Integration of Embedded Systems into Building Assemblies

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This paper discusses strategies to facilitate Internet of Things (IoT) implementations within buildings and building assemblies. It looks into emerging concepts of adaptable buildings from the perspective of the inner operational logic and required functionalities such as plug-and-play (PnP) architecture to orchestrate larger intelligent systems for architectural applications. The paper discusses the use of the ESP8266 microcontroller (also known as NodeMCU) asone of the current approaches forIoT systems, particularly in the do-it-yourself (DIY) movement. Presented case studies adopt the ESP8266framework based on machine-to-machine (M2M) communication protocols as apotential solution for embedded building systems.

INTRODUCTION

[The adaptive building components such as transformative envelopes (façade elements) or movable partitions accommodating multifunctional spatial uses have been in use in architecture for a long time. Façade elements such as sunscreens, window shutters, or removable window sashes helped to adapt to climatic and seasonal changes by improving building use and performance. Movable partition walls and screens helped to address changing functional needs and adapt spatial requirements to user activities. While these elements were dynamic in nature—opening and closing shutters or louvers—architects usually refer to them as passive environmental techniques for managing building performance, because of the manual nature of their operations. Similarly, the spatial reconfigurations were performed as human-operated and preplanned activities that considered a functional intent rather than an actual measured of user activities and needs. The inclusion of mechanical and electrical systems within a building, and more recently embedded electronic intelligence that connects automated control systems with networked data sets and environmental sensing, changed this passive approach to an active and dynamic framework. Elements like shutters and sun louvers adjust continuously and in real time to external environmental conditions in the attempt to optimize indoor climate based on preprogrammed algorithms. Building access controls, such as doors and elevators, monitor user patterns and the utilization of various indoor spaces. They respond to user feedback, implicit and explicit, by registering activities, or the lack thereof, and enabling occupant-initiated overrides to balance global (algorithm-driven) control goals against individual user needs.

In these scenarios, building performance goes beyond measuring physical values of solar gains or heat losses, and includes a possibly deeper understanding of user behaviors and individual comfort levels. It could lead to designs where building itself is a facilitator of user interactions (Schwartz, 2014). This expanded approach considers a building as an enclosed habitat with full-spectrum analyses of factors, including behavioral factors, that shape human activities. Specifically, adding a human factor into building performance considerations gives a promise of developing a greater fit between users and buildings. This optimization could be achieved through close real-time monitoring of user activities within built environments.

With the introduction of building environmental control systems, the automation started to control temperature, air quality, and lighting levels. These automated controls not only provided increased comfort for living but also translated into more energy-efficient and environmentally friendly buildings (Guillemin, 2001). However, automated controls were often structured around a central control dashboard system with a limited number of sensing points delivering the same solution to a broad number of space conditions.The need for more deliberate and fine-tuned approach to building controls that goes beyond the size of a single room into the scale of individual building components is needed.

While buildings and cities are increasingly filled with smart objects and devices that monitor traffic, track inventories, or respond to occupants, building assemblies themselves do not demonstrate a similar level of interactivity and autonomy (Achten, 2015). There is an opportunity to extend these smart and interconnected device networks into the very matter of buildings and their assemblies.

This paper discusses and demonstrates an integration of embedded electronic systems utilizing distributed sensors and localized actuators to increase the adaptability and environmental performance of a building envelope. It reviews state-of-the-art technologies utilized in other fields that could be adopted into smart building designs. In the case studies discussed here, sensors are embedded in construction assemblies provide a greater resolution of gathered data with a finer degree of actuation.

These case studies adopt the Internet of Things (IoT) framework based on machine-to-machine (M2M) communication protocols as a potential solution for embedded building systems.

