WESBES: A Wireless Embedded Sensor for Improving Human Comfort Metrics Using Temporospatially Correlated Data

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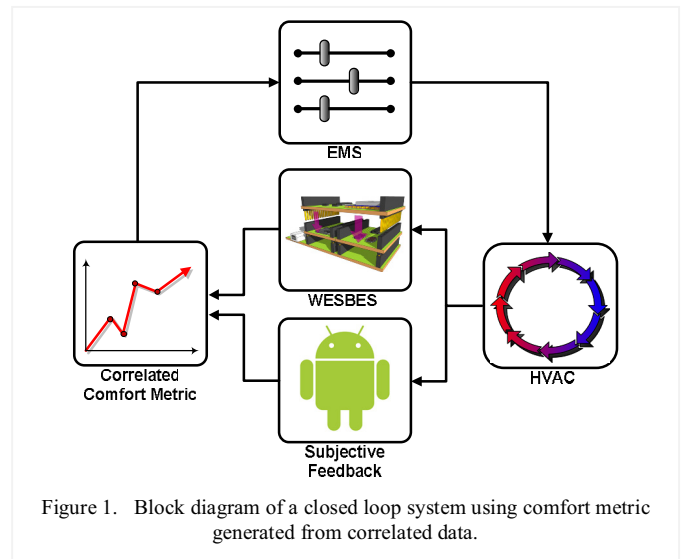Idaho Falls, Idaho, USA
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Abstract—**When utilized properly, energy management systems (EMS) can offer significant energy savings by optimizing the efficiency of heating, ventilation, and air-conditioning (HVAC) systems. However, difficulty often arises due to the constraints imposed by the need to maintain an acceptable level of comfort for a building's occupants. This challenge is compounded by the fact that human comfort is difficult to define in a measurable way. One way to address this problem is to provide a building manager with direct feedback from the building's users. Still, this data is relative in nature, making it difficult to determine the actions that need to be taken, and while some useful comfort correlations have been devised, such as ASHRAE's Predicted Mean Vote index, they are rules of thumb that do not connect individual feedback with direct, diverse feedback sensing. As they are a correlation, quantifying effects of climate, age of buildings and associated defects such as draftiness, are outside the realm of this correlation. Therefore, the contribution of this paper is the Wireless Embedded Smart Block for Environment Sensing (WESBES); an affordable wireless sensor platform that allows subjective human comfort data to be directly paired with temporospatially correlated objective sensor measurements for use in EMS. The described device offers a flexible research platform for analyzing the relationship between objective and subjective occupant feedback in order to formulate more meaningful measures of human comfort. It could also offer an affordable and expandable option for real world deployment in existing EMS.**

Keywords-EMS; HVAC; human comfort

I. Introduction

Due to the growing emphasis on energy efficiency for reducing the burden on powers systems infrastructure, as well as reducing the use of and dependence on fossil fuels, real world deployment of EMS for HVAC in commercial and government facilities is becoming commonplace [1] [2] [3]. The use of EMS allows building managers to adjust the operational parameters of HVAC systems based on the requirements and usage patterns of a specific facility. With over 50% of the total energy use in buildings used for HVAC and lighting [7], this can result in significant energy savings when done correctly. Still, the potential gains of using EMS are often not fully realized due to the lack of actionable data that can be clearly interpreted and utilized by system operators [4], and though EMS can still manage pretty well, good

Figure 1. Block diagram of a closed loop system using comfort metric generated from correlated data.

operation is dependent upon a good design, implementation and optimum equipment performance, as temperatures are often only measured in one place to control a variable air volume (VAV) that actually feeds several rooms. Failures are often unrecognized until total loss. Efforts have been made to characterize such failures as early as possible [12] [13], however, even these correlations lack the benefit of a "carpet bombing" of sensors to characterize individual spaces.

