Collectively Intelligent Material Systems

Compositing Digital Systems within Architectural
Smart Material Applications

By

Matthew Lerch

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Carleton University
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Matthew Lerch

Abstract |

Developed through the field of material science in the late 90's, 'smart materials' have been employed by the fields of science and engineering to miniaturize, expand and reflect a physical world saturated with information rich environments. However, these 'smart-materials' are infrequently employed by architects to address both technical, aesthetic and spatial architectural issues. This thesis aims to uncover this hesitation by design professionals, critiquing the reference of 'smart' and proposes a Collectively Intelligent Material system (CIM system). This design proposal sets forth a practical response to truly intelligent architecture through specific models of Collectively Intelligent Material (CIM) applications by producing 'smart composite' facade experimentations. The work seeks to combine the process of optical lithography and Arduino based digital processing to develop a CIM system. This can be employed by the architect over new or existing façades to facilitate intelligent building surfaces.

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“The things to be prepared are these, lime, timber, sand, stone, as also iron, brass, lead, glass and the like. But the thing of greatest consequence is to choose skillful workmen.”

- Leon Battista Alberti 1485

Identifying with materials

While our living environments are conceived through architecture, they are limited by the materials which are available to the architect.¹ This distinction has always been projected through my process and conception of design and is a partial motive to pursue a material based thesis. This approach has grown my ability to effectively design space and has codified an appreciation for the unique awareness which architects have of materials. Therefore, I find it of great interest to explore architecture through unconventional material applications, undoubtedly returning to unconventional architecture. In doing so, this thesis focuses specifically upon exploring unconventional material properties, proposing advanced manufacturing methods and alternative smart material applications within architecture. The necessity to alter

¹ Marx, Karl, and Friedrich Engels, *The German Ideology*, 4.

proto-tool //
Earliest form of an implement
used as a means of
accomplishing a task or purpose

analogical reasoning //
any type of thinking that cites
accepted similarities between
two systems to support the
conclusion that some further
similarity exists.

meta-tool //
Concept of tools in which three
traits must be satisfied - 1.
individual must recognize that
tools can be used on nonfood
objects 2. individual must initially
inhibit a direct response toward
the main goal of obtaining food
3. an individual must be capable
of hierarchically organized
behavior; they must be able
to flexibly integrate newly
innovated behavior (tool>tool)
with established behaviors as
a subgoal in achieving a main
goal (tool>tool>food).

Right //
New Caledonia Crow holding
fashioned impliment.

nature is one of the many characteristics, which define intelligent beings. Take for example the tool wielding Crows of the French Territory of New Caledonia. This particular species of crow have been observed to use **proto-tools** such as sticks and grasses to complete tasks that would require **analogical reasoning**. In particular, the secondary act of using tools to retrieve or make new tools have been observed; the **meta-tool**.²

fig. 1

2 A. Whiten, R. Byrne (Eds.) Machiavellian Intelligence Vol II: Evaluations and Extensions. Cambridge University Press, Cambridge; 1997: 289–311

reveal //
As defined by Heidegger,
technology is a fundamental
mode of revealing, to make
known the truth and framing
previously concealed processes.

While it is argued within behavioural science that the use of meta-tools is the artifact that facilitated hominid technological evolution and the harnessing of nature,³ it would overlook the fundamental property which allows the tool to physically **reveal** its usefulness; as the medium through which humanity can alter their environments. The human (just as the crow) must have the physical presence of material to make, as the tools requires materiality to be made in the first place.⁴ This endowment of physicality as Martin Heidegger defines is better known as, “causa materialis , the material, the matter out of which [our tools] are made”.⁵ In his description causa materialis makes up one of four essential causes for instrumentality, a kind of physical manifestation of technology. As technology is a means to an end, the shaping and controlling of our environments, it is not the tools which humanity uses to shape the environment. Rather, it is our capability to identify what is material; what we can use to alter our landscapes. Humans can also define themselves as a collection of beings and consequentially, beings made from materials. We are not separate from our material bodies, rather our physical presence enables us to make our environments. We reign in a sort of earthy paradise of material,⁶ intrinsic to not only our being , but further to what our being then creates.⁷

3 Taylor, Alex H., Gavin R. Hunt, and Jennifer C. Holzhaider. “Spontaneous Metatool Use by New Caledonian Crows.” *Current Biology* 17, no. 17 (September 4, 2007): 1504-507. doi:<http://dx.doi.org/10.1016/j.cub.2007.07.057> showArticle Info.

4 Heidegger, Martin. 2008. *Martin Heidegger - Basic Writings: from Being and Time to the Task of Thinking*. Modern Thought Edition. Edited by David Farrell Krell. New York, NY: Harper Perennial, 313.

5 Ibid.

6 Bachelard, Gaston. 1994. *The Poetics of Space*. Translated by Maria Jolas. Boston, MA: Beacon Press, 7.

7 Marx, Karl, and Friedrich Engels. 1932. *The German Ideology : Idealism and Materialism*. Moscow: Marx-Engels Institute, 3.

smart materials //
Materials and products that are
able to reversibly change their
shape and/or properties in
response to one or more stimuli
through external influences.

parametric //
Relating to or
expressed in terms of a
parameter through algorithmic
thinking.

26 55.85 Fe Iron	28 65.38 Ni Nickel
	29 63.55 Cu Copper

fig. 2

Above //
Elements entries as taken from
the period table.

When referring to unconventional material properties, the phrase does not simply denote unusual or unexpected properties of materials. It is in fact the opposite; we have a detailed understanding of material behaviour. Since the conception of the periodic table by Mendeleev circa. 1869,⁸ matter has been organized categorically and element behaviours have become relatively predictable. Instead, unconventional material properties of our recent generation, dating back to the early 90's, refer to materials which have the unexpected capability to respond to their environments.⁹ These 'smart materials', as termed in 1992 by the National Aeronautics and Space Administration¹⁰ (NASA), are increasingly used by engineers to miniaturize, simplify and adapt existing engineered systems (mechanical, electrical, chemical, etc.). Through a series of tangential developed interests in both digital design and advanced fabrication techniques, architects have not only become aware of smart materials applications but have begun preliminary design trials, incorporating select typologies of smart materials within highly specialized architectural applications. Smart materials have also gained popularity with architects, in part due to opportunities of economization and optimization.

The tools which architects are offered are indeed more flexible (parametrically conceived),¹¹ and therefore material properties ought to be as flexible as the environments in which

8 Rittner, Don, and Ronald A. Bailey. 2005. Encyclopedia of Chemistry. New York, NY: Facts On File Inc. s.v. 'periodic table'

9 Ritter, Axel. 2007. Smart materials in architecture, interior architecture, and design. English Edition. Edited by Andreas Müller. Translated by Raymond Peat. Basel: Birkhäuser, 7.

10 Addington, Michelle, and Daniel Schodek. 2005. Smart Materials and Technologies: for the architecture and design professions. Oxford: Architectural Press, 1.

11 Jabi, Wassim. Parametric design for architecture. 2013 London: Laurence King Publishing, 15.

dumb material //
An anthetic definition of smart
materials as coined by Axel
Ritter. A material which does
not actively change state in
response to environmental
stimuli.

digital system //
A computational
system which handles discrete
signals.

transistor //
a semiconductor device which
regulates electrical signals

Methodology

Arduino //
A brand of open source
microcontrollers which is
aimed at enthusiasts level
programming applications.

sensor //
A device which detects input
(usually environmental) and
converts input into an electrical
signal.

actuator //
A device which converts
electrical signals into
mechanical action to act upon
an environment.

transducer //
A device which converts one
type of electrical signal into
another type of electrical signal.

they are conceptualized. The current opportunities, however, of smart materials should be addressed critically. Architects should consider the limitations of smart materials and therefore be keen to refuse their application where 'dumb material'¹² would be preferable. The question then follows; how can smart materials be used intelligently within architecture to create the bespoke architectural environments desired by an era of information rich environments? Through answering this question an underlying inquiry into how such intelligence might be addressed critically will respond to their claim as a unilateral solution for complex architectural problems.¹³ smart material and technologies.

It will be the first task of this thesis to convey the misunderstanding of the term smart materials, not only because 'smart' improperly defines their capabilities but also because smart materials are over simplified as a solution to architectural problems involving the maintaining and monitoring of building design and systems. Through probing a series of case studies by Doris Sung and Nick Packett, the distinction between material intelligence and high performance materials will be addressed. Digital systems, which use smart materials as actuators , sensors and transducers apply themselves in a similar fashion but have been used by engineers since the early 60's upon the advent of the transistor .

Machine based logic in the form of proprietary Arduino based hardware will be the mechanism through which sensors, actuators and transducers will be explored, to apply an existing

¹² Addington, Michelle, and Daniel Schodek. 2005. Smart Materials and Technologies: for the architecture and design professions. Oxford: Architectural Press, 9.

¹³ Ibid. 216.

thermostatic bimetals //
A composite smart material
comprised of two metals with
different coefficients of thermal
expansion that are bonded
together. The material can bend
based on thermal input (ie.
change in temperature).

C programming language //
A programming
language that is ideal for
developing firmware or portable
applications on devices such as
micro controllers.

hardware understanding to an existing category of smart materials.

These existing materials known as **thermostatic bimetals** are chosen as an optimal substrate for experimentation because they react with the primary environmental stimuli with which architecture is concerned (i.e. sun light, heat gain, and climate.¹⁴ A brief critique of what defines intelligence from a machine mind (machine learning) perspective will be used as a catalyst to redefine smart materials.

In doing so, this redefinition will propose a system based approach to materials, integrating the digital logic of the Arduino into a thermostatic bimetal façade system. I term a Collectively Intelligent Material system (CIM systems), expanding upon both the traditional mode of materials and proposing a medium by which true 'smart material' can be achieved. As the thesis will propose a CIM System to be tested, Part 2 of this thesis explores the manufacturing principles, comments on tested prototypes, and proposes a final CIM system design.

Scope

The future design proposals and methods will begin to explore the software of CIM system components. Using the Arduino microcontroller and the **C programming language** a comprehensive design and physical prototype will be created and tested. The goal of the physical prototype will be to test the final CIM system iteration upon a real exterior façade system. This would be accomplished through developing a small working CIM system array that could be installed upon a south facing building façade. The chosen site to be considered is the Urbandale Solar Research center located on the

¹⁴ Banham, Reyner. 1984. The Architecture of the Well Tempered Environment. London: Architectural Press, 18.

north campus of Carleton University. Testing would be conducted over multiple solar cycles and under varying conditions as overseen by the Carleton Graduate School of Engineering and Design.

Right //
Urbandale Center for Home
Energy Research Axonometric

fig. 3

fig. 4

artificial intelligence //
A branch of computer science
dealing with the simulation of
human behaviour such as visual
perception, speech recognition
and decision making.

It will not be within the scope of this thesis to explore a strategy to develop the artificial intelligence (AI) or machine learning components of the CIM system. Areas within neuroscience and computer science/engineering have developed suitable strategies to accompany the physical components of the proposed system. However, further research will be conducted in the area of AI so that a suitable strategy can be chosen for the particular CIM system which this thesis submits.

“Some material innovations are unlike plastics, metals or ceramics, invisible: the information you receive from materials will change the physical interaction you have with them, rather than change the way they look”

- Chris Lefteri 2013

The Smart Material

While the architect, developed from the master builder of the 14th century, has an intimate understanding of the materials used to fabricate and design, this intimacy has moved to the technical specification of the engineer over the course of the last two decades. This offloading of specific building material knowledge to the architectural consultant can be traced back to the industrial revolution yet the specific alienation of smart materials felt by architects is primarily expedited by the digital revolution of the 1960's. Specifically, when methods to miniaturize and quantify material characteristics were required to make early computer hardware components, engineers began to develop materials that required greater specificity of response. Miniaturization required components that could passively act, thereby requiring materials that could do the same. This new world of semiconductors and digital machines became the tools through which action could be programmed, aided by these new smart material abilities to switch state based on a defined input (either mechanical or electrical in the case of the digital machine).¹⁵

¹⁵ Addington, Michelle, and Daniel Schodek. Smart Materials and Technologies, 8.