BUILDING AUTOMATION

Building automation is a centralized and automatic control of lighting, heating, and cooling, as well as other systems including security, fire, and occupant safety, through a building automation system (BAS) or building management system (BMS). The goals of a BAS are improved efficient operation of building systems, including reduction in energy use and operating costs, as well as increased occupant comfort and the life cycle of the building. Recently constructed buildings include some sort of BAS/BMS, and many older buildings have been retrofitted with these systems. BASs/BMSs include software and hardware architecture that integrates controls for all or most building systems within one dashboard (interface). They are offered by many established companies, such as Siemens, Honeywell, and Cisco, thatalready manufacture various building environmental system equipment. While these systems are effective and deliver significant cost savings (~20%) as compared to non-BAS/BMS buildings (Siemens, p.10)[1], they include various levels of autonomy and intelligence. In many cases, they respond to matrix-oriented algorithms without understanding the real-time considerations of building occupants or building assembly conditions. Furthermore, BASs/BMSs are usually implemented in non-residential buildings where a single owner or interested party is in control of centralized building systems.

While building automation is an example of the smart environment approach and is often referred to as the framework behind intelligent buildings, it currently limits itself to controlling already mechanized and electric/electronic devices such as heating and cooling systems, without necessary broader implementation of embedding sensors and actuators into building components and assemblies. It is partially because BASs/BMSs 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. They facilitate an improved performance of installed equipment not necessary of the building itself. What is needed in the next wave of transformation of the building industry and buildings themselves, and is advocated in this paper, is to develop technologies that integrate and take advantage of the embedded systems within building assemblies. 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.

ADAPTATION OF INTERNET OF THINGS FOR BUILDING ASSEMBLIES

Smart and connected devices are objects embedded with microcontrollers, sensors, and actuators, with connectivity that allows data exchanges between the product and its environment, user, manufacturer, and other products and systems. They allow for enhanced interactions with people and other objects, utilizing radio-frequency identification (RFID) tags or wireless networks. Connectivity enables certain capabilities of the product to exist outside its physical form as part of a larger data set (cloud). Collected data can be analyzed to inform decision-making and enable operational efficiencies of the product and the entire system. As envisioned by Mark Weiser in his Scientific American article titled "The Computer for the Twenty-First Century"(1991), "When almost every object either contains a computer or can have a tab attached to it, obtaining information will be trivial." BAS/BMS platforms discussed earlier are often beneficiaries of these collected data points—tabs attached to physical objects. The IoT is the network of smart objects with embedded technologies able to communicate, sense, and interact with the outside environment (Kortuem et al., 2010). However, this network of smart and interconnected devices provides opportunities for greater interoperability and resiliency of the entire system, with data coming from and access to individual subcomponents—devices and objects—as compared to BASs/BMSs.

In addition to sensing and actuation, smart systems incorporate decision-making abilities, utilizing previously gathered data in a predictive or adaptive manner thatoften employs machine learning algorithms. In these cases, the "smartness" of the system is attributed to autonomous operation meeting its performance and user satisfaction expectations. While current BAS/BMS platforms follow an established (pre-programmed) set of rules, the expectation is that the underlying reasoning (algorithm) for smart systems would adapt over time based on environmental and user feedback.

SMART OBJECTS AND ENVIRONMENTS

While smart objects can function autonomously and perform complex performance optimizations or user tracking, they do not necessarily need to exhibit intelligence in the sense of artificial intelligence (AI). As such, the term "smart objects" is a rather inclusive category of object types, from those that perform basic building automation, such as traditional sensor-based thermostats (even mechanical) or automated louver systems, to sophisticated and predictive devices such as the Nest thermostat utilizing machine learning algorithms.

Independently of their level of autonomy and "smartness," smart objects commonly exhibit the following three typologies or design dimensions:

- Awareness is a smart object's ability to understand (that is, sense, interpret, and react to) events and human activities occurring in the physical world.
- Representation refers to a smart object's application and programming model—in particular, programming abstractions.
- Interaction denotes the object's ability to converse with the user in terms of input, output, control, and feedback (Kortuem et al., 2010, p.31).