One of the primary difficulties in effective use of EMS stems from the fact that the optimization of the system's energy efficiency must be balanced with the constraints of maintaining a sufficient level of comfort for the building's occupants. This can be difficult due to the subjective nature of human comfort, which is difficult to measure in a meaningful fashion. As a result, methods for generating such measurements are still not well defined, and user comfort is often addressed using broad generalizations based on a priori knowledge from empirical studies that do not account for the unique characteristics of a specific facility or workforce, which may result in less than desirable conditions for the building's occupants. Furthermore, since this is an open loop approach, there is very little that the building manager can do to improve the level of comfort without actionable data. While efforts have been made to close the loop by supplying building
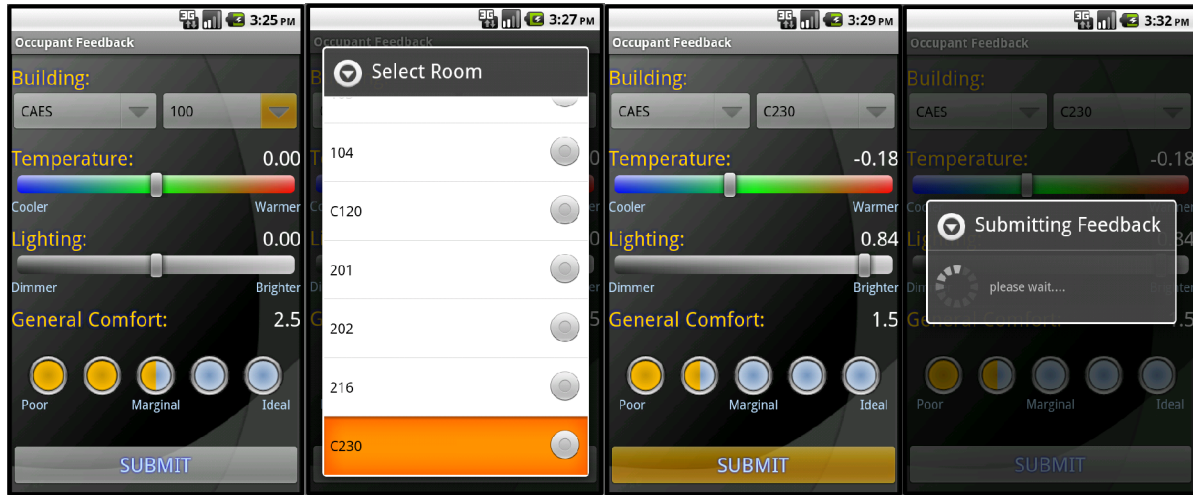
Figure 2. Occupant feedback app for the Android smartphone.

managers with user feedback, the data is highly subjective and relative in nature, making it difficult to determine an appropriate corrective action.

Clearly, there is a relevant need for additional temporospatially correlated data in order to maximize the efficiency of EMS for the control of HVAC systems. Not only is this data needed for providing a baseline for occupant comfort feedback, it is also useful for characterizing aspects of the environment that are not just due to the norms of the individual, but due to building issues such as high air flow, draftiness, etc. Therefore, the additional data would not only allow these aspects to be normalized out, but would also provide a characterization of the human feedback with respect to the building temperatures in order to make active corrections in the building performance measure. This measure would be a combination of all of the available forms of data, and would provide improved temporal-spatial awareness of the EMS ability to fulfill comfort expectations.

The contribution of this paper is the WESBES platform; a versatile sensor platform that can be used to overcome the challenges of providing meaningful metrics of human comfort by combining subjective occupant feedback with temporospatially correlated objective sensor measurements. The correlated data is obtained using a modular sensor platform that can be interfaced with a PC or smartphone. The data is then combined with subjective human comfort feedback submitted by the building's occupants and stored in a database where it can be retrieved and processed for use by the building manager. By placing the sensors in the user's workspace, the recorded data is directly correlated with the subjective feedback. This offers a reference point for the otherwise relative comfort data. The data can then be combined to generate a more meaningful and actionable metric of human comfort.

The paper is organized as follows. An overview of the use of human comfort data for EMS is given in Section II, and a smartphone app for collecting subjective feedback is described. A detailed description of the design and functionality of the proposed sensor platform is presented in Section III. Section IV contains a discussion of the system's benefits as a research platform, as well as the potential challenges and path forward for real world deployment. The paper closes with a short conclusion in Section V.

II. FEEDBACK FOR BUILDING MANAGERS

The primary role of an HVAC system is to maintain a safe and comfortable environment within an occupied space, and the role of an EMS is to optimize the performance and efficiency of the system within the associated constraints. Therefore, human comfort is the primary objective of the combined system, while efficiency is secondary. Still, most EMS systems only actively monitor objective sensor data in the

Figure 3. An HTML table displaying the submitted feedback data stored in the SQL database.

