Embedded Building Components

Prototyping with Emerging Technologies

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This paper discusses research into embedded building assemblies with a focus on distributed sensing, real-time building envelope monitoring, and smart material integration. It looks into extending the concept of the Internet of Things from devices and appliances housed within a building to assemblies and a structure itself. The paper presents a number of embedded research prototypes that address thermal and moisture monitoring as well as introduce capacitive sensing as an opportunity for user monitoring and engagement. Finally, the paper points to opportunities for further extending sensing and actuating capabilities of a building envelope by combining them with embedded materials as a form of user interface.

Keywords: Embedded Systems, Distributed Sensing, Smart Buildings, Internet of Things, Prototyping

INTRODUCTION

As interconnected devices and autonomous agents continue augmenting daily lives through virtual networks and new communication modes, the built environment remains relatively isolated from the pace and the intensity of technological progress associated with the third and fourth industrial revolutions. The built environment is still heavily invested in the mind-set of industrialization with mechanical mindset without the added benefits of informational technologies and modern sciences. While there is certainly an increase in adoption of various smart technologies in buildings and cities (Achten 2015), there is a lack of more comprehensive rethinking of what buildings should and could be-rethinking of systems, materiality, and conceptual frameworks. On the business side, authors like Klaus Schwab (2017) point that the fourth industrial revolution-characterized by the amplification of the technological progress by fusing the physical, digital, and biological worlds-is a disruption that will affect all aspects of our lives. This fusion of disciplines [1] and existential realms (physical, virtual, biological, or human-made) is perhaps the main characterization of the future built environment. With the memorable statement that it is not a matter of “if” but rather “when” and “in what form” this change will come, Schwab assures readers that “The question is not am I going to be disrupted but when is the disruption coming, what form will it take and how will it affect me and my organisation?”

While these words do represent a futuristic mindset, they also reflect the current state of affairs in many disciplines. If correct, this statement signals significant incoming changes to the way buildings
are made and used. Building automation is an example of what is often referred to as the framework behind intelligent buildings. However, it is currently limited to controlling already mechanized and electronic devices such as cooling and heating systems, without broader implementation of embedded technologies (sensors and actuators) into building components and assemblies. This may be partially a result of the fact that building automation systems (BAS) and building management systems (BMS) are developed by companies that manufacture building system components and their controls (HVAC or air handling units), not by construction companies or building component fabricators. BASs/BMSs facilitate an improved performance of installed equipment and provide feedback to the manufacturer, not necessarily helping the building to approach it more comprehensively. What is needed in the next wave of transformation of the building industry and buildings themselves—the fourth industrial (construction) revolution—is to develop technologies that integrate and take advantage of the embedded systems within building assemblies as well as a biological paradigm. Windows, doors, floors, and wall panels all could and should function as part of the building digital interface, sensing user and environmental inputs as well as actuating desired spatial outcomes.

**FUTURE DIRECTIONS**

There is a strong interest in designing materials with novel properties and behaviors (Addington and Schodek 2005); (Furuya and Shimada 1990). Many of these materials will be made of hybrid structures incorporating what are commonly considered “smart” materials and embedded electronics. For the purpose of this discussion, a separation is made between nonelectronic and electronic smart materials. Many sensors and actuators are considered smart materials, since their properties can be controlled and changed by outside stimuli, such as force, temperature, moisture, light, and electric or magnetic fields.

The distinction made here considers nonelectronic smart materials as quasi-equivalent to embedded systems on the level of operational logic, meaning that smart materials are capable of performing computationally equivalent actions—resolving simple logical statements. However, the addition of electronic capabilities into materials allows for outside communication with other distant physical objects or materials and for access to a database. This larger connection can lead to new material properties typical for electronic networks, such as awareness and anticipation, driven either by concurrent events happening within a building assembly or by accumulated knowledge residing in the database and crystalized through machine learning and statistical methods. These new material properties, associated with embedded (smart) materials, would further transform the idea of materiality, particularly when the integration of computational capabilities becomes fully distributed and indigenous to base materiality, as it often is in smart materials.

Another important development and distinction coming from embedded material systems is that their “smartness” to a significant degree resides outside their own physicality and depends on external knowledge systems. This is particularly true for properties such as awareness and anticipation, which benefit greatly from outside connectivity. This significantly shifts the concept of physicality from “here and now” to a broader chronological and spatial framework.
This paper presents research focused on the embedded systems driven by electronic logic with a high level of integration with an actual base material. The goal of these systems is to be distributed, autonomous, and self-reliant-like any physical material—yet fully interconnected within broader networked systems such as the Internet of Things (IoT). Ideally, the sensor and actuator integration would be scale independent, so that a part of the embedded assembly (subset) would display the same set of behaviors and functionalities as the assembly itself.