While these typologies are rather general, Das and Cook (2005) define smart environment with more nuance as having the following features:

1. Remote Control of Devices: the ability to control devices remotely or automatically.
2. Device Communication: the ability of devices to communicate with each other, share data, and retrieve information from outside sources over the Internet or wireless communication infrastructure.

3. Sensory Information Acquisition/Dissemination:the ability of sensors to share information and make low-level decisions.
4. Enhanced Services by Intelligent Devices: includes context and location awareness.
5. Predictive and Decision-Making Capabilities: full automation and adaptation that rely on the machine learning, or acquiring information that allows the software to improve its performance.

INTERNET OF THINGS IMPLEMENTATIONS

The ESP8266 chip-based architecture(also known as NodeMCU) is one of the recent approaches to IoT, particularly in the do-it-yourself (DIY). Developed by Shanghai-based Chinese manufacturer Espressif Systems it combines functionalities of the microcontroller and Wi-Fi communication module (2.4 GHz, 802.11 b/g/n, supporting WPA/WPA2) in a simple system-on-a-chip (SoC) design. ESP8266 is a highly integrated SoC solution with 16 general-purpose input/output (GPIO) pins, analog-to-digital conversion (10-bit ADC), Inter-Integrated Circuit (I^2C), Serial Peripheral Interface (SPI), I^2S interfaces with DMA (sharing pins with GPIO), UART (on dedicated pins, plus a transmit-only UART that can be enabled on GPIO2), and pulse-width modulation (PWM). It is running at 80 MHz (or overclocked to 160 MHz). Most recent ESP-12F modules are FCC (USA) and CE (EU) approved.

ESP8266 was originally developed as a low-cost Wi-Fi add-on for Arduino boards. However, with the release of the software development kit (SDK) in October 2014, the chip could be directly programmed and no longer required a separate microcontroller such as Arduino (Benchoff 2014). ESP8266 can be implemented in a number of programming environments (open-source SDKs), such as NodeMCU[2], a Lua-based firmware, or MicroPython, an implementation of Python for embedded devices, and it similarly could be integrated with sensor and actuators. For those using the Arduino platform, the ESP8266 chip allows for a convenient migration path to IoT architecture that provides highly reliable Wi-Fi support that can be arranged in various network configurations, including mesh networks. As compared to Arduino Uno V3 with Ethernet shield (not Wi-Fi) in the installations and prototypes discussed later in this paper, ESP8266 proved to be significantly more reliable, particularly during the high network demand and time-out situations. ESP8266 was able to recover faster and more easily from any communication errors without hanging up. This does not reflect on the hardware itself, but rather on the overall hardware–software implementation and available libraries.

As a very capable processor and communication module ESP8266 is an intentionally highly compact design with only a single analog input. While this may be a limitation with some sensor implementations it can be resolved with an additional Analog to Digital Converter (ADC) or an analog multiplexer add-on shield. However, in most applications there is no need to up-size the original ESP8266 module since most IoT implementation use compact, single-functionality modules that address a singular sensing or actuation functionality such as the monitoring of temperature and moisture or an actuation of individual relays, motors, or lights.

PLUG-AND-PLAY BUILDING ASSEMBLIES

An important feature of future smart buildings and embedded building assemblies is a plug-and-play (PnP) capability of construction components. The same functionalities that we have come to expect from computers or electronic devices, and their ability to interface with other objects without a need for significant user involvement, could and should be applied to building components and design. A building component's ability to be connected and integrated into the overall framework of a smart building will be critical in improving the construction efficiency and in dealing with the increasing complex technology implementations. A window, or any other building component, should be able to recognize its place (localize itself); it should also recognize its role within the overall building as well as its performance and users' expectations toward it. It should also be aware of surround components and be able to cooperate with them. While this could be achieved with centralized BAS/BMS discussed earlier, a more lateral and distributed approach, such as a peer-to-peer building component network, could increase the overall reliability.The history and building knowledge should be passed to, or at least accessible to, newly installed components for self-configuration and performance optimization. In this instance, mass-produced building components would need to be localized and reconciled within their assembly, respond to their physical and spatial configurations—windows facing south may need to perform differently than those facing north—and understand regional and microclimatic conditions. Thanks to embedded technologies, generic manufactured building components would adapt to local circumstances and acquire highly specialized properties, possibly hard-reconfiguring their original composition.