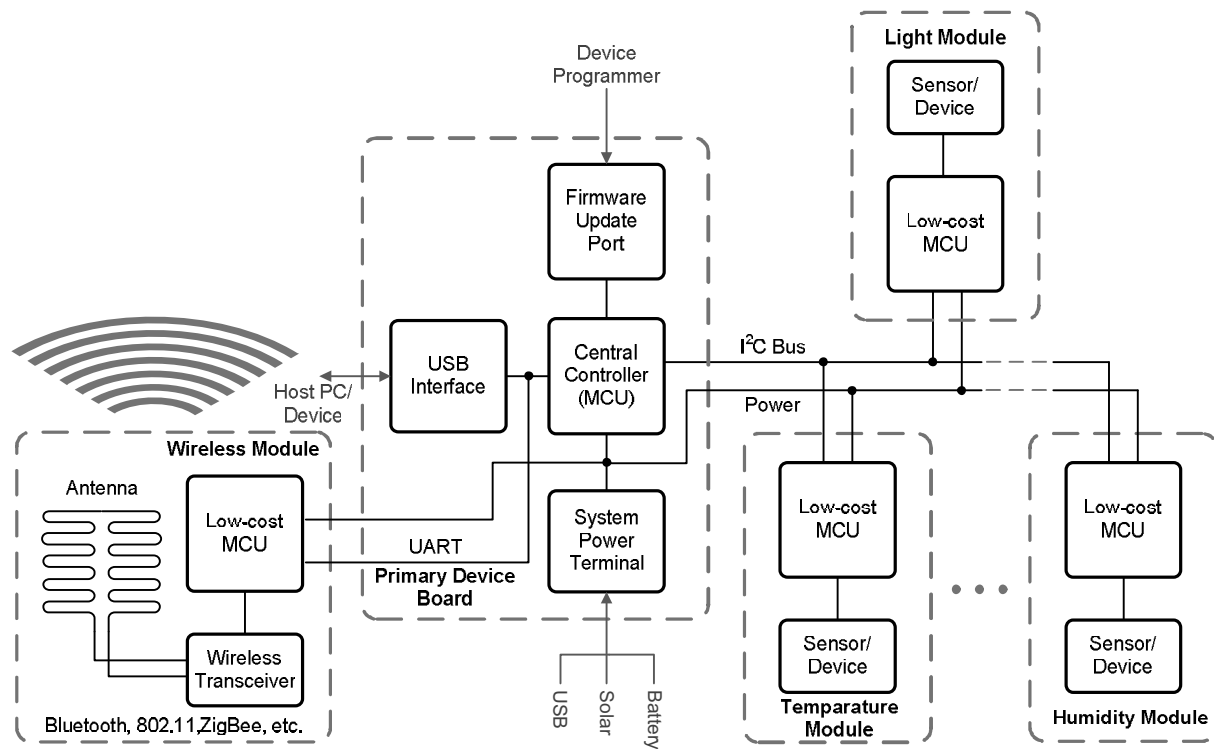loop. Human comfort is then addressed indirectly using

Figure 4. A block diagram showing the structure of the proposed WESBES sensor platform.

general assumptions and rules-of-thumb based on the collected data, rather than using direct feedback from the building's occupants [8] [9]. While some attempts have been made to directly address subjective human comfort in a closed-loop manner[5] [6] [10], the subject remains largely unexplored. This is primarily a result of the difficulties arising from the fact that human comfort is a highly subjective concept, and meaningful metrics are not easily defined. A building's occupants are generally only able to provide relative information about the level of comfort in a given space. For instance, one may be able to provide statements such as "the temperature is too cold," or "the light is too bright," but to put a meaningful, measurable number on these statements is much more difficult.

The proposed solution for generating more meaningful metrics of human comfort is to use correlated sensor measurements as a reference point for subjective user feedback. However, to do this effectively, the sensor measurements must offer an accurate representation of the conditions in the space from which the corresponding occupant report was submitted. Therefore, to provide the necessary spatially correlated data, a flexible, low-cost sensor platform is proposed that can be placed within the occupied space. The device is designed to interface with a JAVA based occupant feedback app for the Android smartphone, which was developed using the Android SDK [11]. User feedback is submitted from the Android phone as a form post. The sensor

board is polled automatically when a report is submitted, and the correlated data is included in the post. On the server side, the post is handled by a PHP script that writes the fields to a table in a SQL database. The data can then be retrieved and processed as needed, such as in Figure 3, where the data has been formatted in a HTML table that was generated automatically using PHP.

A detailed description of the proposed sensor platform is presented in the next section.

III. WESBES PLATFORM

The details of the WESBES design are presented in this section. An overview of the design is given first, followed by the details of the current working prototype. A block diagram of the system layout is shown in Figure 4 for reference.