**SENSING AS INTERFACING**

Distributed sensor and actuator systems provide an opportunity for data collection that can be used for building management, performance analysis, and real-time interconnection with other devices and appliances. Many of the sensors that are deployed in monitoring buildings and tracking users could also function as a form of user interface (UI). This dual approach not only allows for buildings to respond to human activities but also provides opportunities for users to interact with them intentionally. While this seems like a relatively straightforward idea, there are different types of sensors and sensor arrangements used for both ways of interacting. Humans interact with their hands and bodies through touch and gestures (Kinect) as well as through voice commands (Amazon Alexa). Sensors that simply track motion, such as passive infrared (PIR) or microwave radar, would not work effectively as interaction devices, since they have binary inputs: on or off. Hand, gesture or voice recognition can provide a large diversity of feeds and possibilities. Similarly, touch sensors are used to provide user feedback, as is the case with touch screen devices that use capacitive sensing. Even though many of the implementations of touch interface have binary inputs, they can be easily used in multiple button or keyboard scenarios.

The Hidden Touch Interface project (Figure 1) looked into an integration of capacitive sensors into various building materials, both as an explicit interactive element and as a hidden functionality. Philosophically, the project was looking at both conscious and unconscious computer-human interaction, and ways both could be used and interconnect. Touch is a type of interaction that can be intentional (conscious) as well as unintentional (unconscious). People step on objects as part of walking or climbing, not paying attention to where and how; they also use the foot as a pedal for precise actuation. Similarly, we use hands and other body parts to accomplish tasks and also as output devices. Capacitive and pressure sensors are good examples of sensing technologies that could service both types of interactions. They provide a gradient of input values and can be visually present or hidden.

The Hidden Touch Interface prototype utilized an MPR121 capacitive sensor controller module driven by an I2C interface on ESP8266 (Figure 2). The chip can control multiple individual electrodes. Electrodes and connecting wires have a certain amount of inherent capacitance that is balanced against user-induced capacitance. Since the sensor electrode and user’s body (human flesh has a relatively high dielectric constant) form a capacitor, the overall capacitance is increased and can be measured by the microcontroller. The convenient part of this system is that electrodes can be (1) nonmetallic as long as they are electrically conductive, (2) connected with only a single wire, (3) concealed under any nonmetallic materials, (4) used to detect objects centimeters away, and (5) inexpensive. This allowed the Hidden Touch Interface project to test a wide range of building materials, from wood and ceramic/stone tiles to acrylic, glass, and mirror (Figure 3). Depending on the types of resistors used, direct touch or just proximity could be implemented in both on-surface and under-the-surface arrangements.
BUILDING INTERFACE OPPORTUNITIES
The introduction of capacitive sensing into construction assemblies allows for greater integration of building materiality and enhanced user interaction without making technology visually explicit or dominant. It extends the user interface (UI) qualities present in everyday objects into the building itself and opens new possibilities for architecture and the ways users interact with it. This presents an important aspect of new embedded architectural systems, with potential for designers to use various building materials and assemblies not only for sensing and actuation but also as controls and UI. Since these controls can be seamlessly integrated into the materiality of architecture, they can function in less explicit ways and on an as-needed basis, leading to further virtualization of materiality in architecture.

The design benefits of using capacitive sensing in building assemblies come from the ability to integrate sensor pads within the base material: hiding electrodes and allowing finish materials to maintain their uninterrupted visual presence as well as protecting sensors and electrodes from the impact of an outside environment. The depth of encapsulation and the effect on capacitance can be controlled by the size of the capacitive surface.

Capacitive sensors can be made from a variety of different media, such as copper, aluminum, indium tin oxide (ITO), or printed conductive inks. Metallic capacitive sensors can be implemented on surfaces of solid and flexible materials, extending the range of possible design applications. Capacitive sensing works effectively through various nonconductive materials, even relatively thick ones, that do not ground the charge present when an object or a person interacts with sensor pads. ITO-based electrode pads allow the capacitive sensor to be up to 90% transparent, providing yet another important design opportunity. This approach is commonly implemented in touch screens. However, the same technology could be integrated into building assemblies using ITO-coated glass and films to provide extended sensing opportunities as well as using electrically conductive properties of ITO to support various actuation needs. A common example could be combining capacitive-sensing UI with digital displays or illumination. Integration of multiple functionalities into a conductive capacitive surface would require a careful study of the electrode sizes and spacing to maintain the optimal sensor performance. Since indium is a rare metal, which most likely would prevent its large-scale application in the building industry, there is a line of research that looks at replacing it with other materials while maintaining conductive properties.

