AUGMENTED MATERIALS

Towards reconnecting Bits of Mind and Atoms of Hand

By

Yasaman Tahouni

B.Arch, M.Arch.
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Submitted to the Department of Architecture and the Department of Electrical Engineering and Computer Science in Partial Fulfillment of the Requirements for the Degrees of

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Master of Science in Electrical Engineering and Computer Science
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Abstract

Multi-sensory interaction with material is the source of embodied design knowledge in the process of creative design. Through bodily engagement with material in the process of *making*, the integration of thinking and doing— or mind and hand— results in generating iterative design solutions. While computer-aided design (CAD) tools have brought various benefits to the field of design, such as speed and accuracy in modeling, their detachment from physical world eliminates the multi-sensory interaction between designer and material. I argue that in order to overcome the separation of design and making in the context of computer-aided design tools, we need to rethink the interfaces by which designers interact with the digital world. If we aim to bring back material interaction to the computer-aided design process, the material itself should become the interface between designer and computer.

I propose Augmented Materials— defined as physical materials embedded with digital and computational capabilities— to fill the gap between physical and digital model making. By embedding functional components such as sensors, actuators and microcontrollers, directly within modules of physical interface, an integrated system emerges that can offer computational capabilities such as speed and precision of modeling, while allowing designers to engage in a hands-on multi-sensory interaction with material.

I implement my thesis by introducing NURBSforms, a modular shape-changing interface that lets designers create NURBS-based curves and free-form surfaces in a physical form, just as easily as they do in CAD software. Each module of NURBSforms represents a base curve with variable curvature, with the amount of its curvature being controlled by the designer, and represented through real-time actuation of material. NURBSforms bridges between digital and physical model making by bringing digital capabilities such as such as real-time transformation, programmability, repeatability and reversibility to the physical modality. I implemented two modalities of interaction with NURBSforms, one using direct manipulation, and the other using gestural control. I conclude this work by evaluating NURBSforms interface based on two sets of user studies, and propose potential future developments of the project.

My thesis contributes to the fields of Design and Human Computer Interaction by introducing Augmented Materials as a framework for creating computer-aided design interfaces that integrate physical and digital modalities. The NURBSforms interface can be further developed to be used as a pervasive design interface as well as a research and education tool. The software, hardware and fabrication techniques developed during implementation of NURBSforms can be applied to the research projects in the fields of architecture, product design, and HCI.

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1. Introduction

1. 1. Problem

Designing artifact, from product design to sculptures to architecture, is by nature entangled with material. Through multi-sensory interaction with material, the designer *imagines* how "stuff"- whether it's a white canvas and paint tubes, a piece of clay, or an empty building site and tons of steel and concrete- become "things". Physical interaction with material is the source of embodied design knowledge in the process of creative design. Through the bodily engagement with material, the integration of thinking and doing, or mind and hand, results in generating iterative design solutions.

While creating objects and spaces is by nature a multi-sensory activity, when designing these artifacts, we often rely solely on our visual perception and 2D visualizations, and we barely get in direct interaction with physical material. The separation between design and making has been intensified with the introduction of Computer-Aided Design tools into the field of architecture. While digital technologies have brought various benefits to the field of design, such as ease, speed and accuracy in modeling, their detachment from physical word has eliminated multisensory interaction between designer and material from the creative design process.

The question is, considering the advantages of both digital tools and physical model making, how we can fill the gap between these two worlds in order to enhance the design process. In the context of development of digital technologies, how can we re-connect the two realms of digital and physical, bits and atoms, or design and making, in order to create computer-aided design tools and interfaces that enhance design knowledge and creative design process?

> *"Design knowledge is* ***knowing in action****… It is mainly* ***tacit****, in several senses of the world: designers know more than they can say, and can best (or only) gain access to their knowing in action by putting themselves into the mode of doing."*
>
> *Donald Schon, 1987*

Figure 1: hands-on interaction with material in arts and crafts. (Source: https://pixabay.com/en/photos/pottery/)

1. 2. Vision

I argue that in order to bring back *making* to the process of computer-aided design, we need to rethink the interfaces by which we interact with the digital tools. If we aim to bring back material interaction to the computer-aided design process, the material itself should become the interface between designer and computer.

I propose Augmented Materials- defined as physical materials embedded with digital capabilities, in order to fill the gap between physical and digital model making and re-connect design and making. In Augmented Materials, inert material gets augmented with digital capabilities such as sensing, data processing, and shape transformation. By embedding functional, electric components such as sensors and actuators directly within the material units, the designer will be able to access and communicate with digital world through direct interaction with material.

As a result, while the user of such interface can engage in a hands-on and multi-sensory interaction with material, they can take advantage of *computational capabilities* such as ease and speed of modeling, real-time data representation, precision, and reversibility and repeatability.

1. 3. Steps

I start this thesis by elaborating on the problem of disjoint between physical and digital interfaces through the lens of Human Computer Interaction (HCI), and give an overview of the state-of-the-art research on tangible interaction and materiality within HCI. I will then review precedent work related to material augmentation, for which I review concepts and ideas represented through mutations of the term *material* such as Programmable Matter, Shape-changing Materials and Digital Materials.

In the third chapter, I introduce my thesis of *Augmented Materials*, defined as materials embedded with digital and computational capabilities, to fill the gap between physical and digital media and re-connect design and making. I continue this chapter by elaborating on the properties of augmented materials, such as modularity, transformation, and embedded computation.