As a research tool, it was desired that the proposed sensor platform offer as much flexibility as possible. To that end, a modular approach was taken with respect to the physical interface, allowing the system to be customized to the needs of a specific application without modifying the basic design of the hardware. The modular design allows various sensors to be added or removed as needed. This was done by designing the system such that all of the sensor modules could use the same header-pin interface with a common footprint and pin assignment.
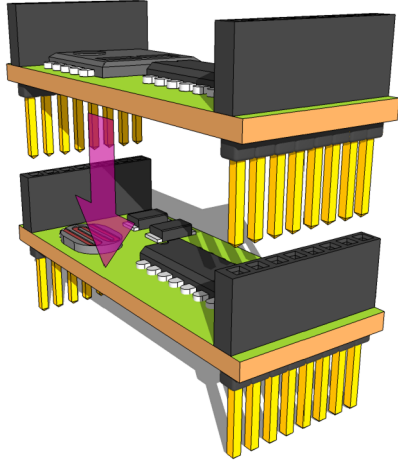
Figure 5.   Unique header-pin interface allows peripheral modules to be stacked vertically.

In order to allow for a common pin assignment to be used for all sensors, each module was given its own dedicated microcontroller (MCU) with an Inter-Integrated Circuit (I^2C) interface. The I2C interface was chosen both because it is widely supported in hardware, and because it allows multiple devices to interfaced over a single bus, which reduces the amount of software and number of pins required to connect with the central MCU. Therefore, all modules can be interfaced with the central MCU board using only four pins: an I2C clock line (SCL), an I2C data line (SDL), power, and ground. In this way, new sensors could be added to the system without the need to address unique device specifications since they can be handled by the module MCU instead.

In addition, the module MCUs can provide some preprocessing of the data from individual sensors, when necessary. Therefore, in order to offer greater flexibility, it was desired that each module would have the capability to be reprogrammed if needed. To do this, three additional pins were assigned to allow the module MCUs to be connected to a PC for software updates.

To reduce the footprint of the device, the physical interface for the sensors was designed to allow the sensor modules to be stacked vertically. This was done using vertically aligned header-pins and sockets that allow the modules to be connected one on top of another, as shown in Figure 5, similar to the way LEGO blocks are connected. Thus, various modules can be connected to the board in any arbitrary order, allowing the system to be quickly and easily reconfigured or expanded as necessary.

The 8-bit PIC12LF1822 device by Microchip was selected to serve as the onboard MCU for the sensor modules. The 12LF1822 was chosen for its low cost, small footprint and hardware I2C interface. The 12LF1822 is also a low power 3.3v device, which makes it ideal for battery powered systems. In addition, the 12LF1822 is supported by the Microchip ICD3 in-circuit debugger and programmer, as well as the Hi-Tech PICC C compiler. Therefore, the module software can be easily updated and debugged using the 3-pin interface of the ICD3.

A.   Wireless Interface

For added flexibility, the system was designed to be able to interface with a PC or smart phone wirelessly. In addition, it was desired that the system would be able to support multiple wireless protocols, depending on what was most appropriate for a specific application (Bluetooth, 802.11, ZigBee, etc.). Therefore, the systems was designed to allow wireless devices to be connected using the same interface as the sensor modules. As with the sensor modules, this allows the wireless communication protocol to easily customized, and even changed on the fly, by simply adding or replacing wireless modules. Therefore, two additional pins were added to the footprint of the header interface in order to allow for UART communication between the wireless modules and the central MCU. The UART serial protocol was chosen for the interface because it is a widely used standard, and is supported by nearly all wireless devices.