An important part of these embedded systems will be an integration of wireless communication with a localization protocol, possibly using RFID/NFC tags and energy sources or storage. While this may seem like a lot packed into a window or an individual building component, current material research supports future implementations of these designs. For example, translucent lithium-ion batteries charged with sunlight, developed by researchers at Stanford University,[3] could be integrated into glazing or frit panels and providethe necessary energy to power embedded components. However, glazing and other visually present components need to satisfy not only technological but also aesthetic and user experience considerations. *Skeletouch,*[4] developed by Hiroyuki Kajimoto, is an example of heptic/tactile display that uses transparent glass plate with electrodes to provide a tactile feedback to users. While this particular project implements the tactile display as an overlay to a smartphone's video display, the same technology could be applied to building glazing as part of building user interface. A similar investigation was part of the Transparent Touch Interface project (fig.1) that looked into developing transparent and flexible printed circuit board (PCB)-like components that would respond to touch using an MPR121 capacitive sensor controller module driven by an I2C interface (fig.2).

MULTIPLE SYSTEM INTEGRATION

With adaptive designs and the ever-looming possibility of a power outage or system failure, the ability for a building or an assembly to return to the off state, or execute what is often referred to in IoT as the "last will" command/protocol, must be considered in overall design. This most

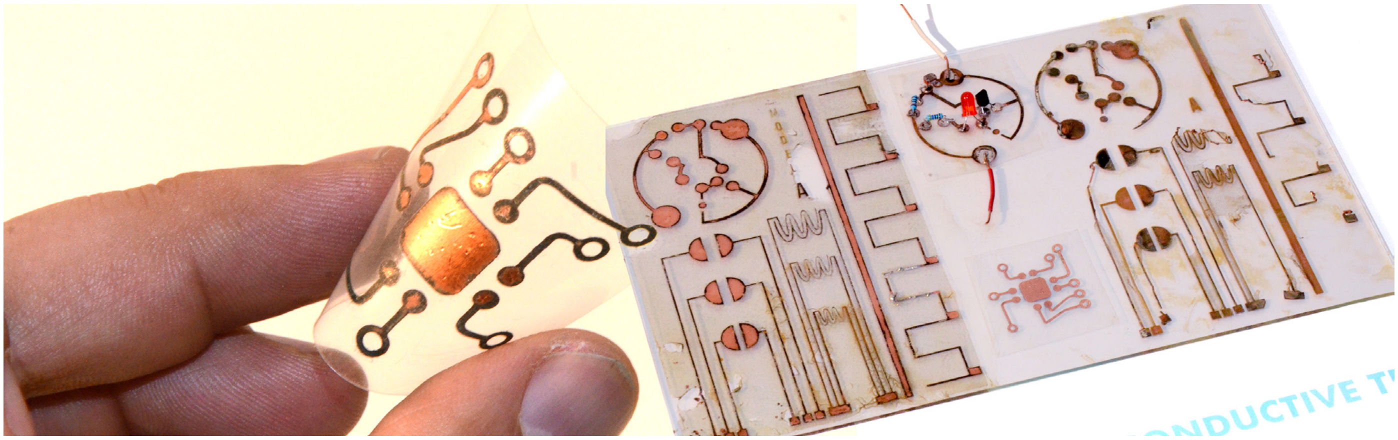

Figure 1: Transparent Touch Interface project using a rigid and flexible base focused on embedding smart systems into the conventional building materials.