The fourth chapter introduces a preliminary case study, called Struct[k]it, which is a physical modeling toolkit for learning structural analysis. This case study sets the stage for my main project, NURBSforms which stands as a proof of concept and implementation of Augmented Materials thesis.

I then introduce NURBSforms, a shape-changing, augmented material interface for creating NURBS-based curves and free-form surfaces in physical modality augmented by computational capabilities such as real-time transformable modeling, repeatability and reversibility. NURBSforms presents a full implementation of hardware to software and design to fabrication of an Augmented Material interface.

After elaborating on the conceptual and technical aspects of NURBSforms implementation, I evaluate the interface as well as my big-picture vision through two sets of user studies. At the end of this chapter, I review the results and conclusions of the two user studies, and discuss the future developments of NURBSforms interface. I conclude this thesis by giving a review on the contributions of my work to the fields of design and Human-Computer Interaction, and depict paths for future developments of Augmented Materials.

1. 4. Contributions

In this thesis, I contribute to the fields of Design as well as Human-Computer Interaction by:

- Framing the issue of separation of design and making in the context of CAD/CAM tools through the lens of Human Computer Interaction research.
- Introducing Augmented Materials as interfaces that bridge between designs and making through integrating Digital and Physical modalities, defining their properties, and offering suggestions for development of these interfaces.
- Creating NURBSforms interface as a proof of concept for Augmented Materials, and consolidating its hardware and software implementation so that it can be used as a usable, reliable design interface.
- Developing innovative solutions for creating integrated system, combining software, hardware, and fabrication techniques. These solutions, such as the NURBSforms actuated modules, can be further developed and used in the fields of architecture, product design, and human computer interaction.

2. Background

2. 1. Material Interaction in the context of Human Computer Interaction

We interact with our environment through our sensory-motor system. Depending on the interfaces between our bodies and the objects of environment around us, specific senses get stimulated, and combined with our corresponding action, the mode of interaction with gets shaped. As for any object in real world, this interaction is multi-sensory: we can see, hear, touch, and smell the physical entities around us. But the issue of interfaces gets complicated when talking about the digital world. As digital entities have no physical representation of their own, we need some external "interfaces" to interact with digital information.

Today, most of the interaction with digital world happens through the Graphical User Interfaces (GUIs). PC Monitors, cellphone displays, and Tablets screens are among examples of graphical user interfaces. Mainly because of their high flexibility in data representation, GUIs are the favorable user interface for most of the digital tools. However, GUIs implement a crucial limitation on the mode of interaction with digital technologies. In GUIs, digital information is only accessible through user's visual sensory systems, and the mode of interaction is limited to unnatural interfaces such as keyboard, mouse, or touch screen. This contradicts the human nature in bodily engagement with her surroundings. For some tasks, such as writing a paper or reading news on the web, GUIs provide a relatively appropriate mode of interaction. But when thinking about an activity such as design, the defects of Graphical User Interfaces become more evident.

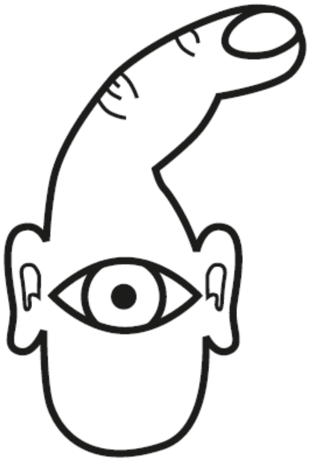

Figure 2: Interaction with GUI, by Dan O'Sullivan and Tom Igoe

2. 1. 1. Digital vs. Physical: Bits and Atoms

The issue of materiality within the context of Human Computer Interaction lies beneath the inherent difference between physical material and digital bits. While physical entities are perceived through their physical features such as shape, color, temperature, taste, and smell; digital bits have no embodiment of their own. Thus, if we want to interact with digital information, we need some in between Interfaces that let us perceive and interact with bits through characteristics of the secondary interfaces.

During the last 50 years of history of Human Computer Interaction, designing computer interfaces has gone through dramatic changes. Shifting from command-based interfaces to Graphical User Interfaces has been a radical change in the way we interact with computers. Invented by Xerox in 1981, The Star Work-station was the first commercial system which demonstrated the power of a mouse, windows, icons, property sheets, and modeless interaction The apple Macintosh brought this new style of HCI into the public's attention in 1894, creating a new stream in the personal computer industry. Because of their high flexibility in data visualization, low energy consumption and customizability, Graphical User Interfaces have remained the most popular user interface for interaction with digital tools.

However, researchers in the field of HCI have long been looking into bringing the realms of bits and atoms more close to each other. As Ishii and Ulmer put it: "We live between two realms: our physical environment and cyberspace. Despite our dual citizenship, the absence of seamless coupling between these parallel existences leaves a great divide between the worlds of bits and atoms. At the present, we are torn between these parallel disjoint spaces" (Ishii and Ulmer, 1997).