Although the system was designed to offer flexibility with respect to the choice of wireless protocol, it was primarily intended to act as a Bluetooth peripheral for the smart phone. The reason for this is that the Bluetooth protocol allows the a user's smartphone to be quickly paired with a specific sensor board. Therefore, when the user submits subjective feedback from their smartphone, in the form of a comfort report, the objective sensor data polled from the paired device is automatically correlated with the users location within the building, as well as the time at which the report was made.
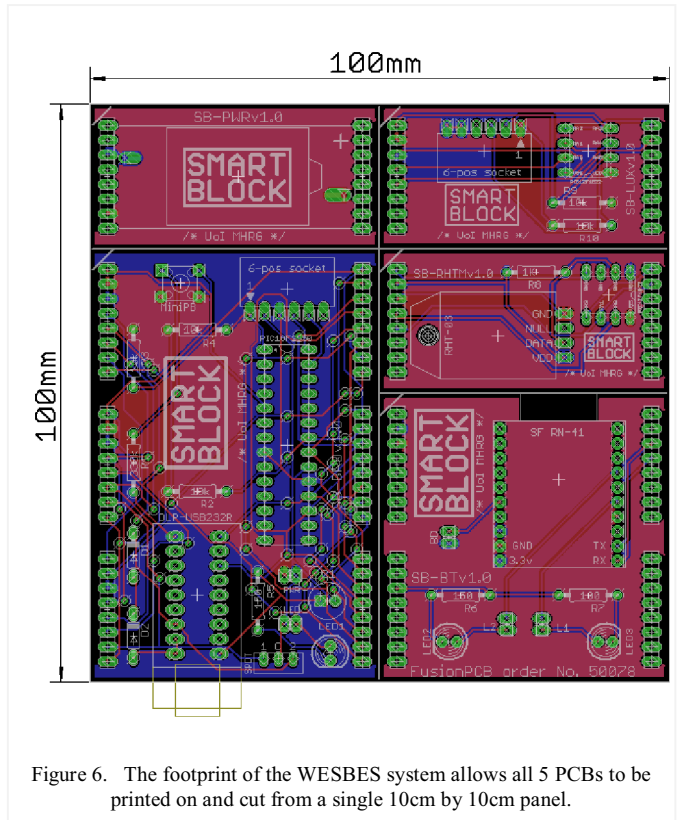

Figure 6.   The footprint of the WESBES system allows all 5 PCBs to be printed on and cut from a single 10cm by 10cm panel.

B. Central MCU board

The peripheral modules for the sensors and wireless communication are interfaced with a central MCU board that handles data processing and communication with the host device (PC/android). In addition to the central MCU, the board also holds a programming port for software updates, a USB-to-TTL interface for wired connection to a PC, and header sockets for three separate module stacks. The 8-bit PIC 18LF2550 was chosen as the central MCU. The device was chosen due to its low cost and power consumption, and because it supports hardware UART and I2C communication. In addition, the 18LF2550 is also compatible with the Microchip ICD3 in circuit debugger and programmer.

C. System Power

To conserve space on the central MCU board, the power source for the WESBES system is connected using the same interface as the peripheral modules. This also adds flexibility by making the power sources interchangeable, which offers a number of different options for customization, from standard batteries to photovoltaic cells. It also allows sources to be stacked in parallel for extended operation. Power from the source module is supplied to the central board via a dedicated header pin, which is routed back to the other modules through a power switch. The system may also be powered the USB interface when connected directly to a PC.

D. Working Prototype

A bread boarded prototype of the sensor platform has been built, and the operation of the design has been verified using wireless and USB communication with both the PC and Android interfaces. The wireless communication for the prototype was implemented in Bluetooth using the Roving Networks RN-41 Bluetooth module. The prototype currently supports two sensor modules that provide measurements for temperature, relative humidity, and ambient light intensity. Temperature and relative humidity are measured using the Maxdetect RHT03 digital sensor. Light intensity measurements are taken using the TAOS TSL2560 digital light sensor. The data values from the light module are preprocessed by the PIC 12LF1822, and converted to units of LUX.

Printed circuit boards (PCB) designs based on the breadboard prototype have been drawn in CADsoft Eagle, and are currently in the process of production. The PCB for the central MCU board was designed to give the WESBES prototype a combined footprint of 50mm by 75mm, allowing all 5 of the system's PCBs to fit exactly within a square area of 10cm by 10cm, as shown in Figure 6, which reduces the cost of printing by allowing the entire system to be printed on a single panel with no wasted board space.

Once the PCBs are received, the prototype sensor boards will be assembled for use in a research testbed facility, and the process of collecting data will begin.

IV. CONCLUSION

In this paper, a sensor platform was proposed for the purpose of generating more meaningful metrics of human comfort for use in HVAC EMS. The sensor platform is used to offer a reference point for subjective feedback submitted by a building's occupants. The system is designed around a flexible modular platform that allows it to be easily customized, reconfigured or expanded as needed. A prototype design for the system has been constructed and verified, and PCBs for the design are currently in production.

The work presented in this paper simply provides a user nonintrusive, versatile platform for collecting correlated data to supplement user feedback reports. The next steps for the project will involve incorporating that data into the generation of meaningful human comfort metrics. The short term goal for the sensor platform is to generate a dataset of user feedback reports and correlated sensor measurements that can be used to formulate algorithms for providing meaningful and actionable metrics of human comfort. The longer term goal is to develop and validate the algorithms for use in real world EMS for HVAC systems.

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