Micro electro-mechanical systems

right //
Two views of a spider mite
crawling across the surface of
a micro electro-mechanical gear
chain.

fig. 5

Micro-electro-mechanical-systems (MEMS) exemplify the shift to miniaturize and optimize electronic components. MEMS were first produced commercially in 1958 in the form of strain gauges using silicon as a base material.¹⁶ Silicon, discovered to have smart-material properties (piezo-resistive effect: when deformed resists electrical current) only 4 years before, was already being used to produce semiconductors within the first computers.¹⁷ As correlated by Addington, “smart materials and microtechnology had adhered to parallel, albeit close, research and development tracks”, and as such they can be found in a symbiotic relationship within digital machines today.¹⁸ MEMS are commonly used as sensors to detect environmental conditions, transducers to relay digital information (electrical signals), and actuators to interact with the physical environment. The significant architectural applications of MEMS derive from the very thing which historically alienates them from architects; they present the opportunity to miniaturize building materials and program functionality not perceived through sight rather by being experienced.¹⁹

16 Cressler, John D. *Silicon earth: introduction to microelectronics and nanotechnology*. 2016. Boca Raton: CRC Press, Taylor & Francis Group, 332.

17 Ibid.

18 Addington, Michelle, and Daniel Schodek. *Smart Materials and Technologies*, viii.

19 Spiller, N., & Armstrong, R. (2011, Mar/Apr). *Procell Architecture*. (H. Castle, Ed.) *Architectural Design*, 81(2), 27.

Since materials at a micro scale act differently from the same material at the macro (building scale), the engineer and the architect have a fundamentally different understanding of the same materials. An example of this disjointed awareness is illustrated by ceramics.²⁰ Commonly ceramics are used by engineers as insulators of either electrical or thermal energy. At the micro-scale ceramics act as resistors, allowing only small amounts of electricity/heat to flow through them. This property is essential to producing computer components that can regulate and interpret electrical current. However, architects select the very same ceramics not for the task of regulation but as a finish. The properties of durability and resistance to chemical, thermal, and electrical resistance are also exploited by architects but not with a similar intention, nor understanding. The architect has different performance criteria which are met by ceramics at the macro scale of a building material, while the engineer uses ceramics at the micro scale to satisfy a different task. Smart materials in general present themselves with the same unifying challenges. Therefore, smart materials which are used in architecture today must not only be smart, they should be conventionally buildable.

right //
A comparison between ceramic
in electronic components
(resistors) and architectural
components (roof tile).

fig. 6

20 Lefteri, Chris. 2014. Materials for Design. London: Laurence King Publishing, 202.

immediacy //
the quality of bringing one into
direct and instant involvement
with something, giving rise to a
sense of urgency or excitement.

transiency //
passing especially quickly into
and out of a particular state.

self-actuating //
the achievement of full
potential through creativity,
independence, spontaneity, and
a grasp of the real world

selectivity //
the ability of a device to respond
to a particular frequency without
interference from others

directness //
having the ability to discreetly
manage or interact with others in
an authoritative manner

To make a conventional 'thing' buildable one must understand how it is manufactured, and understanding smart material manufacturing requires a characterization of what makes a smart material. The first characteristic of any smart material is **immediacy**. Smart materials must respond in real time, as such they are temporal, changing frequently between states or converting energy in an immediate manner. A smart material must also have **transiency**, meaning it must change based on differing environmental states.²¹ Environmental states when referring to smart materials are not specifically from the natural environment, rather differing states of environment should be thought of more as stimulation or input via energy transfer (e.g. changes in temperature (thermal energy) converted to movement (mechanical energy)). Smart materials must be bi-directional, meaning that the changes incurred by different environmental states must be repeatable and reversible.²² A smart-material is **self-actuating** through its internal programming of molecular structure, composition, assembly, and chemical properties. A smart-material does not require an external intelligent system to function, such as an electronic actuator or sensors to provide input. Building on programming, smart-materials must have **selectivity**. They must respond discreetly to environmental conditions and be predictable to control their variability. Lastly, the characteristic of **"directness"** [which] poses the greatest challenge to architects"²³, describes the ability for a smart material to respond

21 Addington, Michelle, and Daniel Schodek. Smart Materials and Technologies, 10.

22 Ritter, Axel. Smart materials in architecture, 9.

23 Addington, Michelle, and Daniel Schodek. Smart Materials and Technologies, 10.

locally to environmental state change. As building service systems (HVAC, lighting, etc.) within current architecture is neither discrete nor respond directly to environmental changes, the characteristics of smart material systems offers an opportunity to rethink building environments at the small scale; the human scale.²⁴

right //
Smart Material Characterization Table. Highlighted terms in table 1. denote smart materials which are explored in this thesis

Type of Smart Material	Input	Output
Type 1 Property Changing		
Thermochromics	Temperature difference	Colour change
Photochromics	Radiation (light)	Colour change
Mechanochromics	Deformation	Colour change
Chemochromics	Chemical concentration	Colour change
Electrochromics	Electrical potential difference	Colour change
Liquid crystal	Electrical potential difference	Colour change
Suspended particle	Electrical potential difference	Colour change
Electrocaloeological	Electrical potential difference	Stiffness/viscosity change
Magnetorheological	Electrical potential difference	Stiffness/viscosity change
Type 2 Energy Exchanging		
Electroluminescents	Electrical potential difference	Light
Photoluminescents	Radiation	Light
Chemoluminescents	Chemical concentration	Light
Thermoluminescents	Temperature difference	Light
Light-emitting diodes	Electrical potential difference	Light
Photovoltaics	Radiation (light)	Electric potential difference
Type 2 Energy Exchanging reversible		
Piezoelectric	Deformation	Electric potential difference
Pyroelectric	Temperature difference	Electric potential difference
Thermoelectric	Temperature difference	Electric potential difference
Electrorestrictive	Electrical potential difference	Deformation
Megnetorestrictive	Magnetic feild	Deformation
Thermostatic	Temperature difference	Deformation

table 1.

24 Ibid.

Thermostaic Bi-metals

Thermostatic Bi-metals (TB) are laminated composite materials that consist of at least two components, usually bands or strips, made of metals with different thermal expansion coefficients, which are permanently bonded to one another.²⁵ The component with the lower coefficient of thermal expansion is called passive, the one with the higher coefficient active.²⁶ Depending on the way the temperature changes over time, the components used and their geometries, the composite takes up a curved shape and can be used as an actuator in mechanical applications (see fig. 7). Architecturally, thermostatic bi-metals have been used primarily in experimental façade systems to control natural light and sense temperature change within building service systems (via service system components such as thermostats).

left//
Digram showing to operative
qualities of a bimetalic strip.

right//
Digram showing to operative
qualities of a bimetalic strip.

fig. 8

fig. 9

25 Ritter, A. (2007). Smart materials in architecture, interior architecture, and design (English Edition ed.). (A. Müller, Ed., & R. Peat, Trans.) Basel, Switzerland: Birkhäuser. 53.

26 Ibid, 54.

“Architectural surfaces are derived first through the visual qualities of the material and second by understanding materials as a barrier”

- Micheal Hensel 2013

Approaching our Environments

Architecture which incorporates smart-materials engage the local physical environment. It does this functionally through its façade system, which resists the changes of the natural environment and allows an augmented interior environment to exist (referred to as biophysical environment by Hensel, see fig.10).²⁷ This augmented interior environment is facilitated through building management systems, including HVAC, lighting controls, passive systems and others. Consequentially, the façade system is the component which separates this boundary; a surface. The surface on the interior, being that of finished and pleasant tactically for the occupants, contrasted by the exterior surface which operates to resist the natural elements. In Smart Materials and Technologies, it is understood by Addington that, “architects [do not] design space, the reality is that architects make (draw) surfaces”.²⁸ Therefore, since architecture’s physicality is derived from surface, it would follow that this surface’s material is profoundly essential in defining how that surface will behave (what relationship it will have with the interior and exterior environments).

²⁷ Hensel, M. (2013). Performance-Oriented Architecture: Rethinking Architectural Design and the Built Environment. (M. Swift, Ed.) Chichester, WS, UK: John Wiley & Sons Ltd, 56.

²⁸ Addington, Michelle, and Daniel Schodek. Smart Materials and Technologies, 12.

below//
 The diagram illustrates the relationship between elements within a facade system and their interaction within the biotic environment (interior) and the abiotic environment (exterior)

fig. 10

Doris Sung
Case Study

right/
Exterior architectural installation
utilizing the material properties
of thermostatic bimetals.

fig. 11

Bloom

DOSU Studio Architecture is Los Angeles based material research studio that is primarily focused on producing physical prototypes using thermostatic bimetals. Commenting on her most recent installation (2012) entitled 'Bloom', Doris Kim Sung suggests, "challenging the traditional presumption that building skins are static and inanimate".²⁹ The project examines the replacement of the static building facade by proposing a prosthetic layer between people and their environment as a responsive and active skin. Using smart materials as the active component which facilitates animation of her facades, Sung demonstrates the efficacy of thermostatic bimetals as an exterior building surface with two functions. The first is the use of thermostatic bimetals as a sun shading mechanism that controls light exposure of an exterior courtyard as the temperature increases throughout the day.³⁰ The second function of the skin is to ventilate hot air through the same perforation which expose the bimetal flaps.³¹ The project illustrates the practical use of smart materials through a unified surface method.

²⁹ Sung, Doris. 2014. "Digital and Parametric Architecture." Edited by Carlo Aiello. (EVOLO, Inc) (6): 117.

³⁰ Fox, Michael. 2016. Interactive architecture: adaptive world. New York: Princeton Architectural Press, 132.

³¹ Sung, Doris. 2014. "Digital and Parametric Architecture." Edited by Carlo Aiello. (EVOLO, Inc) (6): 117.

Breezing Blocks

In contrast her approach to window shutter systems utilizes 'breezing blocks'.³² These smart material components are synthesized using thermostatic bimetals and traditional glass facades aimed at developing building components for industry. Based on the principal of solar heat gain, Sung explores a series of patterns which utilize programmed bimetallic strips. These strips within the wall components bend based upon the amount of thermal gain, shading the interior environments. Sung speculates "this panel system can help reduce heat gain, reduce the need for artificial air-conditioning, and conserve energy".³³

fig. 12

right/
facade construction utilizing TB
flaps to regulate solar exposure
within wall cavity.

³² Ibid.

³³ Ibid, 118.

Nick Puckett Case Study

Project Black Box is a research initiative authored by Nick Puckett, founding director of AltN Research+Design. Begun in 2012, Project Black Box explores the application of shape memory polymers (SMPs) in two distinct methods.³⁴ The first method applies open source methodologies of software and hardware development to the realm of materials science. Developed in 1980, SMPs are classified as temperature responsive materials (thermostatic), but unlike bimetals they can be programmed to shape to a specific curvature.³⁵ This is done through heating the material to the Glass Transition Temperature; the specific temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery material.³⁶ Essentially the material can be programmed, in the same manner by which we program open source hardware (i.e. Arduino). In this way the design community is beginning to claim material as the new software.³⁷

Project Black Box

fig. 13

³⁴ Puckett, N. (2014). If material is the new software, then how do I write it? In D. D. Gerber, *Paradigms in Computing* (pp. 288-297). Los Angeles: eVolo Press, 289.

³⁵ Ibid, 290.

³⁶ Ibid, 293.

³⁷ Nicholas, P. (2013). *Designing Material Materialising Design*. (R. Roke, Ed.) Waterloo, ON, Canada: Riverside Architectural Press.12.