> *"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked." (Sutherland, 1965)*
>
> ***-Ivan Sutherland, The Ultimate Display***

2. 1. 2. The Material Turn in HCI

In the past few years, there has been a growing focus on the material dimensions of interaction with computational devices and information in the field of HCI. With the advent of smart materials, ubiquitous computing, computational composites, interactive architectures, the Internet of Things, and tangible bits, HCI has increasingly recognized the role that non-computational materials play. (Wiberg et al., 2013)

At CHI 2012 Conference, a panel titled "Material Interactions - From Atoms and Bits to Entangled Practices" was specifically organized to discuss assemblages of digital and physical materials, and how these compositions might form and enable new experiences (Wiberg et al., 2012). The theme for ACM CHI 2012 conference emphasized an important shift in HCI research: a move away from a perspective that treats people and computers as two separate and entities towards a perspective that acknowledges how people, computational materials, and even traditionally non-computational material are coming together as a whole, forming our experience in and of the world. (Wiberg et al., 2013)

In HCI, ''the material turn'' emerged from the vision of Tangible Interfaces Introduced by Ishii and Ullmer (Ishii and Ullmer, 1997). Since then, Tangible Interaction has inspired research in the field of HCI that aims to rethink the relationship between material and computation. Today, Computing is re-imagined as just another material, operating ''on the same level as paper, cardboard, and other materials found in design shops'' (Bdeir ,2009 as cited in Wiberg, 2013) and physical materials are now being re-imagined as substrates invested with computational properties (Wiberg et al., 2013).

Here, based on the panel discussion of CHI 2012 and UbiComp 2013 conference with special theme issue on Material Interactions, I review the latest ideas in the HCI research regarding the integration of Materiality in Human Computer Interaction.

From Tangible User Interfaces to Computational Materiality

Introduced by Hiroshi Ishii in the paper *"Tangible bits: towards seamless interfaces between People, bits and atoms"* (Ishii & Ullmer., 1997) the vision of tangible interfaces is to move beyond the graphical representation of digital information, and engage the user in a bodily and multi-sensory interaction with physical, tangible interfaces. Tangible interfaces take advantage of human's haptic sense and peripheral attention in order to make information directly manipulable and intuitively perceivable through the foreground and peripheral senses. (Ishii et al., 2012)

From the early years of introduction Tangible User Interfaces, creating tools for architectural and urban planning design have been of an interest in the field. *metaDESK* (Ishii & Ullmer., 1997) and URP (Underkoffler & Ishii., 1999) are of the first examples of such projects. Although the tangible representation allows physical embodiment to be directly coupled to digital information, it has a limited ability to represent change in many material or physical properties (Ishii et al., 2012). This issue has led to the early works in Actuated Tangibles, and later "Radical Atoms" (Ishii et al., 2012), in order to bring the shape transformations to the tangible interfaces as the central means of computational feedback. (Ishii et al., 2012).

"*Radical Atoms"* is "the new vision for human interaction with dynamic physical material that are computationally transformable and reconfigurable" (Ishii et al., 2012). Radical Atoms is based on a hypothetical, extremely malleable and dynamic physical material that is bi-directionally coupled with underlying digital model (Ishii et al., 2012). *Zeron* (Lee et al., 2011)*, inFORM* (Follmer et al., 2013) and *TRANSFORM* (Ishii et al., 2015*)* are among the examples of Radical Atoms projects conducted at Tangible Media Group at MIT Media Lab.

Vallgrada and Redstorm bring the discussion about computation and materiality further. As Gross describes it, "if materials are understood as the elements or components out of which designs are made, there is no reason to limit materials to the physical realm. Examining how computation can serve as a material in its own right leads to an interesting set ideations." (Gross et al., 2014). Vallgarda and Redstrom propose the term Computational Composites (Vallgarda and Redstrom, 2007) as a framework for treating computation as material: the property of a computer can be seen as the computational property that is completely different from that of other materials, but a property no less. The computations allow for conditioned changes of whatever the output devices are combined with–pixels on a screen, shape of a wall, or patterns on a floor. (Vallgarda and Redstrom, 2007). However, In order to be able to exploit the properties of Computation, it should co-exist with at least one other material, hence, the notion of composites.

Together, the integration of bits and atoms can shape a new types of interfaces that coexist between the two realms, with features and functionalities that can go way beyond each individual entity. Exploring the ways of integrating materiality and computation is my goal and my passion for developing this thesis, and by introducing the term Augmented Materials, I am trying to take a step into the future where we can realize Sutherland's Ultimate display.

2. 2. Material: Permutations

In this section, I review the precedent work related to material augmentation, which is the basis on which this thesis is built. To do so, I review concepts and ideas that are represented through mutations of the term *material* such as Programmable Matter, Shape-changing Materials and Digital Materials.

These mutations, each pointing to come of the the most recent technical advances in the field of Computer Science, Robotics and Material Science, vividly challenge and change the conventional notion of material. This discussion with both set the stage for introducing Augmented Materials, and also, will introduce terms and references that this thesis will cite in the next chapters.

2. 2. 1. Digital Materials

Digital Materials are assemblies of small-scale discrete building blocks. In the paper "Digital materials for digital printing" Neil Gershenfeld and George Popescu define Digital Materials as "a discrete set of components that can be of any sizes and shape, made out of various materials and that can fit together in various ways (press fit, friction fit, snap fit, reflow binding, etc.)" (Popescu, 2006)