SENSING WALL
The Sensing Wall project (Figure 4) aimed to create a sensing building skin for real-time performance monitoring. The first prototype focused on thermal sensing using an array of thermistors on 10 cm by 10 cm (approx. 4 inch by 4 inch) grid.

TECHNOLOGY DISCUSSION
The ESP8266 chipset comes with a single analog pin (port). Since the Sensing Wall project requires a significant number of analog inputs—the ability to measure continuous changes in input voltage-thermistor multiplexing was required. Similar to LED displays (actuators), multiplexing of multiple sensors allows for reading individual analog values of a larger thermistor array. Multiplexing comes at the cost of time,
since each sensor reading is performed separately. With a larger array of sensors, this may add up to a longer period of time, particularly when considering multiple samplings for each reading to average them for higher precision. However, in the case of sensing a building wall, where the temperate change is relatively infrequent and gradual, the reduced refresh rate associated with multiplexing is acceptable.

The prototype discussed in this paper provided a real-time refresh rate with all 16 sensor readings performed within approximately 2 seconds, which included 10 samplings for each sensor every 10 milliseconds, averaging them and the executing HTTP connection to the server with MySQL database submission. Database data was displayed real-time via web interface (Figure 5).

The multiplexing was achieved with a single 74HC4051 8-channel chip. While the prototype panel deployed only 16 thermistors (sensors), the ESP8266 and 74HC4051 setup could be scaled up to 40 with full use of digital pins and up to 32 (one digital pin less) in cases when the chip hibernation would be desirable. These values could be scaled significantly using a 16-channel multiplexer and a demultiplexer. However, the intention of this approach is to provide embedded and highly localized solutions that would serve relatively few sensors and actuators but at the same time would be deployed in large numbers. In this scenario, each piece of gypsum wallboard or plywood sheathing could be embedded with multiple separate logical units.

Other considerations include the quality of soldered connections; the distance between distributed sensors, with their susceptibility to noise (electrical interference); and the need to calibrate the panels, since the electrical resistance of long connecting leads can add to the sensor reading. However, the electrical resistance of the system can be easily established and adjusted for.

Finally, to address energy consumption and conservation, chip hibernation (sleep cycle) was implemented. During the wake state, the assembly used on average 30-40 mA, with peaks around 300mA for WiFi communication as compared with the sleep state of 0.1 mA. The recovered sleep mode values were higher than those provided by the manufacturer datasheet [2] (10 µA for deep-sleep), so there is a possibility of further lowering this value. Energy consumption is an especially important consideration in large-scale sensing wall implementations, so proper fine-tuning would be required. The prototype used the generally available ESP8266 microcontroller, with
features that were not utilized. In an actual implementation, the microcontroller would be designed for the specific function without LED indicators (5 mA drain) and fine-tuned power regulators.

APPLICATION AND INSTALLATION CONCERNS

While the initial prototyping of Sensing Walls worked effectively as a distributed sensory assembly, the actual fabrication technology relied on embedding sensors physically into sheathing (in this case medium-density fibreboard (MDF)). To increase the adaptability of this approach and potentially also the range of applications, alternative installation methods were tested by embedding thermistors into building wrapping membrane and using copper tape as a conductive trace (Figure 6). This approach (Sensing Wall 2) provided the same performance as Sensing Wall 1, and it could have been installed in a broader range of conditions, including renovation projects (not a new construction), with no need to replace or modify sheathing. The issue of fragmentation and scaling down the system could be addressed by developing smaller sensing zones, with each zone functioning as a self-contained and autonomous system. This would allow for the embedded building wrapping membrane to be treated and installed in a similar way as conventional systems such as Tyvek. Any damage to an individual zone associated with cutting the membrane would be alleviated by the installation practice of overlapping membranes on the seams and sealing them with aluminum or copper tape. Currently, building membranes are sealed with synthetic tape. The membrane overlap would provide continuous or occasionally doubled sensor coverage. The use of the metallic tape would provide an opportunity to power individual zones. If the exposed electrically charged (3.3-5V DC) aluminum tape were to be a problem—a possibility of a galvanic action or shorting a circuit—a second layer of a protective nonconductive tape could be installed over the conductive tape.

INTEGRATING MULTIPLE SYSTEMS

The second prototype (Sensing Wall 2) provided opportunities for doubling the functionality of the sensing membrane beyond temperature monitoring and led to the development of the third prototype: Sensing Wall 3. Sensing Wall 3 (Figure 7) departed from the approach used in the previous two prototypes, measuring thermal conductivity, and focused on measuring moisture penetration of the membrane itself—a common concern for outside building envelopes. The conductive leads, similar to the copper stripes used in the second prototype, were used in combination with various building papers to measure the electrical conductivity of moist building paper. This approach was based on the fact that the amount of moisture in building paper or felt-like substrates impacts their electrical conductivity, which can be measured with microcontrollers such as ESP8266. By developing initially imbedded conductive threads and measuring conductivity between them, a coordinate system could be implemented to track moisture and water penetration within a wall. Two approaches were tested: one- and two-directional grids with leads going in one
or two directions (Figure 8). Since the water tends to travel vertically within the building envelope, driven by gravity, systems using single-direction conductive threads could be implemented in a vertical direction.