Not so smart

In his second book of the Ten Books on Architecture, Vitruvius writes about “Materials Suited for the Construction of Buildings”.³⁸ These materials for traditional construction, such as wood, stone and timber, have been used for their unique material properties, exhibiting stable and predictable behaviours for specific architectural purposes. As described by Addington, traditional materials would seem dumb in comparison to smart materials exhibiting transient behaviours.³⁹ While traditional ‘dumb’ materials seem more akin to the raw materials found within nature, “dumb materials and structures contrast sharply with the natural world”.⁴⁰ Nature displays the ability to adapt to the environment in real time.⁴¹ Therefore, through the cultivation of materials we produce dumb materials; they are essentially zombies of their natural being, defined as a dead body given the semblance of life but mute and will-less.⁴² This approach of identifying dumb materials yields an anthropic perspective, one where ‘smartness’ and ‘dumbness’ have been appropriated to vaguely define characteristics which distinguish material epochs.

This phenomenon is correlated with the marketing approach of smart material technology. In its infancy, the term smart material developed in an era designated by the George Bush administration as ‘the decade of the brain’.⁴³ It was a decade occurring between

38 Vitruvius. (1914). *The Ten Books on Architecture*. London: Harvard University Press, 41.

39 Addington, Michelle, and Daniel Schodek. *Smart Materials and Technologies*, 10.

40 Friend, C. (1996). *Smart materials: the emerging technology*. *Materials World*, 4, 16.

41 Ibid.

42 Penguin Reference. (2004). *Concise English Dictionary*. (R. Allen, Ed.) Oxford, UK: Penguin Group, s.v. zombie.

43 George, J. D. (2001). *The Decade of the Brain - A decade of Scholarship*. *Journal of the History of the Neurosciences*, 10(1), 113.

1990-2000, which sensationalized cutting-edge research on cognition and neuroscientific research, encouraging public dialogue through interagency initiatives.⁴⁴ Heavily funded, these initiatives not only spurred original research, it also marketed the brain and subsequently its function as the zeitgeist of the 90's. Therefore, the term 'smart' being that of quick witted intelligence,⁴⁵ is not so much defining the functionality of the material as it is retailing material research.

Moreover, the term 'smart' in smart materials can be critiqued from an etymological perspective. If smart infers quick witted intelligence, then it would follow that smart materials not only have to be intelligent but are quick witted as well. Quick witted, superficially references the ability to respond with wit.⁴⁶ Again, the anthropic trait suggests that smart materials as something derived from cultivation by humans is false. In fact, nature uses materials in a much more intelligent fashion (eg. DNA within a cell which encodes biological data through material properties). The latter term of intelligence is even more problematic as it insinuates that materials can learn, understand or deal with new or trying situations.⁴⁷ Through the case studies presented, by Doris Kim Sung and Nick Puckett, smart materials are used not to process environmental data, like that of a brain (referring to artificial intelligence when referencing machine based minds), rather they are reactionary elements. This is illustrated by the act of programming materials to do cyclical

44 Ibid.

45 Penguin Reference. (2004). Concise English Dictionary. (R. Allen, Ed.) Oxford, UK: Penguin Group, s.v. smart.

46 Ibid, s.v. wit.

47 Ibid, s.v. intelligence.

tasks. In the case of the thermostatic bi-metal skin used in the Bloom project by Doris Sung (see fig. 10), the façade system is programmed to react based on the daily exposure of direct sunlight. It is not capable of reacting beyond what its programmed surface features and material properties allow. Therefore, its response is more like that of a transducer, than a brain. The capability of Nick Puckett's shape memory polymers is more intelligent, as the substrate can be reprogramed at will within the same thermal input. This enables actuation yet the material is still directly changing in response to its environmental stimuli.

Looking back to the field which is directly implicated in understanding intelligence, cognitive neuroscience defines non-biological cognition as artificial intelligence (AI).⁴⁸ Developed by George Miller, Eugene Galanter, and Karl Pribram in 1959, the first theory for an AI was developed based on the concept of feedback loops, which they called TOTE units (TOTE stands for Test-Operate-Test-Exit).⁴⁹ The basic concept was that, within the brain, an initial test evaluates a given current state (the state could be derived from environmental stimuli) against a given goal. If the states do not correlate, instructions are given to carry out an operation to reduce the differences until a match occurs through a series of repeating tests.⁵⁰

48 Kolak, D., Willkiam, H., Mandik, P., & Waskan, J. (2006). *Cognityive Science: An Introduction to Mind and Brain*. London: Routledge, 24.

49 Ibid.

50 Ibid, 25.

To link artificial intelligence with smart materials the following question must be asked. If all forms of traditional materials come from nature but lose their naturalistic traits upon cultivation, are they then considered artificial? As the Oxford English dictionary defines, artificial is: “something produced by human beings rather than occurring naturally, typically as a copy of something natural”.⁵¹ This would imply that if a material has been processed in a fashion that replicates something from nature, it would be artificial. Therefore, if smart materials aim to replicate cognitive processes found within nature, they must then be considered artificial yet as already proven through the previously mentioned case studies by Doris Sung and Nick Puckett, smart materials are not intelligent, they are responsive. If so, it then follows that the word ‘smart’, in smart materials, seems to be an ill-fitting adjective.

right/
Created by IBM in 1989, Deep Blue exemplified the push to create artificial intelligence through the TOTE method. Its task was to defeat world class chess champions, which it succeeded at in 1997 against Garry Kasparov

fig. 14

51 Penguin Reference. (2004). Concise English Dictionary. (R. Allen, Ed.) Oxford, UK: Penguin Group, s.v. artificial.

“There are also apparatuses that inform dynamically ... these ‘smart tools’ replace human work and liberate human beings from the obligation to work: from then on they are free to play”

- Vilém Flusser

Collectively Intelligent Material Systems

The following chapters elaborate upon an approach of material design called Collectively Intelligent Material systems (CIM system). This approach will be used to fabricate a test material system using smart materials as a substrate, optical lithography to produce sensors and Arduino based microcontrollers to connect the functionality of both the substrate and the sensors together. A final design is later proposed through which intelligent architectural façade systems can become realized using CIM system.

Smart materials offer imbedded capabilities of acting in response to environmental input. Focusing upon thermostatic bi- metals, these actions are actuated (movement), particularly when an environmental change of radiation (light) or heat occurs. While not satisfying the traditional definition of intelligence as discussed earlier, these materials do possess the ability to interpret their environment and act within it; similar to an actuator or sensor. If smart materials do not provide the full solution to intelligent architecture or even an approach to a system that could be applied architecturally; what is this particular smart system and what

materials make it up?

There are three major approaches to characterize intelligent architectural systems (environments) based upon their functionality: environment characterizations, cognition characterizations, and implementation characterizations.⁵² The first stream, environmental characterizations, encompasses the advancement of human occupation and use of spatial environments.⁵³ Specifically processes that embed sensing and computing to make our homes and workplaces contextually aware.⁵⁴ Cognition characterizations include approaches that engage human emotions thoughts and cognitions occurring in the environments. Finally, implementation characterizations, focus on strategies which enhancements are invoked, operated and controlled.⁵⁵ Many attempts to make 'intelligent spatial environments' focus specifically upon one approach, potentially ignoring the benefits of combining approaches which express simultaneity and congruency, while relinquishing the idea of a universal system.⁵⁶

The approach which the proposed Collectively Intelligent Material system takes is to operate within all three characterizations. Future intelligent environments, as Addington suggests will

⁵² Addington, Michelle, and Daniel Schodek. *Smart Materials and Technologies*, 205.

⁵³ *Ibid*, 206.

⁵⁴ Glynn, R. (2014, 01 01). *Animating Architecture*. (B. Sheil, Ed.) *High Definition: Zero Tolerance in Design and Production*, 102.

⁵⁵ Addington, Michelle, and Daniel Schodek. *Smart Materials and Technologies*, 209.

⁵⁶ *Ibid*, 216.

incorporate combined approaches which not only enhance the physical environment surrounding human users, but also maintains approaches that aid in work processes (see table 3,4 and 5).⁵⁷ Due to the collective approach of CIM Systems, functional categorization is not an ideal approach to defining its spatial and material organization implications. Therefore, Michael Hensel's concept of active agency domains is a better strategy. Agency as described by Hensel, defines the capacity of a CIM to act within four architectural domains (refer to table 2.):⁵⁸

1. local communities
2. biotic factors and interactions
3. the local physical environments: abiotic processes
4. the spatial and material organization complex.

The first two domains, spatial and material organization complex are combined to make up the physical manifestation of the CIM system model. As such, all components which make up collectively intelligent material systems including hardware and software delineate themselves as actuators - intelligent building system, transducers - Arduino microcontrollers, and sensors – CIM system façade modules (see fig. 13). The physical components of the system allow the spatial and material complex to interact with the third domain – the local environment.⁵⁹

⁵⁷ Ibid.

⁵⁸ Hensel, M. (2013). *Performance-Oriented Architecture: Rethinking Architectural Design and the Built Environment*. (M. Swift, Ed.) Chichester, WS, UK: John Wiley & Sons Ltd, 55.

⁵⁹ Ibid.

The local environments which the CIM system concerns itself with, was explained earlier in the 'approaching our environments' chapter. Local environments, of the proposed CIM system, facilitate the major environmental inputs of the solar activity which modulate temperate and light exposure. The goal of the CIM system is to actively mediate the effects of the local environment upon the building before they can directly interact with the spatial or material complex and simultaneously communicate the state of the local environment to an intelligent building system.

Lastly, the domain of local communities is effected by the local environment controlled by the CIM system. Hensel describes this process as either supporting or diminishing local ecosystems and cultural patterns.⁶⁰ Ultimately the goal of creating such a complex architectural material system is to benefit this domain, therefore as Ruairi Glynn affirms, "the key role in the scenario will be to 'close the loop' – designing the forms of actuation that feed back into the built environment".⁶¹

⁶⁰ Ibid.

⁶¹ Glynn, R. (2014, 01 01). *Animating Architecture*. (B. Sheil, Ed.) *High Definition: Zero Tolerance in Design and Production*, 103.

“Holistic approaches are good at dealing with well-defined domains such as room temperature and light levels but not so good at dealing with unpredictable domains like human behaviour”

- Ruairi Glynn

right //
Conceptual image presenting
the 'self' masked by the
complexity of information and
logic.

fig. 15

top //

Current approaches to using smart materials in making smart environments via enhanced mechatronic, constitutive I and II models.

Current smart environment approaches using Type 1 and 2 smart materials

Autonomous embedded sensin and response elements acting intrinsically or directly

table. 3

middle //

Current approaches to making intellegnt enviroments using mico-controllers, actuators, sensors and transducers.

Current intelligent environment approaches

table. 4

bottom //

Furture (proposed) approach using a combination of smart materials and current intellegent enviroment approaches. Atifical intelligence uses context to define resulting enviornment

Transparent interfaces

Spaces defined by phenomenological boundaries (e.g., use, thermal, light and other boundaries), which may or may not be coincident or be a physical construction

table. 5

Sensors, Actuators and Transducers

Collectively intelligent material systems require components which can convert energy from one type of energy to another. Like smart materials, conversion is facilitated through an input of stimuli which is not necessarily environmental. Alternatively, input could be produced through directly connecting materials together (one material augmenting another). In CIM system, environmental inputs are first received by either transducer components or sensors and then sent, received and converted by actuators.

right//
Diagram summarizing CIM
system panel components

fig.16

Producers of micro-controllers, such as Scott Fitzgerald of Arduino define the first set of components (i.e. transducers) as, “devices that convert variations in physical quantity, such as pressure or brightness, into an electrical signal, or vice versa”.⁶² The initial iterations of the proposed CIMS façade uses the Arduino itself as a kind of complex transducer; converting analogue input from the CIM system modules to a form which can be interpreted by an intelligent building system. Sensors, defined as components which convert other forms of energy into electrical energy are used by the Arduino to gain an understanding of the environmental conditions.⁶³

The sensors used in the initial iterations focus on converting environmental conditions of movement and heat into an analogue signal ; in the initial iteration, this analogue signal is a consistent DC current which is augmented based on the number of stimulated CIM system modules. Finally, the actuators, defined as components which convert electrical energy into other forms of energy, use the digital information converted by the Arduino to augment architectural environments intelligently.⁶⁴ The actuator in intelligent architectural environments might be as Glynn describes as, “machine learning algorithms running on remote servers collecting and making sense of these complex interconnections”.⁶⁵ Ultimately, the information provided by the CIMS modules (effectively the exterior façade system), encompasses all three types of components.