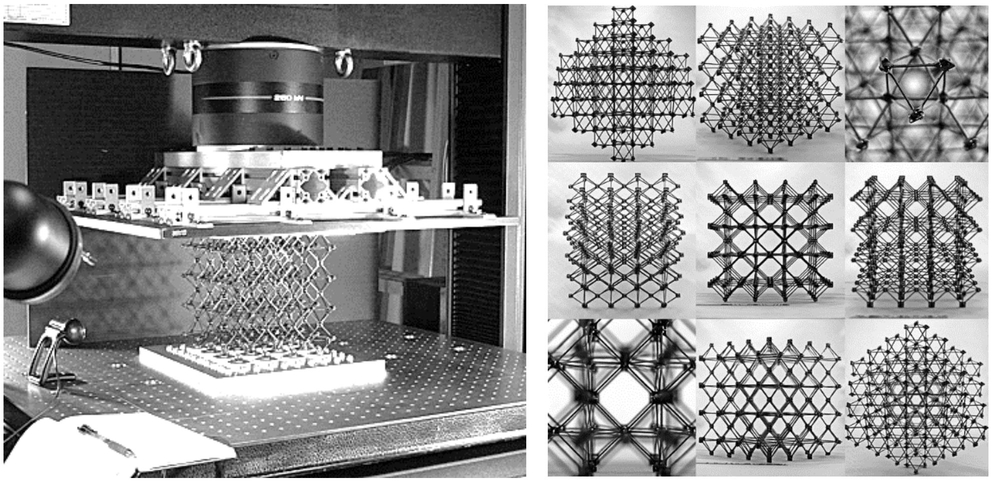

Figure 3: Digital Materials: By Center for Bits and Atoms, MIT.

Digital materials bring reversibility, simplicity, low cost and speed to free form fabrication in addition to a larger material set. (Popescu, 2006)

Motivation behind Digital Materials is the precise, fast and atomized fabrication (assembly) process enabled by discretized and standardized building blocks. Digitalized Fabrication is the term used for such fabrication process, which indicates an emigration from traditional additive manufacturing based on depositing or removing material to assembling structures from discrete parts, which is accountable for the fast and precise fabrication of digital materials.

Digital Materials can be best explained in comparison with LEGO Blocks. Similar to larger scale LEGO blocks, Digital Materials consist of discrete modular blocks that allow for only discrete positions and rotations in reference to each other, which is accountable for the automatic high precision in their assembly. Assemblies of LEGO blocks (LEGO structures) are cheap, quick, and easy to make. Their fabrication is reversible, which makes the structures potentially recyclable.

In his master’s thesis, William Longford describes digital materials as followed: “In a digitally assembled structure, discrete parts interlock with neighboring ones such that they register to a lattice and have a discrete set of possible positions and orientations. The connections between parts are made with reversible, mechanical snap-fit or press-fit connections. The function of these is akin to a chemical bond in which some activation energy is needed to overcome the energy barrier of adding or removing a part. These traits enable the assembly of precise structures with imprecise tools.”(Langford, 2014)

For further reference, the following are among the most prominent people and research groups that develop research on Digital Materials:

- Center for Bits and Atoms, Massachusetts Institute of Technology
- Gramazio Kohler research group, ETH Zurich

2. 2. 2. Shape-Changing Materials

Shape-changing materials are material systems that undergo mechanical deformation under the influence of an environmental or computational (electrical) stimuli. Shape-changing materials are by nature dynamic, in addition to the static properties that we find in other conventional polymers or alloys (Coelho, 2011.) While materials science literature is replete with examples of shape-changing materials, most of these materials are in the early stages of development and only a few are sufficiently mature today to be reliably implemented. (Coelho, 2011.)

While dynamic properties with environmental stimuli can also be found in natural materials, such as wood, shape-changing material systems are engineered and synthesized to present enhanced performance in the amount and time-scale of chape-change compared to natural materials.

Figure 4: Shape Changing Materials: by Self-Assembly Lab, MIT

For further reference, the followings are among prominent people and institutes that develop research on Shape-changing materials:

- Skylar Tibbits, Self-assembly Lab, Massachusetts Institute of Technology
- Achim Menges, Institute for Computational Design, Stuttgart University
- Lining Yao, Morphing Matter Lab, Carnegie Mellon University
- Tangible Media Group, MIT Media Lab

2. 2. 3. Programmable Matter

Programmable Matter are "materials whose properties can be programmed to achieve specific shapes or stiffness upon command" (Hawkes et al., 2010). By combining the intricate design in the structural formation of a material, material-based actuation, and new techniques in multi-material fabrication, various programmable matter projects have been realized and published in the recent years. Self-folding machines (Felton et al., 2014) and Programmable Matter by Folding (Hawkes et al., 2010) are among the significant examples in the field.

Figure 5: Shape Changing Materials: by Self-Assembly Lab, MIT

In the large scale, Programmable matter and self-assembly have been proposed as a vision for assembly of human-scale structures. Envisioning a world where material components can self-assemble to provide adapting structures and optimized fabrication solutions, MIT Self-assembly lab is one of the pioneers in the field, and their projects in 4D printing (Tibbits, 2014) and self-assembly (Tibbits, 2012) presents their vision for future of fabrication and assembly in architecture.

For further reference, the following are among the prominent people and institutions that develop research on Programmable Matter:

- Daniela Rus, CSAIL, Massachusetts Institute of Technology
- Skylar Tibbits, Self-assembly Lab, Massachusetts Institute of Technology
- Robert Wood, Harvard School of Engineering and Applied Sciences
- Claytronics Research, Carnegie Mellon University
- Programmable Matter Research Group, Autodesk Inc.

2. 2. 4. Robotic Materials

Robotic materials are material composites that combine sensing, actuation, computation and communication. Ideation and creation of robotic materials is the direct results of recent technological advances: "Recent advances in manufacturing, combined with the miniaturization of electronics that has culminated in providing the power of a desktop computer of the 1990s on the head of a pin, is enabling a new class of "robotic" materials that transcend classical composite materials in functionality." (McEvoy and Correll, 2015) "Such Artificial materials can enable airplane wings and vehicles with the ability to adapt their aerodynamic profile or camouflage in the environment, bridges and other civil structures that could detect and repair damages, or robotic skin and prosthetics with the ability to sense touch and subtle textures" (McEvoy and Correll, 2015)

The idea of creating materials that embed computation is closely related to the concept of Programmable Matter. However, the key difference is that robotic materials provide programmability through directly embedding electronic components and microcontrollers within the material. In other words, instead of relying on physical properties of material and structures to provide some levels of programmability, Robotic materials embed a microprocessor in the material, the one that can be programmed in any imaginable way, and can define the overall behavior of material in regards to sensors and actuators.

