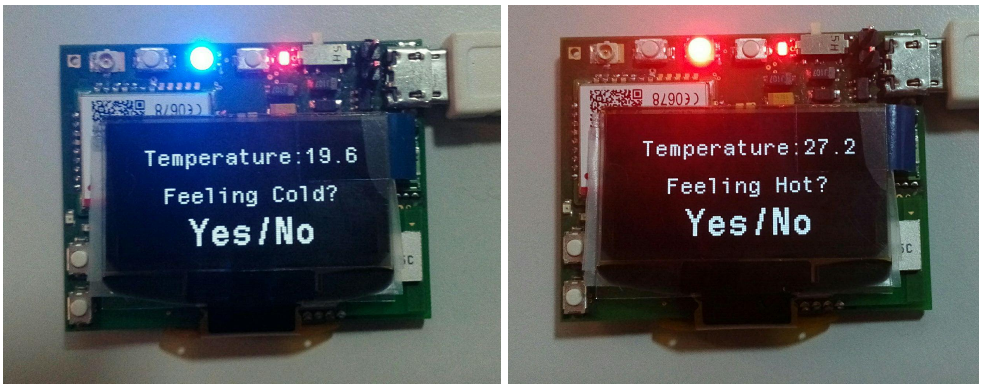

Figure 8 : Collecting users' feedback through the wearable nodes.

2.3 Control strategies

Table 3 shows a sample control strategy for the case shown in Figure 6. This table includes the space type, typical occupancy rate during 24 hours, and a sample static and dynamic control strategy for the heating system. Occupancy rate has been obtained by processing all previous localization data, while current occupancy shows the current localization data. In a dynamic and adaptive control system and based on the mentioned human-based factors, set points are being changed automatically in the time which will cause higher energy consumption efficiency with respect to the static control strategies.

Table 3 : Static and dynamic control strategy for a heating system for the case of Figure 6.

Space type	Occupancy	Current occupancy	Static set point	Dynamic set point
Living room	25% occupied	3 people	23°C	24°C
Master Suite	42% occupied	—	23°C	21°C
Kitchen	30% occupied	1 person	23°C	21°C
Bedroom 2	35% occupied	—	23°C	20°C
Bedroom 3	18% occupied	—	23°C	19°C
Master bath	4% occupied	1 person	23°C	23°C
Bath 2	6% occupied	—	23°C	19°C

3. CONCLUSIONS

The proposed system provides the inhabitants with higher level of convenient and higher building energy efficiency. The following objectives can be achieved through this system.

- Obtaining real-time feedback from people and adding new human-based parameters to the control states and decision variables of an energy consumption control unit.
- Adaptation of the energy consumption profiles based on the obtained data like distribution of people as a new state variable in order to increase the energy efficiency and also to improve people's level of comfort.
- Increasing the flexibility and functionality of the current solutions and presenting an intelligent system that can adapt itself to the energy state of the system in real-time.

By exploiting this system in residential and industrial buildings beside the current tools like IoT-based thermostats, occupancy sensors and son on, it is possible to achieve a higher efficiency in buildings and increase the comfort level of their habitants.

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