62 Fitzgerald, S., & Shiloh, M. (2015). *Arduiono Projects Book* (3 ed.). (T. Igoe, Ed.) Torino, Italy: Arduino Srl, 21.

63 Ibid.

64 Ibid.

65 Glynn, R. (2014, 01 01). *Animating Architecture*. (B. Sheil, Ed.) *High Definition: Zero Tolerance in Design and Production*, 103.

CIM system design concept

1. TB Substrate // Preliminary design incorporates iron nickel alloy on top active surface (facing to exterior).
2. Resistive silkscreened circuit // Identifies panel in module as having a unique resistance rating through altering the length of printed wire.
3. Conductive Sub-Structure // Contacts are located below each bimetallic substrate. When strip bends to the closed position copper the resistive circuits contact in parallel with the conductive sub-structure. This in turn, increases the overall resistance in the system which is relayed back to the microcontroller.
4. Adhesive layer // Bonds the CIMS components together. This Adhesive layer is halftoned to allow for expansion of substrate.
5. Fasteners // Single CIM system components are bolted to the conductive sub structure to make CIM system modules.

bottom //
CIM system composite panels
Iteration 2.

fig. 17

fig. 18

CIM system module //

CIM system components bend
based on heat generated
through solar intensity. Modules
are made up of several CIM
system components which are
then coupled to form larger
arrays.

fig. 19

fig. 20

CIM system array:

Arrays are conceived to make up the sensor component of a CIM system. These sensing array are fastened to facades using the conductive substructure. As the sun exposure (environmental conditions) changes the array is able to actuate, sense and relay its programmed interpretation of the environmental conditions.

fig. 21

fig. 22

Smart material properties of thermostatic bi-metals, are used in the making of the substrates as the active component within the CIM system modules. The active component serves as the elements which directly interact with the local environment. Using the bending actuation of the bimetallic materials, a logic is created in two ways. The first is the bending indicating that the material is receiving thermal simulation.

Making substrates

right //

First sensor iteration with circuit layering method

fig. 23

d occur due to the
secondly the bending

is used to electrically contact the sub grid structure as proposed in the first design iteration (see fig. 13, 14 and 15). Additionally, the thermostatic bi-metal layer is conceived to passively act as a sun shading device regardless if the system is engaged. This strategy by itself is exemplary of current smart environmental approaches (see table 5.).

right/
Concept rendering of CIM
system panel on Urban dale
Solar Research Center

fig. 24

these circuits to sense the bending actuation of the thermostatic bi-metallic component. The proposed sensors use the detection strategy of resistance circuits to gauge the proximity and degree of actuation of each CIM system module. The initial sensor iterations were modeled off of beat frequency oscillation sensors (see. fig. 17), a common technology used in consumer metal detectors. This method had the additional benefit of not only communicating if the module is open or closed (binary) but also communicating a range of actuation (analogue).⁶⁶ While this strategy was the first to be explored, it was impractical to produce this type of sensor with the tools at hand. Therefore the final CIM system prototype will not use this particular method.

right/
Using a digital multimeter to take
resistance measuremnt of a the
first beat frequecny ocillation
sensor iteration.

fig. 25

⁶⁶ Kroschwitz, J. (1992). Encyclopedia of Chemical Technology. New York, NY, USA: John Wiley & Sons.

right/
Water based coating containing
tarnish resistant copper particles
for superior conductivity.

See Appendix B for product
specifications

fig.26

Optical lithography

of the CIM system. The first are the conductive traces which allow electrical signals to be transferred from the sensors to the micro-controller; the second are the sensors themselves.

As defined by the Society of Photo-optical Instrumentation Engineers, “optical lithography is a photographic process by which a light sensitive polymer called a photo-resist, is exposed and developed to form 3d relief images on the substrate”.⁶⁷ This developed substrate (see fig. 13-15) can then be used to print the intended design or pattern. Both the sensors and the electrical traces are required to be electrically conductive once printed and cured, therefore conductive inks must be used as the printing medium. Since the smart material, which the pattern is being printed onto is a conductive substrate(thermostatic-bimetal), patterns for insulation masks must also be manufactured to print insulation layers. The insulation layers are printed using a water based ink, which provides not only a surface that prevents short circuiting between electrical components but also allows the design of the sensors and traces to be layered. This method of optical lithography, developed in 1940 by Oscar SuB⁶⁸, also facilitates an efficient printed circuit design and is integral to the sensors functionality. The inks are also both water based so proper adhesion between layers may occur.

The following manufacturing process outlines a general overview of the specific method of optical lithography used in

⁶⁷ Mack, C. A. (2006). Field guide to optical lithography (Vol. FG06). Bellingham, WA, USA: SPIE, 2.

⁶⁸ Wilson, C. G., Dammel, R. R., & Reiser, A. (1997). Photoresist materials: a historical perspective. Advances in Resist Technology and Processing XIV. 3049. Santa Clara: SPIE, 32.

this thesis. Although the functionality of the conductive traces and sensors within the CIM systems are different, the process for manufacturing either are essentially the same. Therefore, the following describes the manufacturing of the sensor component, as it is technically more complicated and is one of the functional components within the final CIM system design.

right/
Screen print frame with sensors
designs made with light
sensitive emulsion.

he

fig. 27

photo-resist substrate . This is done by first selecting an appropriate mesh; coarse for printing thicker insulation layers, fine for printing detailed electrical components. The mesh must then be stretched over the frame and a layer of sensitized photo resist applied. The photo resist is then left to dry in low light conditions (approx. 3 hours). Once dry the prepped frame is moved to an exposure table where a film positive of the intended design (i.e. electrical traces and sensors) is placed over the area to be developed. A high intensity UV lamp (approx. 800W) is used to expose the frame for twelve and a half (12.5) minutes. This cures the exposed photo-resist (not covered by the film positive). The frame is then soaked in a water bath and then a high-pressure jet of water is used to expunge any remaining unexposed photo resist. The final frame, also known as a silk screen, is then left to completely dry under the exposure lamp, in a step called post baking. Post baking hardens the remaining photo resist and readies the frame for its first use.

The next step aligns the various screen print frames with one another. A jig is built using proprietary clamping hinges, which not only align all the layers to be printed but also allows the silkscreens to be swapped out efficiently. The jig, which is built in this thesis, utilizes a set of slots which are pre-milled out of the plywood frames using a CNC mill. Bolts are threaded through these slots and tightened once the desired alignment is achieved.

The final step before printing can occur is the loading of the screen. This is key to producing prints which have an even thickness and crisp transfer. Ink is placed within the silk screen frame but outside of the printing area. A light, even pass with a

silk screen squeegee loads the print area with ink. The print is then aligned onto the bimetallic substrate, and the ink is forced through the uncovered scene by a single firm pass. This applied sensor design is then cured onto the substrate through drying and then subsequent baking at 170°C. This last step is crucial, especially for the conductive ink, as the space between copper particles shrinks as heat is applied. Thus reducing the overall electrical resistance of the cured design and vulcanizes the binder to increase long-term durability.

top //
220 thread per-inch mesh
(circuit details)

fig. 28

bottom //
100 thread per-inch mesh
(masking)

fig. 29

Sensor iteration 1.

Masks necessary for the first
sensor iteration.
Refer to fig.28 fig.29 and fig.30

reference layer appears as a tiny percent nanometers, pattern mm, (fig. 30 of fig. xx). The base shielding layer, applied as a base over the bimetallic substrate before the coil layer is applied. (bottom of fig. xx).

fig. 31

same direction to increase the sensors strength as more layers are applied.

fig. 32

Appearing on the right template is a miniature array of coils, its purpose was to test the limitations of scale and printing resolution.

1. Unexposed Silkscreen Frame 13" x 19" – 220 thread per inch polyester fabric screen stretched over CNC milled plywood frame complete with dried sensitized

Exposure Process

fig. 33

emulsion.

2. Vacuum Unit 16" x 24" bed size - vacuum pump facilitates even clamping pressure using 1/8" acrylic sheet.
3. Acrylic Sheet 16" x 24" – applies pressure to positive film, flattening the design to unexposed silkscreen frame. (required to make positive contact)
4. Film Positive Circuit Design – Printed using two (2) 8.5" x 11" inkjet transparency film.
5. Safety UV glasses – UV glasses filter high intensity light from halogen lamp during exposure.
6. Halogen Exposure Lamp 800w – Exposure lamp is placed approximately 30" from film surface. Exposure lamp is controlled by enlarging lamp timer.
7. Enlarging Lamp Timer – Used to control exposure time (approximately 12.5 minutes). Timer is connected to household power and then outputs to exposing lamp.
8. Alternative Film Positive Designs – includes electrical shielding layers (insulation), wiring lead designs, adhesive layer and small scale sensor array test.
9. Emulsion Applicator – used to evenly apply sensitized emulsion to stretched silkscreen frame.

Micro-controllers such as the Arduino platform are commonly associated to the Internet

“Through the coupling of high definition sensing and actuation, space will become ever more animate, perceptively processing a life of its own, populated with agency, in constant conversation with its surroundings”

- Ruairi Glynn

Micro-controllers

fig. 34

above //
Arduino Uno R3 Micro Controller
Plan View

of Things (IoT) movement which was first established by the Global Standards Initiative in July of 2012.⁶⁹ Defined by the Encyclopedia of Electronic Engineering as a single integrated circuit which is dedicated to perform one task and execute one specific application, they contain memory, programmable input/output peripherals as well a processor.⁷⁰

In the proposed CIM system, the Arduino micro-controller is used as a transducer to receive and transmit analogue signals from the CIM system modules. The design of the Arduino is conceived in two parts; one as the transmitting module (fig. 34, fig. 35, fig. 36, fig. 37) and the other as the receiver module (fig. 38, fig. 39, fig. 40, fig. 41, fig. 42).

69 ITUT. (2012, July 04). NEW ITU STANDARDS DEFINE THE INTERNET OF THINGS AND PROVIDE THE BLUEPRINTS FOR ITS DEVELOPMENT. Retrieved from itunewslog: <http://newslog.itu.int/archives/245>

70 Webster, J. G. (1999). Wiley Encyclopedia of electrical and electronic engineering. New York: John Wiley and Sons.

top //
Final transmitting module inside
waterproof housing. Base micro-
controller is an Arduino Uno R3
with Micro bread-board and 9v
power supply.

bottom //
Transmitting module inside when
housing is closed

The transmitting module is tasked with converting the
analogue signal of the CIM system modules into a digital signal
which is then transmitted over a proprietary radio frequency
transmitter. This transmitter allows the Arduino to communicate
wirelessly, limiting the need to penetrate the building envelope and
allowing for expandability.

fig. 36

top //
Final receiving module inside
waterproof housing. Base micro-
controller is an Arduino Mega
2556 R3 with bread-board.
RF receiver enables wireless
communication between
devices. SD card module
enables data to be written to
file. LCD Screen buttons and
switches are mounted to the
exterior of the case for ease of
use.

bottom //
Receiving module inside when
housing is closed

fig. 37

fig. 38

right //
 Final receiving module inside
 waterproof housing. Base micro-
 controller is an Arduino Mega
 2556 R3 with bread-board.
 RF receiver enables wireless
 communication between
 devices. SD card module
 enables data to be written to
 file. LCD Screen buttons and
 switches are mounted to the
 exterior of the case for ease of
 use.