For further reading, refer to:

- Correll Lab, University of Colorado at Boulder
- Claytronics Research, Carnegie Mellon University

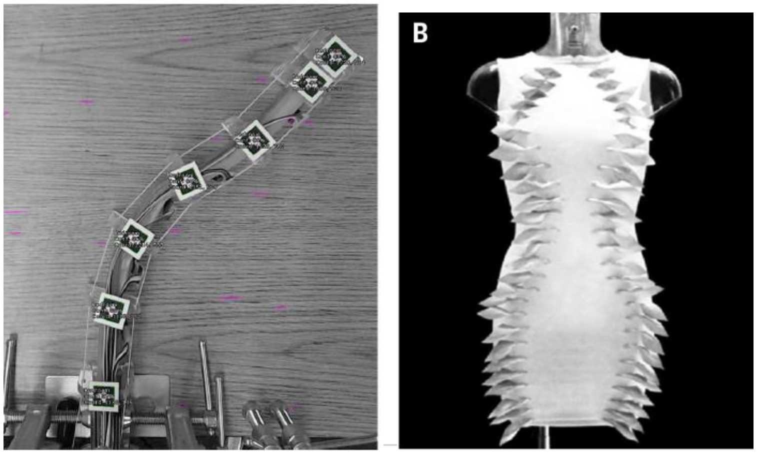

Figure 6: Examples of robotic materials that combine sensing, actuation, computation, and communication. Reference: Correll Lab (http://correll.cs.colorado.edu)

3. Augmented Materials

3. 1. Introduction

In this chapter, I will introduce Augmented Materials and explain their role in reconnecting design and making in the context of digital design tools. Then, I will define features and properties of augmented materials, for which I reference to previous mutations of material introduced in the second chapter.

Earlier in this thesis, I outlined the problem: while Computer Aided Design and Manufacturing technologies have brought various benefits to design process such as speed, precision and ease of modeling, the lack of tangible interaction between designer and physical material has been a significant defect of these tools. Using these tools, the interaction between designer and *stuff* has shrunk into using Mouse and Keyboard and Monitor, with full detachment from material interaction. Through such detachment, the design process has been separated from making, depriving designers from an important source of embodied knowledge and creativity, which is specifically critical in the early stages of design.

Further on, I contextualized the issue of interfaces of CAD/CAM tools within the bigger picture of Human Computer Interaction, and elaborated of the source of the issue which lies under the inherent separation of the worlds of bits and atoms. Then, I discussed the recent movement in the field of HCI emphasizing on the necessity of Material Interaction. Lastly I gave a short review on the latest research in the fields of Computer science, Robotics and Material Science that provide technological context for bridging between bits and atoms.

> I claim that in order to bring back *making* to the process of computer-aided design, we need to rethink the interfaces by which we interact with the digital tools. If we aim to bring back material interaction to the computer-aided design process, the material itself should become the interface between designer and computer.

3. 2. Augmented Materials

I propose Augmented Materials- defined as physical materials embedded with digital capabilities, in order to fill the gap between physical and digital model making and re-connect design and making. In Augmented Materials, inert material gets augmented with digital or computational capabilities such as sensing, data processing, and shape transformation.

By embedding sensors and actuators directly within the material units, user is able to access and communicating with digital world through direct interaction with materials. Through embedded sensing, the data from user interaction gets extracted from the physical environment, and gets translated into the form of electric voltage by sensor hardware. This data will then be sent to the computational brain of the system, or the *computer*. According to the software program embedded in the microcontrollers, this data gets processed and mapped output data. At the end point of the system, actuators will play the role of translating back the bits into the world of atoms by enabling changes in shape, color, lighting, or texture of physical matter. Whether the actuator is an LED display, a microphone, or an electro-mechanical motor, it will act on the physical world according to its controlling bits.

Augmented materials are able to change their shape, color, stiffness, or other physical properties, and these transformations are the *direct implication of the underlying computational models*. In this way, instead of interacting with digital information through an external interface, i.e. GUI, the designer perceives and interact with digital data directly through interaction with material. As a result, while the user of such interfaces can engage in a hands-on and playful interaction with physical matter, they can take advantage of features of digital tools such as fast interaction, real-time data representation, precision, and etc.

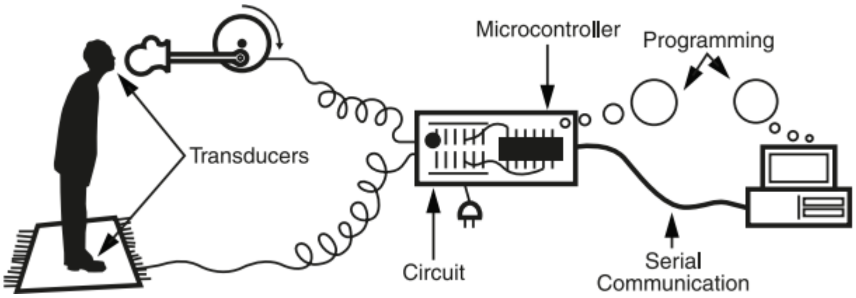

Figure 7: The elements of a physical computing system, by Dan O'Sullivan and Tom Igoe

Positioning Augmented Materials within Ubiquitous Computing: from *environments* and *objects* to *material*

Introduced by Mark Weiser in 1991, ubiquitous computing is the vision of "enhancing computer use by making many computers available throughout the **physical environment**, while making them effectively invisible to users." (Weiser, 1991) The core idea behind ubiquitous computing is to push the computer in the background and attempt to make them invisible (Ishii and Ulmer, 1997).