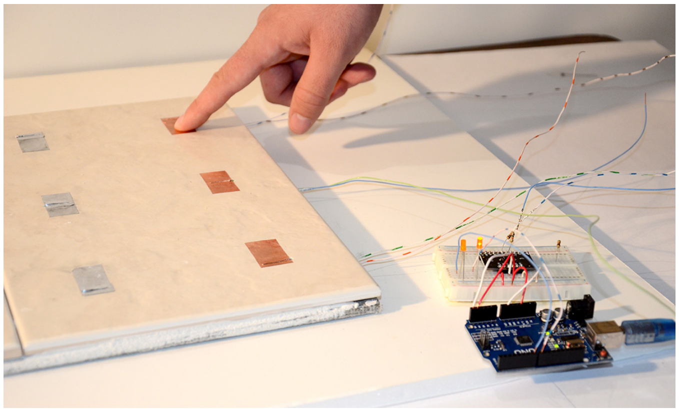

Figure 2: A capacitive sensor controller integration with a mirror as a possible user interface (UI) for IoT applications.

likely will require an integration of material intelligence with mechanical/pneumatic systems that would be able to maintain their functionalities in situations when electronic systems fail. This is an important area for future smart material research as companions to electronic systems creating highly integrated and reliable embedded designs (Decker and Zarzycki 2014). Since material behavior can increasingly be preprogrammed into highly esoteric and counterintuitive behaviors, such as 3D printed correlated magnets (polymagnets[5]), an integration of custom-made actuators could effectively support electronic embedded designs.

An additional benefit of the electronics–materiality integrations could include a system security with un-hackable material physicality that, even when highly esoteric and unintuitive, still obeys unchangeable physical laws. This form of integration would provide a secondary level of reliability for smart buildings and cities.

BUILDING AS DYNAMIC INTERFACE

While distributed sensor systems provide a dense network of data input points, the same channels of communication can be used to actuate and interface with building occupants. Embedded systems not only provide localized intelligence in materials and objects but, more importantly, can serve as an informational and control interface: an interface that provides on-demand functionalities and contextualizes knowledge. This is evident not only in the Transparent Touch Interface and Skeletouch projects mentioned earlier, utilizing touch-based inputs or tactile feedback, but also in many current consumer products, such as LED faucets and showerheads relating water temperature to light color, with embedded devices providing users with the relevant feedback.

While smart environments—buildings and cities—are initially intended to increase performance and efficiencies as well as to enhance user experience, there are many other side benefits to technologies deployed in smart environments. Sensing and actuating technologies embedded into buildings are compatible and can interface with autonomous mobility agents, not only providing navigational clues but also facilitating autonomous wheelchair driving. Similarly, the localization techniques that are used to track and interact with building occupants can also be deployed to assist nonhuman robotic agents during building construction and post-occupancy phases (Schwartz, 2015).

ESP8266 IMPLEMENTATIONS

Number of discussed technologies were implemented and tested in adaptive façade and building assembly prototypes developed as part of academic and research work at New Jersey Institute of Technology (fig. 3,4). While initially a number of “smart” prototypes used Arduino microcontrollers to interface sensors, actuators, and for data communication, it quickly became evident that for some of the projects a more robust microcontroller eco-system with wireless communication would be required. A number of projects adopted ESP8266 chip for its integrated microcontroller andWiFi capabilities. Most of the projects used a small number of controllers (3-4) but one of the projects tested twelve concurrently reporting ESP8266 units continuously connected and accessing outside Internet services with a minimal bandwidth impact on the WiFi network. During heavy data transfers on the same WiFi network (large file downloads and uploads) module connection time-outs would be a common occurrence with no effective data transfer between modules and the cloud database. While this could be associated with a data loss, these situations could have been resolved with additional code establishing protocol that would verify received communication. In the context of the research projects, this was not necessary since any unreceived-data from environmental sensors (light, temperature) would have been