fig. 39

CIM System Transmitting Module

- 1 1500 mAh rechargeable battery pack - Battery life of approximately 60 hours when continuously active.
- 2 Arduino Uno R3 - Estimated battery life is based upon an active state and therefore does not reflect duration of sleep mode between logging intervals. If sleep mode is enabled, expected battery life increases to approximately 7500 stand-by hours. If logging intervals are set to every 10mins @ a 1 minute transmitting period this translates into the module transmitting 6 times in 1 hour or about a 1:9 active to standby ratio. The Arduino Uno R3 has an active mA draw of around 25 mA and a standby mA draw of around 0.2mA. Conservatively, the estimation of battery life would be around 47 days.
- 3 Male to Female DC adapter - Used to reroute and compact power cable management.
- 4 CIM Panel Input connector - Constructed from a modified female DC connector. Weather proofs connection between panel and transmitter. Environmental separation is essential to ensure durability of electronic components.
- 5 Radio frequency transmitter 433MHz - used to send RF signals to CIM receiver module. Range is limited to within the house however the lack direct wiring prevent building envelope penetrations. This is the essential component which allows the system to operate wirelessly.
- 6 Insulating Foam - Insulation is provided around all electronic components to provide cushioning around all sensitive components. This insulation also provides some thermal protection when in operation.
- 7 Male to Male DC adapter cable - connects CIM System panel to Transmitting Module
- 8 USB Type B to Type A connector - Allows transmitter code to be updated / modified.

right //
Transmitting Module Schematic
Diagram

fig. 40

top //

Final receiving module inside waterproof housing. Base micro-controller is an Arduino Mega 2556 R3 with bread-board. RF receiver enables wireless communication between devices. SD card module enables data to be written to file. LCD Screen buttons and switches are mounted to the exterior of the case for ease of use.

bottom //

Receiving module inside when housing is closed

fig.41

a storage device which logs the information in a form which can be read by an intelligent building system. Through this design, information is organized based upon module location, degree of smart material substrate response and time/date e in which the data is associated, unifying the embedded logic in the CIM system modules with the intelligent building system.

fig. 42

top //
Final receiving module inside
waterproof housing. Base
microcontroller is an Arduino
Mega 2556 R3 with bread-
board. RF receiver enables
wireless communication
between devices. SD card
module enables data to be
written to file. LCD Screen
buttons and switches are
mounted to the exterior of the
case for ease of use.

bottom //
Receiving module inside when
housing is closed

fig. 43

fig. 44

right //
Final receiving module inside
waterproof housing. Base
microcontroller is an Arduino
Mega 2556 R3 with bread-
board. RF receiver enables
wireless communication
between devices. SD card
module enables data to be
written to file. LCD Screen
buttons and switches are
mounted to the exterior of the
case for ease of use.

fig. 45

CIM System Receiving Module

- 1 9v DC male jack - powers module while separating input plug from module itself in case of servicing.
- 2 9v DC female jack - routes DC power to external on/off toggle switch
- 3 Arduino Mega 2560 - The Mega 2560 is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins, 16 analog inputs, a USB connection, a power jack, and a reset button. This version of the Arduino Mega was required to hold a more extensive code as the memory capacity of the Arduino Uno R3 was no sufficient.
- 4 Push button switches and LCD Shield - Used to control functions of CIM System Receiver Module. LCD displays 2 lines of 16 characters.
USB Type B to Type A connector - Allows receiver code to be updated / modified.
- 5 USB Type B to Type A connector
- 6 Male to Female DC adapter - Used to reroute and compact power cable management from toggle on/off switch to Arduino Mega DC in.
- 7 Radio frequency receiver 433MHz - used to receive RF signals from CIM system transmitting module. This is the essential component which allows the system to operate wirelessly.
- 8 SD Card Shield - device which permits data storage via SD cards. Arduino stores panel data via this component.
- 9 SD Card - stores logged panel data to be used by intelligent system within Solar Research Center
- 10 Insulating Foam
- 11 Toggle on/off switch and external buttons - allows user to operate CIM System Receiver Module while unit is closed within case.
- 12 AC to DC power converter - converts household AC power to DC. Arduino Mega requires household power to be limited to 7-12 V DC @ 1 Amperes max.

fig. 46

Wiring Schematic Design

fig. 47

right //
The design for the Transmitter
and Receiver module has
been adapted from several
open source projects by Alex
Strandburg and Scott Fitzgerald.

Receiver and Transmitter

the hardware components of the radio frequency transmitter and receiver. The upper Arduino module is made using an Arduino UNO R3 fitted to a breadboard (used to prototype circuits) and a radio frequency transmitter with some accompanying passive components. While both modules are powered in this first iteration by a 9v battery, the final iterations will push to make a fully solar powered design. The lower receiver module uses an Arduino Mega with more peripheral pins. This is to accommodate the liquid crystal display (LCD), a radio frequency receiver and an assortment of passive components.

```
double Thermistor(int RawADC) {
double Thermistor(int RawADC) {
double Temp;
Temp = log(((1024000/RawADC) - 10000));
Temp = 1 / (0.001129148 + (0.000234125 * Temp) + (0.0000000876741 * Temp * Temp));
```

CIM System Network

- 1 User interface of computer - used to manipulate code, connect components and connect user with the device.
- 2 Computer Display
- 3 Various data streams - in the case of the Arduino information is sent via USB connections. Since both Atmega chips on the Arduino take serial inputs the USB signal is converted by the proprietary Arduino programmer.
- 4 USB data output to interface
- 5 SD card input / output - data from SD card is loaded onto computer to then be sent to intelligent building management software. Proprietary software for intelligent HVAC within Solar Research Center modifies HVAC functionality.

below //

CIM System Network Diagram

fig. 48

CIM System Interface

- 1 USB data input to interface
- 2 Interface - Coding happens within the C programming language. This language can be interpreted by the Arduino, and more specifically by the Atmega chips, into functions which the modules then perform.
- 3 Arduino Coding Environment - Code controls all functionality and tells Arduino how to take in and send information to other components. This is essential
- 4 what the software looks like.
- 5 Compiler / Warning Message List - This area of the interface displays any error messages or conflicts within the code once verified by the compiler. The Arduino compiler automatically checks that the program runs and if not it will send back an error message instructing the coder how to address any conflict.
- 6 Connection Type - identifies which Arduino is plugged in and/or associated with the code. This area also shows which COM channel is sending the data (this is a virtual serial output created to send code via USB)
- 7 Line Number - indicates which line you are currently editing within the code

below //

CIM System Interface Diagram

fig. 49

fig. 50

Calculating and writing temperature from sensor data

The above code is taken from the program written in the C programming language for the receiver module. This part of the code is essential in converting the electrical signal from the sensors in the panel to a temperature value which can be printed to the LCD or logged to the SD card module. The steps are as follows.

- Step 1. Calculate temperature from analogue input pin 53
- Step 2. Convert temperatrure from Kelvin to Celcius
- Step 3. Print the calculated temperature if in Celcius to LCD
- Step 4. Or print calculated temperature if in Fahrenheit to LCD
- Step 5. Or print calculated temperature if in both units (Fahrenheit first)
- Step 6. Or print calculated temperature if in both units (Celcius first)

CIM System Interface

- 1 USB Connection to Computer - Data from SD card is displayed by computer for viewing purposes. Note that the information would not require viewing to be read by an intelligent building management system
- 2 CSV File - Comma Separated Values File is a standard file type which can be read by programs such as Microsoft Excel and the C programming language.
- 3 Values - Values are separated by date and then panel number

right //
Output file Diagram

fig. 51

“Today, the design of material allows performance and negotiation to be located directly in the organization of a material substructure, rather than through the interface of discreet elements in component assemblies”

- Paul Nicholas

Applying CIM system methodology

The proposal of a CIM system challenges the conventional way in which architects and smart materials relate to conventional architecture. The initial question posed by this thesis asks, how can smart materials be used by architects within architecture to create the bespoke architectural environments desired by an era which looks to become more interconnected, adaptive and information rich? In addressing this question the thesis also touched upon the nature of smart materials and their implications in terms of truly intelligent architectural façade systems. Smart materials, as this thesis concludes, are positioned between the world of optimization – characteristic of the professions; science and engineering – and deriving experience and engagement with the environment – where the profession of architecture specializes. As such, a multidisciplinary approach is necessary to facilitate both necessary facets of a CIM system, the technical and the experiential. Further, the term smart material as presently used provides no real solutions to address this disparity. Although the term itself suggests a physical material which could be ideally manipulated by the architect, its form is directly related to the final functionally - and an

intention to be intelligent. This limits the intricacy and complexity necessary to provide a material which is truly intelligent. The only course of action as reiterated by Addington and Hensel is for the architect to use smart materials as a component within a greater system. This system as this thesis proposes is termed a Collectively Intelligent Material system, which incorporates the benefit of the smart material's ability to engage with the specific local environment.

right //
CIM system mock-up actuating
to heat gain. Image on the left
illustrates closed, cold condition
in contrast to open, warming
condition. Panels were excited
using heat gun at typical
operating temperature.

fig. 52

While, the aim is to provide a single solution to address the question posed, the course of research requires expertise in multiple fields. In particular, the solution requires the development of skills and knowledge of computer science which aide in developing C programming code and building a functioning CIM system prototype. Further knowledge in the fields of mechanical engineering and chemical engineering are required to fully grasp the properties of multiple material typologies including thermostatic bi metals, material composites and conventional building materials. All three typologies are required due to the application of the CIM system upon an existing structure, thereby requiring a precise understanding of conventional material uses (wall details, etc.). Facades which use thermostatic bimetals as the sensing component also require a full understanding of solar orientation and material heat gain properties. This is required before a system can be designed as its functionality will depend on which environmental factor is being exploited (heat gain, radiation, weather).

right //
CIM system proposed location
on south facade of Urbandale
Center for Home Energy
Research

fig. 53

Beyond the Surface

(Post Script)

Through combining approaches the future application of CIM systems is exponentially diverse. Alternative environmental factors in which materials can respond will undoubtedly develop this diversity. As well, the way in which data processing develops in future iterations of a CIM system will allow interior (controlled) environments to respond at higher levels of accuracy and fulfill a more accurate definition of intelligence. One such method of data processing known as neural networking, developed by the field of cognitive science, proposes data processing which mimics that of the human brain. As defined earlier the anthropic perspective of smart lends that if CIM systems were to include a profession which were to specialize in the human mind, one could theoretically produce an ideal intelligent material; one that might blur the line between biotic and inanimate.

fig. 54

Further, the project proposed a CIM system primarily applied to the building facade and envelope components. Such, an approach limits the scope of application to that of surfaces. As discussed earlier in the thesis, Addinton believes that Architecture

is described primarily through surface. While, this point prompted the thesis to focus on redefining surface, CIM systems in this thesis did not cover their application in areas of architecture which cannot be described by surface. It could be further argued that architecture has spatial components, solids, voids and other artifacts which did not fall under the scope of this thesis. It would therefore be interesting to further research the ways in which Collectively Intelligent Materials could be applied to these other components which make up architecture. Questions such as, how does a Collectively Intelligent Material system differ when voids are the object of application?

Such questions would drive towards a more thorough inquiry on the nature of what constitutes architectural materials. Vitruvius mentioned the use of physical materials in his treatise which adopts a definition of materials as tactile and real. However, when material, and components in materials miniaturize it is especially limiting to use such as definition as our perceptions within human bodies can only discern material from no material when we exhaust what our senses will allow. For example, applying materials within voids would require imperceptibility - visual, tactile and auditory. Therefore a material would either have to be made as a conglomerate of micro material or materials would be required to actuate and transduce environmental stimuli from a distance (solid space).

The further effects of integrating programmed and intelligently responsive material within voids constitutes architecture which is not obviously intelligent. Spaces within architecture would

then become aware of occupants without the occupants being aware of the architecture (if void as architectural component was to become a CIM). This is not overtly absurd as data from online usage is tracked daily and used by Internet Service Providers (ISPs) to intelligently “watch” the user. This same strategy could be employed by designers of intelligent environments. Rather than simply watching the user, architecture could use CIM to augment its physical aspects and adjust parameters such as building form, spatial constructs, environmental systems and occupant work-flows. Additionally the embedded sensors, transducers and actuators within materials could be seamlessly used by occupants to direct architectural functionality.

In contrast to the technical advantages of future CIM speculation, the visual implication of actuation and dependency is also a fruitful exploration. Using the proposed CIM system panel construction as an example, facades made with this proposed system would “blush” (reveal underlying red rain screen). This blushing action would propose architecture which passively communicates a building’s response to occupants and environment.