Following the vision of Ubiquitous computing, Ishii and Ulmer introduced the term of Tangible User Interfaces (TUI) as the way to make computing truly ubiquitous and invisible by "augmenting physical world by coupling digital information to everyday **physical objects**" (Ishii and Ulmer, 1997). While Ubiquitous Computing's vision is to embed the computers in the "Environment", and Tangible User Interfaces' vision is to embed computing in "Physical Objects".

In Augmented Materials, we not only move beyond Graphical User Interfaces as specialized objects/screens for interacting with digital world, but also move beyond the conventional Tangible Interaction with physical "objects". Instead, I propose to embed computing within the physical **material units** itself. Here, we interact directly with the material, the same way as a maker interacts with the raw material such as clay. This material then can bring different forms or features to represent "objects"- as the product of process of design.

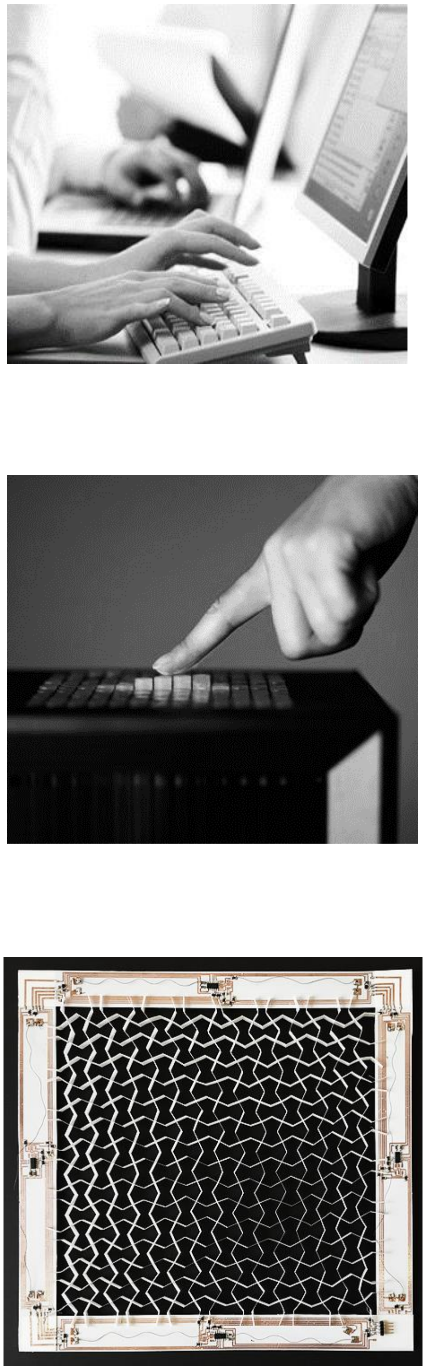

Figure 8: From Ubiquitous Computing to Augmented Materials

3.3. Active Components as raw materials

Augmentation is the process that connects inert physical material to the world of digital bits. The bridge between physical and digital worlds consists of hardware electrical components, such as sensors, actuators, microcontrollers and other functional components. By embedding these hardware components directly within a broad range of inert materials and objects, we can bring the functionalities of digital computing to the physical world.

The definition of Augmented Material opposes the traditional notion in physical computing, where computation happens in a separate physical entity that encompasses parts or all the electronic hardware machinery. Specifically, in conventional Physical Computing systems, there's a tendency to keep the computational brain separated from the rest of physical entity of the system. This computer, which can be a simple Arduino board, a raspberry pie board, or a desktop computer, then gets connected to separate Input/ Output devices in order to communicate with physical world.

> In Augmented materials, I propose to rethink the perspective that separates electric hardware and inert material as two separate physical entities, and to treat *active hardware as a part of raw material library* that can be integrated with inert material in all phases of design to fabrication of a physical interface.

From technical aspect, this approach is highly inspired by Robotic (McEvoy and Correll, 2015) which has been introduced in the second chapter. However, Augmented Materials are focused on the *human interaction* as the controlling agent for defining behavior and properties of a system. What enables us to tread active components as raw materials is based on two arguments regarding the current advances in technology:

Electric components are increasingly small, accessible, and cheap

Advances in semi-conductor manufacturing and MEMS technologies has made active components increasingly cheap and accessible. Today, one can access a broad range of active components, from op-amps and registers to microprocessors to variety of sensors, in the price range of cents to few dollars. Moreover, there components are becoming increasingly accurate and powerful while shrinking in size, which enables us to embed these components in small-scaled objects and material structures. With these opportunities in hand, there will be no actual reason to differentiate between active components and inert materials. What remain will be designer's imagination and skillset to integrate active components alongside inert material while designing physical artifacts, and to make use of their computational capabilities in order to create material system with extraordinary features and capabilities.