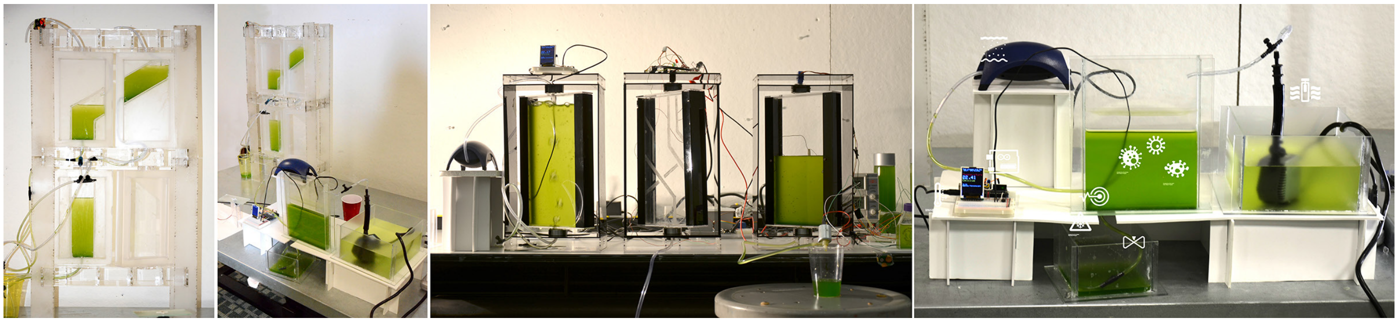

Figure 3: Adaptive façade and building assembly prototypes developed as part of academic and research work to test embedded systems: Algae Bio-Façade panel bio-reactors.

updated within a short period of time. An important finding was that once the WiFi bandwidth became available again, ESP8266 modules were able to resume the communication with no impact on the functionality or stability of the system. Similar tests with Arduino Uno and Ethernet shield showed that connection time-outs often resulted in an unresponsive module and the need to reboot a microcontroller.

While a client reporting of sensor data may be infrequent (every couple of minutes) the connection to clients handling various actuators may require much faster response time particularly when a human input is involved. This need is further compounded considering the pull nature of client communication protocol implemented in discussed prototypes—data could not have been pushed into a client, only a client could have pulled it by establishing a connection. To reduce the time between data pullings, the client would have to be continuously or frequently connected to the network, which could impact network efficiency. Again, this configuration was tested with twelve ESP8266 modules. The results showed a highly reliable configuration with only occasional communication interactions, which resulted in a couple second delay of the actuation time of one of the modules.

One of the embedded prototype project required several analog inputs. To extend a basic ESP8266 module a shield was design with a 12-bit ADC (fig. 5) that allowed for a greater precision in reading analog inputs 4096 (2^12) as compared to Arduino's 1024 (2^10) values. This is particularly useful with very precise measurements or in cases when one would like to cover a wide range of values as would be the case in measuring noise levels and mapping them to decibels (dB)—another research project currently underway in the lab.

Only some of the projects that implemented ESP8266 chipset with WiFi communication used a Node-RED implementation with Raspberry Pi. Remaining deployed a conventionalWiFi network connected to the Internet and HTML/PHP connections to MySQL databases. Majority of the projects stayed within HTML/PHP and MySQL platform partially for a legacy reasons and partially to provide a parallel testing environment to compare ESP8266 and Arduino Uno with Ethernet shield implementations.

CONCLUSION

The projects and technologies discussed above present strategies that could facilitate IoT implementations within buildings and building assemblies. They look into emerging concepts of adaptable buildings from the perspective of the inner operational logic and required functionalities such as PnP architecture to orchestrate larger intelligent systems for architectural applications. This means, in most cases, engaging a broader family of microcontrollers and getting designers and design students involved in interfacing various building systems and assemblies, integrating them with databases and mining data with machine learning algorithms. While this may feel like stepping outside of established notions of architecture embedded systems provide new tools to redefine human-made environments and design more efficient and resource-considerate buildings.