Future iterations of Collectively Intelligent Material systems imply a fundamental shift from effecting localized environments (singular structures) to influencing global (multi-structures). Partially, this is speculated because at every iteration proposed within this thesis modularity was essential in facilitating a working system. Through aggregating information from different sensor nodes, much like if data was gained from multiple structures, a more accurate and subsequently intelligent response could be formulated. In the

case of the CIM system panel, installing such a system upon multi-story structures yields a more useful system than one on a smaller structure such as the Urbandale Center for Home Energy Research. The main benefit derives from the greater diversity of functions and programming of spaces within larger multi-story structures. As an example the system could provide heat gain analytics to best schedule meetings for ideal occupant comfort and lighting within specific workspaces at specific times. Algorithms and future artificial intelligences would use these analytics to predict occupant usage within buildings and ultimately provide users with optimized environments to conduct themselves within architecture.

Appendix A

2. The Deflection of a Cantilever Strip

Figure 3 shows how the deflection is calculated at the free end of a cantilever strip.

From the figure we obtain

$$\left(R_T + \frac{s}{2}\right)^2 = \left(R_T + \frac{s}{2} - A\right)^2 + L^2$$

or

$$\frac{1}{R_T} = \frac{2A}{L^2 + A^2 - A \cdot s} \quad [5]$$

From equations [4] and [5] we obtain

$$k = \frac{s}{T - T_0} \cdot \frac{2A}{L^2 + A^2 - A \cdot s} \quad [6]$$

If we substitute $a = \frac{k}{2}$ for k ,

we obtain

$$a = \frac{A \cdot s}{(T - T_0)(L^2 + A^2 - A \cdot s)} \quad [7]$$

Fig. 3

In Europe the constant a is called specific deflection (DIN 1715, page 126). Normally we can disregard the product $A \times s$ in the denominator. This means that we can use the following equation

$$a = \frac{A \cdot s}{(T - T_0)(L^2 + A^2)} \quad [8]$$

In most calculations A is smaller than 10% of L . Therefore, A^2 can be disregarded in relation to L^2 . Thus we obtain the simplified equation

$$a = \frac{A \cdot s}{(T - T_0)L^2} \quad \text{or} \quad A = a \frac{(T - T_0)L^2}{s} \quad [9]$$

The deflection of the cantilever strip is however affected by the external forces suppressing the cross curvature where the strip is fastened. This circumstance explains why a is not exactly equal to $k/2$.

$$a = \frac{A \cdot s}{(T - T_0)(L^2 + A^2)}$$

$$\frac{a}{A} = \frac{s}{(T - T_0)(L^2 + A^2)}$$

$$A = \frac{s}{a(T - T_0)(L^2 + A^2)}$$

Handwritten calculations:

$$\frac{A}{A} = 1 \quad A = \frac{0.5}{0.0002274 \times 10^{-4} (95^\circ C) (100^2 + A^2)}$$

$$A = \frac{(21.57 \times 10^{-4})}{0.5 \cdot (100,000 A^2)}$$

$$A = \frac{75.65 + 21.57 \times 10^{-4} A^2}{0.00231857 + 43.14 \times 10^{-6} A^2}$$

$$-0.00231857 = A \quad 0.5 \approx 5.3 \text{ mm}$$

Arduino Code for receiver

Appendices | 70

```

NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
UP_ARROW_SYMBOL,
DOWN_ARROW_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
NO_SYMBOL,
};
int helpPos = 0;

// Which mode is the logger in?
#define NOTSET 0
#define DISPTEMP 1
#define LOGSD 2
#define LOGPC 3
#define LOGBOTH 4

int mode = NOTSET;
boolean setupDone = false;

String temp = "";
String fTemp = "";
boolean checkingCelsius = true;

LiquidCrystal lcd(8, 9, 4, 5, 6, 7);
int backLight = 10;

const int chipSelect = 53;

#define FAHRENHEIT 0
#define CELSIUS 1
#define BOTHUNITS 2
#define BOTHUNITS2 3
int unit = FAHRENHEIT;

unsigned long receiveFail = 0;

unsigned long analogReadDelay = 0;

// Log interval
#define LOG1SEC 0
#define LOG5SEC 1
#define LOG10SEC 2
#define LOG30SEC 3
#define LOG1MIN 4
#define LOG10MIN 5
#define LOG30MIN 6
#define LOG1HOUR 7
int logInterval = -1;

// Log time in millisecond form
#define TIME1SEC 1000

#define TIME5SEC 5000
#define TIME10SEC 10000
#define TIME30SEC 30000
#define TIME1MIN 60000
#define TIME10MIN 600000
#define TIME30MIN 1800000
#define TIME1HOUR 3600000
unsigned long logWait = TIME1SEC;
unsigned long lastLogged = 0;

boolean logOn = false;

boolean sdInserted = false;

boolean timersSet = false;

int backLightLevel = 255;

// define some values used by the panel and buttons
int lcd_key = 0;
int adc_key_in = 0;
#define btnRIGHT 0
#define btnUP 1
#define btnDOWN 2
#define btnLEFT 3
#define btnSELECT 4
#define btnNONE 5

// read the buttons
int read_LCD_buttons()
{
  adc_key_in = analogRead(0); // read the value from the sensor
  // my buttons when read are centered at these values: 0, 144, 329, 504, 741
  // we add approx 50 to those values and check to see if we are close
  if (adc_key_in > 1000) return btnNONE; // We make this the 1st option for speed
  // reasons since it will be the most likely result
  if (adc_key_in < 50) return btnRIGHT;
  if (adc_key_in < 195) return btnUP;
  if (adc_key_in < 380) return btnDOWN;
  if (adc_key_in < 555) return btnLEFT;
  if (adc_key_in < 790) return btnSELECT;
  return btnNONE; // when all others fail, return this...
}

void waitUntilNoButtonPressed() {
  while (read_LCD_buttons() != btnNONE);
}

//Rounds down (via intermediary integer conversion truncation)
String doubleToString(double input, int decimalPlaces) {
  if (decimalPlaces != 0) {
    String string = String((int)(input * pow(10, decimalPlaces)));
    if (abs(input) < 1) {
      if (input > 0)
        string = "0" + string;
      else if (input < 0)
        string = string.substring(0, 1) + "0" + string.substring(1);
    }
    return string.substring(0, string.length() - decimalPlaces) + "." + string.substring(string.length() - decimalPlaces);
  }
  else {
    return String((int)input);
  }
}

double Thermistor(int RawADC) {

```

```

double Temp;
// See http://en.wikipedia.org/wiki/Thermistor for explanation of formula
Temp = log(((10240000/RawADC) - 10000));
Temp = 1 / (0.001129148 + (0.000234125 * Temp) + (0.0000000876741 * Temp
* Temp * Temp));
Temp = Temp - 273.15;      // Convert Kelvin to Celcius
return Temp;
}

void printTemp(void) {
double fT;
double t = Thermistor(analogRead(15)); // Read sensor
fT = (t * 1.8) + 32.0; // Convert to USA
lcd.setCursor(0,1);
if(unit==CELSIUS) {
lcd.print(t);
lcd.write((char)223);
lcd.print("C ");
}
else if (unit==FAHRENHEIT) {
lcd.print(fT);
lcd.write((char)223);
lcd.print("F ");
}
else if (unit==BOTHUNITS) {
lcd.print(fT);
lcd.write((char)223);
lcd.print("F ");
lcd.print(t);
lcd.write((char)223);
lcd.print("C ");
}
else if (unit==BOTHUNITS2) {
lcd.print(t);
lcd.write((char)223);
lcd.print("C ");
lcd.print(fT);
lcd.write((char)223);
lcd.print("F ");
}
temp = doubleToString(t,2);
fTemp = doubleToString(fT,2);
}

// Checks if any buttons are pressed and acts accordingly
void backgroundButtonPressCheck() {
int button = btnNONE;
if (read_LCD_buttons()!=btnNONE) button=read_LCD_buttons();
if (button!=btnNONE) {
if (button==btnSELECT&&millis()<(receiveFail+10000)&&mode!=NO-
TSET&&setupDone) {
// Change units
unit++;
if(unit>BOTHUNITS2) unit = FAHRENHEIT;
lcd.clear();
waitUntilNoButtonPressed();
if (sdInserted) {
File dataFile = SD.open("settings.txt",FILE_WRITE);
dataFile.seek(0);
dataFile.print(unit);
dataFile.close();
}
lcd.setCursor(0,0);
if (mode==DISPTEMP) lcd.print("Temperature is:");
else {
lcd.print("Log");
lcd.write(RIGHT_ARROW_SYMBOL);
}
if (mode==LOGPC) lcd.print("PC: ");
else if (mode==LOGSD) lcd.print("SD: ");
else if (mode==LOGBOTH) lcd.print("Both: ");
if (logOn) {
if (logInterval==LOG1SEC) lcd.print("1 sec");
else if (logInterval==LOG5SEC) lcd.print("5 sec");
else if (logInterval==LOG10SEC) lcd.print("10 sec");
else if (logInterval==LOG30SEC) lcd.print("30 sec");
else if (logInterval==LOG1MIN) lcd.print("1 min");
else if (logInterval==LOG10MIN) lcd.print("10 min");
else if (logInterval==LOG30MIN) lcd.print("30 min");
else if (logInterval==LOG1HOUR) lcd.print("1 hr");
}
else {
if (mode==LOGBOTH) lcd.setCursor(9,0);
lcd.print("STOPPED");
}
}
}
else if (button==btnRIGHT&&mode!=NOTSET&&mode!=DISPTEMP&&mil-
lis()<(receiveFail+10000)&&setupDone) {
// Stop/Start logging
lcd.clear();
waitUntilNoButtonPressed();
lcd.print("Log");
lcd.write(RIGHT_ARROW_SYMBOL);
if (mode==LOGPC) lcd.print("PC: ");
else if (mode==LOGSD) lcd.print("SD: ");
else if (mode==LOGBOTH) lcd.print("Both: ");
if (logOn==false) {
if (logInterval==LOG1SEC) lcd.print("1 sec");
else if (logInterval==LOG5SEC) lcd.print("5 sec");
else if (logInterval==LOG10SEC) lcd.print("10 sec");
else if (logInterval==LOG30SEC) lcd.print("30 sec");
else if (logInterval==LOG1MIN) lcd.print("1 min");
else if (logInterval==LOG10MIN) lcd.print("10 min");
else if (logInterval==LOG30MIN) lcd.print("30 min");
else if (logInterval==LOG1HOUR) lcd.print("1 hr");
logOn=true;
lastLogged = millis();
}
else {
if (mode==LOGBOTH) lcd.setCursor(9,0);
lcd.print("STOPPED");
logOn=false;
}
}
}
else if (button!=btnSELECT&&button!=btnLEFT&&button!=btnRIGHT&&-
mode!=NOTSET&&mode!=DISPTEMP&&millis()<(receiveFail+10000)&&logOn)
{
// Increase/Decrease Log Rate
int button = read_LCD_buttons();
if (button==btnUP) if (logInterval!=LOG1HOUR) logInterval++;
if (button==btnDOWN) if (logInterval!=LOG1SEC) logInterval--;
if (logInterval==LOG1SEC) logWait = TIME1SEC;
else if (logInterval==LOG5SEC) logWait = TIME5SEC;
else if (logInterval==LOG10SEC) logWait = TIME10SEC;
else if (logInterval==LOG30SEC) logWait = TIME30SEC;
else if (logInterval==LOG1MIN) logWait = TIME1MIN;
else if (logInterval==LOG10MIN) logWait = TIME10MIN;
else if (logInterval==LOG30MIN) logWait = TIME30MIN;
else if (logInterval==LOG1HOUR) logWait = TIME1HOUR;
if (sdInserted) {
File settingsFile = SD.open("settings.txt",FILE_WRITE);
// if the file is available, read it:
if (settingsFile) {
settingsFile.seek(1);
}
}
}
}