Digital Fabrication technologies enable us to fabricate hybrid systems

Digital Fabrication Technologies allow integration of active and passive materials in a fabricated physical entity. From desktop 3D printers that allow precise fabrication of material system in micro-scale, to advanced additive manufacturing techniques that allow users to place active components and electrical traces alongside the base material, advances in digital fabrication enables designer fabricate physical systems with embedded active components. From the other side, development of broad range of conductive inks that can be printed using off-the-shelf printers as well as flexible electronics manufacturing enables designers to integrate electrical circuitry and hardware within physical artifacts and material systems.

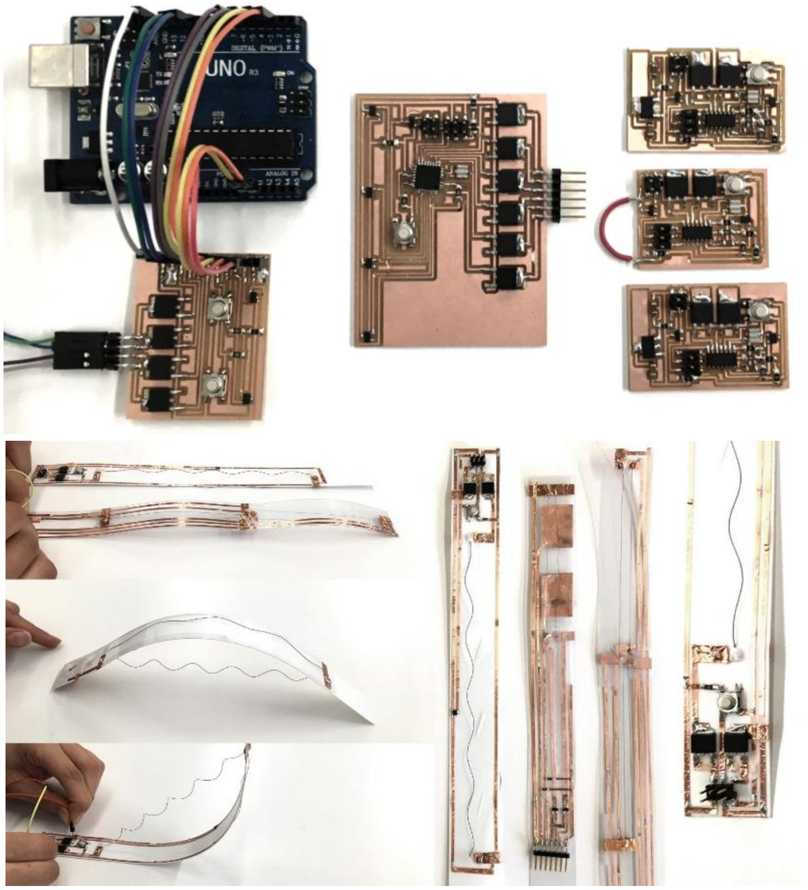

Figure 9: Transition from off-the-shelf Arduino board to embedded computation in NURBSforms Project (reference to chapter 6)

3. 4. Properties of Augmented Materials

In this section, I will elaborate on features and properties that follow the definition of Augmented Materials. In the context of design, if we accept to consider material as the stuff that “objects” are made of, then, material should be an instance that can be formed to various shapes and functionalities to create objects. We start our definition from here, and elaborate on what properties an entity should have to be considered as a material. Next, we will elaborate on augmentation aspect, and will elaborate on the fundamental properties that will be brought by physical computing.

3. 4. 1. Continuous VS. Discrete: Modularity

To our perception, a material can be perceived continuous or discreet. Most of the materials found in nature, such as clay, stone, and metals, are perceived continuous. I emphasize on the word perceive, because if we go beyond our natural perception, for example using a microscope, such classification changes. Under a heavy microscope, we observe the same continuous natural materials as discrete, consisting from millions of molecules, and even further, from sub-atomic particles.

While natural material are mainly perceived continuous, digital world is inherently and physically discrete. While this might change in the future when bio-computers replace the electrical hardware that we have today, at the time being, all the hardware and machinery that makes digital computation possible is also physically digital. For example, we can’t cut a microcontroller into half and have two smaller micro-controllers! However, on the bright side, electrical components are becoming smaller and smaller in size by day, which enables us to integrate them with inert material and still small-scale objects and physical entities.

Positioning Augmented Materials as the bridge between digital and physical, we need to follow the limitations of the more restricted side, which makes augmented materials to be discrete, and *modular*. This definition follows the definition of Digital Materials introduced in the first Chapter, or more simply put, follows LEGO concept in sense of modularity. Through assembling the base modules together, on can create objects and structures across ranges of scales and complexities.

3. 4. 2. Scale and Resolution

Scale is what determines how we perceive a modular system: depending on the ratio between scales of modules to the scale of assembled structure, we tend to perceive structure as a continuous entity with different resolutions. If we are to create an augmented material module, which in turn creates structural assemblies and objects, we have to have scalability in mind from the beginning of design stage.

In case of raw materials, it’s relatively easy to create modules with different scales, and thus creating objects with different resolution. For example, with similar base plastic material, you can create LEGO pieces in range of millimeters to meters. However, in digital world, increasing resolution has long been one of the big goals and motivations of industries. The reason is that increasing the resolution directly correlated to decreasing the size of hardware components and machinery, which comes with the high price of advancing technology.

Here, again, we are bound by the limitations of technical side, which limits how small the base modules can be. However, on the bright side, electrical components are becoming smaller size by day, and one can expect this trend to continue for a while. Using components smaller than the scale of millimeter, we can now provide almost any digital functional capabilities. This small size of active components, alongside the advances in digital fabrication technologies, enable us to create a small-scaled physical system that itself can be considered as a base module for a macro-scale objects and structures.