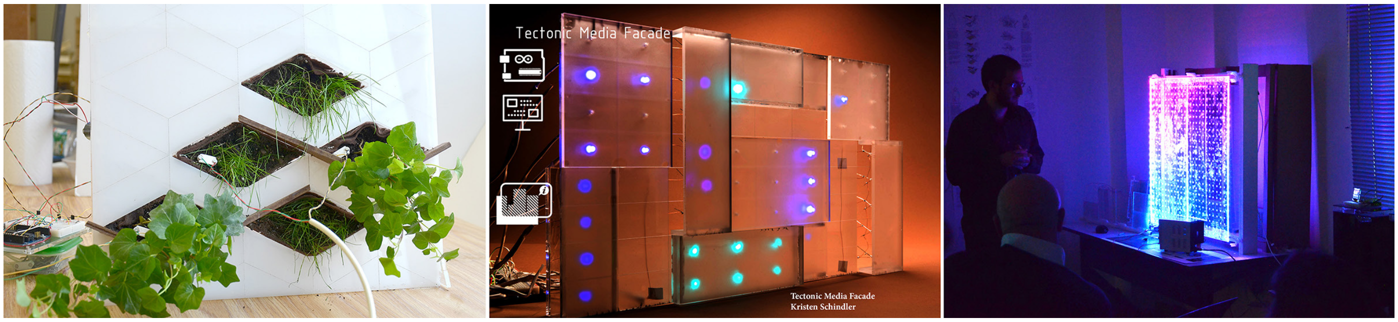

Figure 4: Adaptive façade and building assembly prototypes developed as part of academic and research work to test embedded systems: Adaptive Media Facade and Green Wall projects.

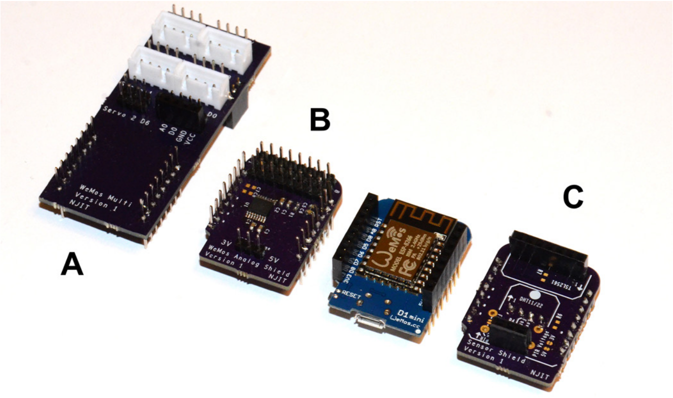

Figure 5: ESP8266/WeMos D1 Mini shields developed as part of the Adaptive Building Components at NJIT to extend and augment base module functionalities: (A) sensor and servo extension shield, (B) 12-bit ADC shield extends a number of analog inputs and increases the range of values to 12 bits, and (C) a motion (PIR), temperature (DHT22), and illumination level[Lux] (TSL2561) sensor shield.

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The following projects are the research contributions from NJIT students:

(a) Transparent Interface project was developed by Anthony Samaha (Figure1)
(b) Touch Interface project was developed by Jorge Cruz (Figure 2)
(c) Algae Bio-Façade was developed by Samantha Bard, Mary Lopreiato, and Libertad McLellan (figure 3)
(d) Green Façade was developed by Milena Popow (Figure 4 left panel)
(e) Media Façade was developed by Kristen Schindler (Figure 4 middle panel)
(f) Adaptive Media Façade was developed by Anthony Morrello and Anthony Samaha (Figure 4 right panel)
(g) ESP8266 module shields were designed and implemented by George Hahn (Figure 5) supported by a Seed Grant from NJIT.
Additional information about discussed projects including a PCB designs and Gerber file with can be accessed at emergentmatter.org

ENDNOTES

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