```

```

        settingsFile.print(logInterval);
        settingsFile.close();
    }
}

lcd.clear();
waitUntilNoButtonPressed();
lcd.print("Log");
lcd.write(RIGHT_ARROW_SYMBOL);
if (mode==LOGPC) lcd.print("PC: ");
else if (mode==LOGSD) lcd.print("SD: ");
else if (mode==LOGBOTH) lcd.print("Both: ");
if (logInterval==LOG1SEC) lcd.print("1 sec");
else if (logInterval==LOG5SEC) lcd.print("5 sec");
else if (logInterval==LOG10SEC) lcd.print("10 sec");
else if (logInterval==LOG30SEC) lcd.print("30 sec");
else if (logInterval==LOG1MIN) lcd.print("1 min");
else if (logInterval==LOG10MIN) lcd.print("10 min");
else if (logInterval==LOG30MIN) lcd.print("30 min");
else if (logInterval==LOG1HOUR) lcd.print("1 hr");
lastLogged=millis();
}
else if (button==btnLEFT&&mode!=NOTSET&&setupDone) {
    // Backlight control
    backLightLevel-=51;
    if (backLightLevel<0) backLightLevel=255;
    analogWrite(backLight, backLightLevel);
    waitUntilNoButtonPressed();
}
}
}

void setup()
{
    Serial.begin(9600);
    pinMode(13,OUTPUT);
    pinMode(backLight, OUTPUT);
    analogWrite(backLight, backLightLevel); // turn backlight on. Replace 'HIGH' with
    'LOW' to turn it off.

    lcd.begin(16, 2); // rows, columns. use 16,2 for a 16x2 LCD, etc.
    lcd.clear(); // start with a blank screen
    lcd.setCursor(0,0); // set cursor to column 0, row 0

    lcd.createChar((char)223, degree);
    lcd.createChar(RIGHT_ARROW_SYMBOL, rightArrow);
    lcd.createChar(UP_ARROW_SYMBOL, upArrow);
    lcd.createChar(DOWN_ARROW_SYMBOL, downArrow);

    lcd.setCursor(0,0);
    lcd.print("Wireless Temp.");
    lcd.setCursor(0,1);
    lcd.print("Logger");

    // Initialise the IO and ISR
    vw_set_ptt_inverted(true); // Required for RX Link Module
    vw_setup(1200); // Bits per sec
    vw_set_rx_pin(3); // We will be receiving on pin 3 () ie the RX pin from the
    module connects to this pin.
    vw_set_tx_pin(31);
    vw_rx_start(); // Start the receiver

    Timer3.initialize(200000);
    Timer3.attachInterrupt(backgroundButtonPressCheck);

    delay(1000);
}

void loop()
{
    if(mode==NOTSET) {
        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("SEL:Instructions");
        lcd.setCursor(0,1);
        lcd.print("or choose mode");
        int button = btnNONE;
        while (button==btnNONE) {
            button=read_LCD_buttons();
        }
        if (button==btnSELECT) {
            // Prints help text according to position in array of text
            waitUntilNoButtonPressed();
            while (helpPos!=-1) {
                lcd.clear();
                lcd.setCursor(0,0);
                if(helpTextSpecialChars[helpPos]==-1) {
                    lcd.print(helpText[helpPos]);
                } else {
                    lcd.print(helpText[helpPos].substring(0,helpText[helpPos].indexOf("")););
                    lcd.write(helpTextSpecialChars[helpPos]);
                    lcd.print(helpText[helpPos].substring(helpText[helpPos].indexOf("")+1));
                }
                lcd.setCursor(15,0);
                lcd.write(UP_ARROW_SYMBOL);
                lcd.setCursor(0,1);
                if(helpTextSpecialChars[helpPos+1]==-1) {
                    lcd.print(helpText[helpPos+1]);
                } else {
                    lcd.print(helpText[helpPos+1].substring(0,helpText[helpPos+1].index-
Of("")););
                    lcd.write(helpTextSpecialChars[helpPos+1]);
                    lcd.print(helpText[helpPos+1].substring(helpText[helpPos+1].index-
Of("")+1));
                }
                lcd.setCursor(15,1);
                lcd.write(DOWN_ARROW_SYMBOL);

                button=btnNONE;
                while(button!=btnUP&&button!=btnDOWN&&button!=btnRIGHT) {
                    button=read_LCD_buttons();
                }
                if(button==btnUP&&helpPos!=0) {
                    helpPos-=2;
                    lcd.setCursor(15,0);
                    lcd.print(" ");
                }
                else if (button==btnDOWN&&helpPos<HELPTXTSIZE-3) {
                    helpPos+=2;
                    lcd.setCursor(15,1);
                    lcd.print(" ");
                }
                else if (button==btnRIGHT) helpPos=-1;
                waitUntilNoButtonPressed();
            }
            helpPos=0;
        }
        else if (button==btnLEFT||button==btnUP||button==btnDOWN||button==bt-
nRIGHT) {
            // Reads settings on SD card
            waitUntilNoButtonPressed();
            if (button==btnLEFT) mode=DISPTMP;
            else if (button==btnUP) mode=LOGPC;
            else if (button==btnDOWN) mode=LOGBOTH;
            else if (button==btnRIGHT) mode=LOGSD;
        }
    }
}

```

```

if (mode==DISPTEMP||mode==LOGPC) {
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("Reading settings");
  if (mode==LOGPC) delay(500);
}

if (mode==LOGBOTH||mode==LOGSD) {
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("Insert SD card");
  while (!SD.begin(chipSelect)) {
    delay(5000);
  }
  sdInserted = true;
} else {
  if (SD.begin(chipSelect)) sdInserted = true;
}

if (mode!=DISPTEMP&&mode!=LOGPC) {
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("Reading settings");
  delay(500);
}

if (sdInserted) {
  File settingsFile = SD.open("settings.txt");
  // if the file is available, read it:
  if (settingsFile) {
    unit = settingsFile.read()- '0';
    logInterval = settingsFile.read()-'0';
    if (mode!=DISPTEMP) {
      lcd.setCursor(0,1);
      lcd.print("Every ");
      if (logInterval==LOG1SEC) lcd.print("1 second ");
      else if (logInterval==LOG5SEC) lcd.print("5 seconds ");
      else if (logInterval==LOG10SEC) lcd.print("10 seconds ");
      else if (logInterval==LOG30SEC) lcd.print("30 seconds ");
      else if (logInterval==LOG1MIN) lcd.print("1 minute ");
      else if (logInterval==LOG10MIN) lcd.print("10 minutes ");
      else if (logInterval==LOG30MIN) lcd.print("30 minutes ");
      else if (logInterval==LOG1HOUR) lcd.print("1 hour ");
      if (logInterval==LOG1SEC) logWait = TIME1SEC;
      else if (logInterval==LOG5SEC) logWait = TIME5SEC;
      else if (logInterval==LOG10SEC) logWait = TIME10SEC;
      else if (logInterval==LOG30SEC) logWait = TIME30SEC;
      else if (logInterval==LOG1MIN) logWait = TIME1MIN;
      else if (logInterval==LOG10MIN) logWait = TIME10MIN;
      else if (logInterval==LOG30MIN) logWait = TIME30MIN;
      else if (logInterval==LOG1HOUR) logWait = TIME1HOUR;
      delay(2000);
    }
    settingsFile.close();
  }
} else {
  settingsFile.close();
  File newSettingsFile = SD.open("settings.txt",FILE_WRITE);
  newSettingsFile.print(FAHRENHEIT);
  newSettingsFile.print(LOG1SEC);
  newSettingsFile.close();
  delay(500);
  lcd.setCursor(0,1);
  lcd.print("None on card");
  delay(2000);
}

} else {
  delay(500);
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("Failed, using");
  lcd.setCursor(0,1);
  lcd.print("default settings");
  delay(3000);
}

lcd.clear();
lcd.setCursor(0,0);
lcd.print("Turn on Transm.");
lcd.setCursor(0,1);
lcd.print("Insert sensor");

uint8_t buf[VW_MAX_MESSAGE_LEN];
uint8_t buflen = VW_MAX_MESSAGE_LEN;
while (analogRead(15)<20&&!vw_get_message(buf, &buflen)) {
  delay(1000);
}
lcd.clear();
lcd.setCursor(0,0);
if (mode==DISPTEMP) {
  lcd.print("Temperature is:");
  setupDone = true;
} else {
  if (sdInserted) {
    File logFile = SD.open("log.csv");
    if (!logFile) {
      File newLogFile = SD.open("log.csv",FILE_WRITE);
      newLogFile.println("Date/Time,Fahrenheit,Celsius");
      newLogFile.close();
    }
  }
  lcd.print("Set log interval");
  lcd.setCursor(0,1);

  int tempChoice = LOG1SEC;
  lcd.print("1 second ");
  lcd.write(UP_ARROW_SYMBOL);
  lcd.print("/");
  lcd.write(DOWN_ARROW_SYMBOL);

  while (logInterval==--1) {
    int button = read_LCD_buttons();
    if (button!=btnNONE) {
      if (button==btnUP) if (tempChoice!=LOG1HOUR) tempChoice++;
      if (button==btnDOWN) if (tempChoice!=LOG1SEC) tempChoice--;
      if (button==btnSELECT) {
        logInterval=tempChoice;
        if (logInterval==LOG1SEC) logWait = TIME1SEC;
        else if (logInterval==LOG5SEC) logWait = TIME5SEC;
        else if (logInterval==LOG10SEC) logWait = TIME10SEC;
        else if (logInterval==LOG30SEC) logWait = TIME30SEC;
        else if (logInterval==LOG1MIN) logWait = TIME1MIN;
        else if (logInterval==LOG10MIN) logWait = TIME10MIN;
        else if (logInterval==LOG30MIN) logWait = TIME30MIN;
        else if (logInterval==LOG1HOUR) logWait = TIME1HOUR;
        if (sdInserted) {
          File settingsFile = SD.open("settings.txt",FILE_WRITE);
          // if the file is available, read it:
          if (settingsFile) {
            settingsFile.seek(1);
            settingsFile.print(logInterval);
            settingsFile.close();
          }
        }
      }
    }
  }
}