Initially inspired by the use of copper tape leads in the second prototype as a way to double up on wiring infrastructure and provide multiple sensing capabilities, Sensing Wall 3 looked at a number of other technologies to embed conductive leads within building wrapping surfaces. Three-dimensional (3D) printing with conductive graphite polylactic acid/polylactide (PLA) filament (Figure 9) originally seemed a natural extension of fabrication technologies that could help to accommodate other electronic parts (serve as joinery), eliminate resistors, and provide electrically conductive wiring. Since PLA is bioactive thermoplastic aliphatic polyester derived from renewable resources, such as cornstarch, it provides opportunities for the use in building assemblies of carbon-neutral and recycled materials [3], lowering the energy footprint and extending the life cycle. It is also semiflexible, which makes it a good candidate for building surface applications.

The tests showed high resistance between connections, which started to impact the reliability of the entire electronic assembly. A number of connection strategies using electronic parts and copper wiring, with 3D printed components were studied. The goal was to, validate the easiness of the integration of electronics and related components with the wrapping building paper. These tests were successful in achieving basic conductivity, but again the issues with electrical resistance were significant.

While the electrical resistance could be controlled through the thickness of printed layers, a broader intent was to reduce the visibility and amount of electrical connections. Another concern is its biodegradability as bioactive thermoplastic.

Finally, the conductive PLA filament has lower level of adhesion to a paper or membrane substrate, which can be overcome by providing a regular PLA base, easily achievable with dual-extruder 3D printers. This filament is also not designed for higher temperatures, as it should be used at temperatures below 50°C. While 3D printing was not used for the final prototype, this was due to the types of available materials, not to any limitation inherent to the technology itself.

CURRENT LIMITATIONS
The ideas discussed in this paper port technologies used in everyday electronics into a broader realm of the built environment. While this is a natural way to extend applications for these technologies, there are many limitations that impact quick adoption of these technologies. The concern about increased energy use, while trying to save energy, is partially addressed above when discussing microcontroller hibernation and sleep mode. Another connected issue is energy harvesting and storage locally within a building or even a wall assembly. There is a significant amount of research in this area and emerging commercial products, such as glass embedded photovoltaic cells of solar roof tiles.

Another concern about embedded systems is that they introduce an extremely large number of
electronics to a building envelope that would impact the price and technical skill required to install them. The examples discussed above rely heavily on factory-produced systems that should be easy to install and power, with the provision of electrical power as the primary installation focus. The cost of electronics, including sensors, can be significantly reduced by scaling up this approach into mass production, with the exception of technologies that rely heavily on rare chemical elements. However, the issue of rare materials would need to be resolved prior to a broader introduction of embedded technologies into buildings and construction. Furthermore, the introduction of embedded (electronic) systems into wall assemblies reflects similar developments in used with various devices, appliances, and technologies in buildings, such as LED light bulbs or motion-triggered lights.

The prototypes presented here used commonly used and easily available materials, such as ceramic-based thermistors, silicon diodes, and aluminum tape. Therefore, there are no rare-material limitations on scaling up these approaches. The microcontroller is not part of this list but generally is inexpensive to manufacture using commonly available materials.

CONCLUSIONS
This paper discusses strategies to facilitate IoT implementations within buildings and building assemblies. It specifically looks into emerging research in embedded technologies that combine distributed sensors, building performance monitoring, and user interactions. The inclusion of mechanical and electrical systems within a building, and more recently embedded electronic intelligence connecting automated controls with network sets and environmental real-time monitoring, is changing this passive approach to an active and dynamic framework.

In these scenarios—reminiscent of parallel developments characterized by the fourth industrial revolution—building performance goes beyond measuring physical values of solar gains or heat losses, and includes a possibly deeper understanding of user behaviors, individual comfort levels, and material assemblies. It provides users with the ability to interact with a building and also allows buildings to facilitate occupant activities and guide their mobility (Schwartz 2013). Specifically, adding a human factor into building performance considerations, both as actors and reactors, gives an opportunity for developing a greater fit between users and buildings.

ACKNOWLEDGEMENTS
The following projects are the research contributions from NJIT students:

1. Sensing Wall projects developed by Jorge Cruz (Figures 4, 6, 7 and 9).
2. Hidden Touch Interface project developed by Jorge Cruz and Anthony Samaha (Figures 1 and 3).

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