```



```

    }
}
lcd.clear();
lcd.setCursor(0,0);
lcd.print("Set log interval");
lcd.setCursor(0,1);
if (tempChoice==LOG1SEC) lcd.print("1 second ");
else if (tempChoice==LOG5SEC) lcd.print("5 seconds ");
else if (tempChoice==LOG10SEC) lcd.print("10 seconds ");
else if (tempChoice==LOG30SEC) lcd.print("30 seconds ");
else if (tempChoice==LOG1MIN) lcd.print("1 minute ");
else if (tempChoice==LOG10MIN) lcd.print("10 minutes ");
else if (tempChoice==LOG30MIN) lcd.print("30 minutes ");
else if (tempChoice==LOG1HOUR) lcd.print("1 hour ");
lcd.write(UP_ARROW_SYMBOL);
lcd.print("/");
lcd.write(DOWN_ARROW_SYMBOL);

waitUntilNoButtonPressed();
}
}
if (mode==LOGBOTH||mode==LOGSD) {
// Asks user to set date/time
lcd.clear();
lcd.setCursor(0,0);
lcd.print("Set");
lcd.setCursor(0,1);
lcd.print("Date:");
lcd.setCursor(7,0);
lcd.print("11/1/00");
lcd.setCursor(7,1);
lcd.write(UP_ARROW_SYMBOL);

int setPos = 0;
int data[7] = {1,1,2000,12,00,0};
while (!timesSet) {
int button = read_LCD_buttons();
if (button!=btnNONE) {
if (button==btnUP) {
if (setPos==0&&data[0]!=12) data[0]++;
else if (setPos==1&&data[1]!=31) data[1]++;
else if (setPos==2) data[2]++;
else if (setPos==3) {
if (data[3]<11) {
data[3]++;
} else if (data[3]==12) data[3]=1;
else if (data[3]==11) {
data[5]++;
if (data[5]==2) data[5]=0;
data[3]=12;
}
}
else if (setPos==4) {
if (data[4]<59) data[4]++;
else data[4]=0;
}
}
else if (button==btnDOWN) {

if (setPos==0&&data[0]!=1) data[0]--;
else if (setPos==1&&data[1]!=1) data[1]--;
else if (setPos==2&&data[2]!=2000) data[2]--;
else if (setPos==3) {
if (data[3]>1&&data[3]!=12) {
data[3]--;
} else if (data[3]==1) data[3]=12;
else if (data[3]==12) {

data[5]--;
if (data[5]==-1) data[5]=1;
data[3]=11;
}
}
else if (setPos==4) {
if (data[4]>0) data[4]--;
else data[4]=59;
}
}
else if (button==btnRIGHT&&setPos!=4) setPos++;
else if (button==btnRIGHT&&setPos==4) {
timesSet=true;
if (data[5]==1) data[3]+=12;
setTime(data[3],data[4],0,data[1],data[0],data[2]);
}
else if (button==btnLEFT&&setPos!=0) setPos--;
}
delay(300);

if (setPos<3) {
lcd.clear();
lcd.setCursor(0,0);
lcd.print("Set");
lcd.setCursor(0,1);
lcd.print("Date:");
lcd.setCursor(7,0);
lcd.print(data[0]);
lcd.print("/");
lcd.print(data[1]);
lcd.print("/");
lcd.print(String(data[2]).substring(2,4));
} else {
lcd.clear();
lcd.setCursor(0,0);
lcd.print("Set");
lcd.setCursor(0,1);
lcd.print("Time:");
lcd.setCursor(7,0);
lcd.print(data[3]);
lcd.print(":");
if (data[4]<10) lcd.print("0");
lcd.print(data[4]);
if (data[5]==0) lcd.print(" AM");
else lcd.print(" PM");
}

if (setPos==0) {
lcd.setCursor(7,1);
lcd.write(UP_ARROW_SYMBOL);
if (data[0]>9) lcd.write(UP_ARROW_SYMBOL);
} else if (setPos==1) {
lcd.setCursor(9,1);
if (data[0]>9) lcd.print(" ");
lcd.write(UP_ARROW_SYMBOL);
if (data[1]>9) lcd.write(UP_ARROW_SYMBOL);
} else if (setPos==2) {
lcd.setCursor(11,1);
if (data[0]>9) lcd.print(" ");
if (data[1]>9) lcd.print(" ");
lcd.write(UP_ARROW_SYMBOL);
lcd.write(UP_ARROW_SYMBOL);
} else if (setPos==3) {
lcd.setCursor(7,1);
lcd.write(UP_ARROW_SYMBOL);
if (data[3]>9) lcd.write(UP_ARROW_SYMBOL);
lcd.print(" --");
}
}

```

```

    } else if (setPos==4) {
        lcd.setCursor(9,1);
        if (data[3]>9) lcd.print(" ");
        lcd.write(UP_ARROW_SYMBOL);
        lcd.write(UP_ARROW_SYMBOL);
    }
}
}
lcd.clear();
lcd.setCursor(0,0);
lcd.print("Log");
lcd.write(RIGHT_ARROW_SYMBOL);
if (mode==LOGPC) lcd.print("PC: ");
else if (mode==LOGBOTH) lcd.print("Both:");
else if (mode==LOGSD) lcd.print("SD: ");
lcd.print("STOPPED");
setupDone=true;
}
}
} else {
    uint8_t buf[VW_MAX_MESSAGE_LEN];
    uint8_t buflen = VW_MAX_MESSAGE_LEN;
    if (vw_get_message(buf, &buflen)) // check to see if anything has been
        received
    {
        if (backLightLevel>0) digitalWrite(13,HIGH);
        if (millis()>(receiveFail+10000)) {
            lcd.clear();
            lcd.setCursor(0,0);
            if (mode==DISPTEMP) lcd.print("Temperature is:");
            else {
                lcd.print("Log");
                lcd.write(RIGHT_ARROW_SYMBOL);
                if (mode==LOGPC) lcd.print("PC: ");
                else if (mode==LOGBOTH) lcd.print("Both: ");
                else if (mode==LOGSD) lcd.print("SD: ");
                if (logOn) {
                    if (logInterval==LOG1SEC) lcd.print("1 sec");
                    else if (logInterval==LOG5SEC) lcd.print("5 sec");
                    else if (logInterval==LOG10SEC) lcd.print("10 sec");
                    else if (logInterval==LOG30SEC) lcd.print("30 sec");
                    else if (logInterval==LOG1MIN) lcd.print("1 min");
                    else if (logInterval==LOG10MIN) lcd.print("10 min");
                    else if (logInterval==LOG30MIN) lcd.print("30 min");
                    else if (logInterval==LOG1HOUR) lcd.print("1 hr");
                }
                else {
                    if (mode==LOGBOTH) lcd.setCursor(9,0);
                    lcd.print("STOPPED");
                }
            }
        }
    }
    receiveFail=0;
    int i;
    // Message with a good checksum received.
    temp="";
    fTemp="";
    for (i = 0; i < buflen; i++)
    {
        if (checkingCelsius) {
            if (buf[i]!='C') temp+=buf[i]; // the received data is stored in buffer
            else checkingCelsius=false;
        }
        else {
            if (buf[i]!='F') fTemp+=buf[i];
            else checkingCelsius=true;
        }
    }

    }
    lcd.setCursor(0,1);
    if(unit==CELSIUS) {
        lcd.print(temp);
        lcd.write((char)223);
        lcd.print("C ");
    }
    else if (unit==FAHRENHEIT) {
        lcd.print(fTemp);
        lcd.write((char)223);
        lcd.print("F ");
    }
    else if (unit==BOTHUNITS) {
        lcd.print(fTemp);
        lcd.write((char)223);
        lcd.print("F ");
        lcd.print(temp);
        lcd.write((char)223);
        lcd.print("C ");
    }
    else if (unit==BOTHUNITS2) {
        lcd.print(temp);
        lcd.write((char)223);
        lcd.print("C ");
        lcd.print(fTemp);
        lcd.write((char)223);
        lcd.print("F ");
    }
    digitalWrite(13,LOW);
}
if (analogRead(15)>20) {
    delay(100);
    if (analogRead(15)>20&&millis()>(analogReadDelay+500)) {
        if (backLightLevel>0) digitalWrite(13,HIGH);
        if (millis()>(receiveFail+10000)) {
            lcd.clear();
            lcd.setCursor(0,0);
            if (mode==DISPTEMP) lcd.print("Temperature is:");
            else {
                lcd.print("Log");
                lcd.write(RIGHT_ARROW_SYMBOL);
                if (mode==LOGPC) lcd.print("PC: ");
                else if (mode==LOGBOTH) lcd.print("Both: ");
                else if (mode==LOGSD) lcd.print("SD: ");
                if (logOn) {
                    if (logInterval==LOG1SEC) lcd.print("1 sec");
                    else if (logInterval==LOG5SEC) lcd.print("5 sec");
                    else if (logInterval==LOG10SEC) lcd.print("10 sec");
                    else if (logInterval==LOG30SEC) lcd.print("30 sec");
                    else if (logInterval==LOG1MIN) lcd.print("1 min");
                    else if (logInterval==LOG10MIN) lcd.print("10 min");
                    else if (logInterval==LOG30MIN) lcd.print("30 min");
                    else if (logInterval==LOG1HOUR) lcd.print("1 hr");
                }
                else {
                    if (mode==LOGBOTH) lcd.setCursor(9,0);
                    lcd.print("STOPPED");
                }
            }
        }
    }
    receiveFail=millis();
    analogReadDelay = millis();
    printTemp();
    digitalWrite(13,LOW);
}
}
}

```

```

else {
  if (receiveFail==0) receiveFail=millis();
  if (millis()>(receiveFail+10000)) {
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Turn on Transm./");
    lcd.setCursor(0,1);
    lcd.print("Insert sensor");
    delay(2000);
  }
}

unsigned long current = millis();
if (current>(receiveFail+10000)&&((current-lastLogged)>=logWait)) {
  lastLogged=current;
} else if ((current-lastLogged)>=logWait) {
  if (logOn) delay(100);
  if (logOn) {
    if (mode==LOGPC||mode==LOGBOTH) {
      // Logs to serial
      Serial.print(fTemp);
      Serial.print("F.");
      Serial.print(temp);
      Serial.println("C");
    }
    if (mode==LOGSD||mode==LOGBOTH) {
      // Logs to SD card
      File logFile = SD.open("log.csv",FILE_WRITE);
      if (logFile) {
        logFile.print(month());
        logFile.print("/");
        logFile.print(day());
        logFile.print("/");
        logFile.print(String(year()).substring(2,4));
        logFile.print(" ");
        logFile.print(hourFormat12());
        logFile.print(":");
        if (minute()<10) logFile.print("0");
        logFile.print(minute());
        logFile.print(":");
        if (second()<10) logFile.print("0");
        logFile.print(second());
        if (isAM())&&hourFormat12()!=12 logFile.print("AM");
        else if (isAM())&&hourFormat12()==12 logFile.print("PM");
        else if (isPM())&&hourFormat12()==12 logFile.print("AM");
        else logFile.print("PM");
        logFile.print(",");
        logFile.print(fTemp);
        logFile.print(",");
        logFile.println(temp);
      }
      logFile.close();
    }
    lastLogged=current;
    delay(100);
  }
}
}
}

```

Arduino Code for transmitter

```
#include <VirtualWire.h> // you must download and install the VirtualWire.h to your hardware/libraries folder
#include <math.h>

#undef int
#undef abs
#undef double
#undef float
#undef round

String textToSend = "";

void setup() {
  pinMode(13,OUTPUT);
  // Initialise the IO and ISR
  vw_set_ptt_inverted(true); // Required for RF Link module
  vw_setup(1200);           // Bits per sec
  vw_set_tx_pin(3);         // pin 3 is used as the transmit data out into the TX Link module, change this to suit
                             // your needs.
  pinMode(10,INPUT);
  pinMode(9,OUTPUT);
  pinMode(11,OUTPUT);
  digitalWrite(9,LOW);
  digitalWrite(11,HIGH);
}

double Thermistor(int RawADC) {
  double Temp;
  // See http://en.wikipedia.org/wiki/Thermistor for explanation of formula
  Temp = log(((1024000/RawADC) - 10000));
  Temp = 1 / (0.001129148 + (0.000234125 * Temp) + (0.0000000876741 * Temp * Temp * Temp));
  Temp = Temp - 273.15;      // Convert Kelvin to Celcius
  return Temp;
}

void printTemp() {
  double fTemp;
  double temp = Thermistor(analogRead(0)); // Read sensor
  textToSend=doubleToString(temp,2);
  textToSend+="C";
  fTemp = (temp * 1.8) + 32.0; // Convert to USA
  textToSend+=doubleToString(fTemp,2);
  textToSend+="F";
}

//Rounds down (via intermediary integer conversion truncation)
String doubleToString(double input,int decimalPlaces){
  if(decimalPlaces!=0) {
    String string = String((int)(input*pow(10,decimalPlaces)));
    if(abs(input)<1) {
      if(input>0)
        string = "0"+string;
      else if(input<0)
        string = string.substring(0,1)+"0"+string.substring(1);
    }
    return string.substring(0,string.length()-decimalPlaces)+"."+string.substring(string.length()-decimalPlaces);
  }
  else {
    return String((int)input);
  }
}

void loop() {
  while (analogRead(0)!=0) {
    if (digitalRead(10)==HIGH) digitalWrite(13,HIGH);
    printTemp();
    char temp[50];
    textToSend.toCharArray(temp,50);
    const char *msg = temp; // this is your message to send
    vw_send((uint8_t *)msg, strlen(msg));
    vw_wait_tx();           // Wait for message to finish
    digitalWrite(13,LOW);
    delay(500);
  }
}
```

Panel Test Output

CSV File

Appendices | 79

Appendix E

Final Print Frames

fig. 55

fig. 56

fig. 57

fig. 58

- Print** Addington, M. (2003, May). Energy, Body, Building. *Harvard Design Magazine*, 1(18), 1-6.
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