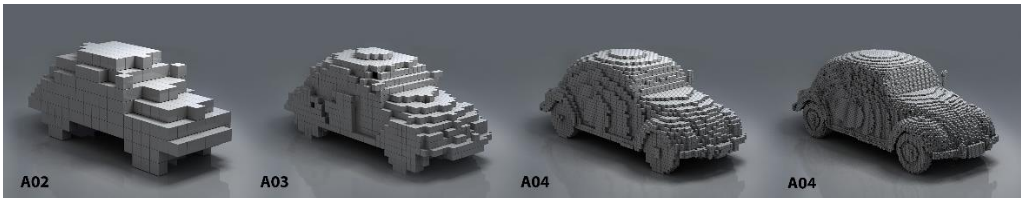

Figure 10: Effect of scale on resolution. From: http://www.bilderzucht.de/blog/3d-pixel-voxel/

3. 4. 3. Reversibility and Repeatability

When talking about inert materials, we can associate reversibility and repeatability directly to the modularity, which refers to the degree to which a system's components may be separated and recombined. To make a physical system reversible, all we need is to devise joining mechanism that allow attachment and detachment of modules.

However, when talking about active systems, we need to revise and expand our definition. In active system, it’s not only the assembly of components that goes under transitions, but transformations in shape, color, stiffness, and texture will come naturally with any actuated mechanism. Coelho defines Reversibility and Reputability in active and shape-changing system as followed: “Reversibility is the capacity of a material to change to a new state and return to its original condition, and repeatability is its capacity to repeat the transformation process innumerous times without considerable performance decay.” (Coelho, 2009).

Especially when dealing with shape-changing mechanisms, reversibility and repeatability should be an important criteria for choosing the actuation mechanism.

3. 4. 4. Human Interaction

Sensing enables an interactive system to sense and receive data from physical world, translate it to bits of data, and send it to the computer. In interactive systems, sensors can extract data from both the users as well as the environment. However, in augmented materials, we’re specifically interested in human interaction.

As a design and making interface, our main goal in Augmented Materials is to provide an intuitive and bodily interaction as close as possible to the interaction between designer and inert material during the process of making and crafts. In the ideal model for Augmented Material, the same interaction that a maker creates with an inert material- for example, a piece of clay- is achieved by interacting with augmented interface. The main difference is that an augmented material would be able to “Sense” every aspect of this user interaction and “translate and restore” it as a set of bit-mapped data. For example, an Augmented Clay would be able to sense touch, force, gesture, heat, moisture, and texture, and restore the data from each of these sensors in its memory for further computation.

While such image is out of reach regarding today’s state of the art in sensor technologies and Human-Computer Interaction methods, we still have a range of options for enabling at least individual components of the image we drew. The input systems to use within augmented materials can range from embedded sensors such as motion tracking sensors, haptic sensors, and pressure sensors to sophisticated systems such as Leap Motion, Kinect and brain-computer interfaces.

3. 4. 5. Transformation: Actuation

Actuation is the process of translating digital data into the physical and tangible action. Actuation can be in form of changes in shape, volume, stiffness, color, texture, and etc. In creating augmented materials, these transformations play a key role in the bit-atom hybrid system, as they are the direct representation of underlying computation within the system.

As reviewed in the previous section, actuation in the physical material is a complex problem when creating Non-GUI interfaces. In contrast to the pixels on the screen that can change their state in real time and synchronous with the underlying bits, creating any form of transformation in the physical material requires a noticeable amount of energy, time, and force. This makes actuation to be one of the most challenging aspects in creating shape-changing physical systems. In order for the actuators to provide transformations in scale of human perception and interaction, they tend to get heavy, bulky and highly energy consuming. This makes it difficult to embed usual actuators, such as motors and hydraulic systems, in material scale.

On the bright side, advancement in technologies in Micro-Electro-Mechanical Systems (MEMS), material science and robotics is making it possible to create smaller, more powerful and more efficient actuators. Still, finding the proper actuator, the one that can be embedded in a small-scale physical system while providing the favorable performance is highly challenging. Some features of the actuators that need to be considered are: Bulkiness, Stiffness, Speed, Force, Range, Resolution, Power Consumption, Risk, and Cost.

Figure 11: Material-based actuators can bring novel and efficient shape-change to Augmented Material systems. From Top/left: Bi-material shape-changing composites, Origami-based Pneumatic Muscles, Pneumatic actuators and Shape-memory Alloys.

3. 4. 6. Embedded Computation

In order to interface with the world of bits, materials need to be embedded with hardware components that enable embedded computation. These components are called *Microprocessors.*

A microprocessor is a computer processor which incorporates the functions of a central processing unit on a single integrated circuit or at most a few integrated circuits. Microprocessors are the computational brains of all the embedded systems we currently know of. From desktop computers to smart wearables to Arduino prototyping boards, Microprocessor is what connects a software *program* to an input /output hardware system. While integrating sensors and actuators enables the data to be communicated between the world of bits and atoms, embedding microprocessors within the material allows it to *function* according to a software *program.*

Embedded computation is the last, and probably most important piece in creating Augmented Materials, because it provides **programmability, autonomy, and connectivity** between physical materials and digital bits. By embedding microprocessors directly within the modules of physical material, we can define the functionality and behavior of a physical system, as well as its degree of autonomy and communication with other modules, all in the scale of its constituting modules.

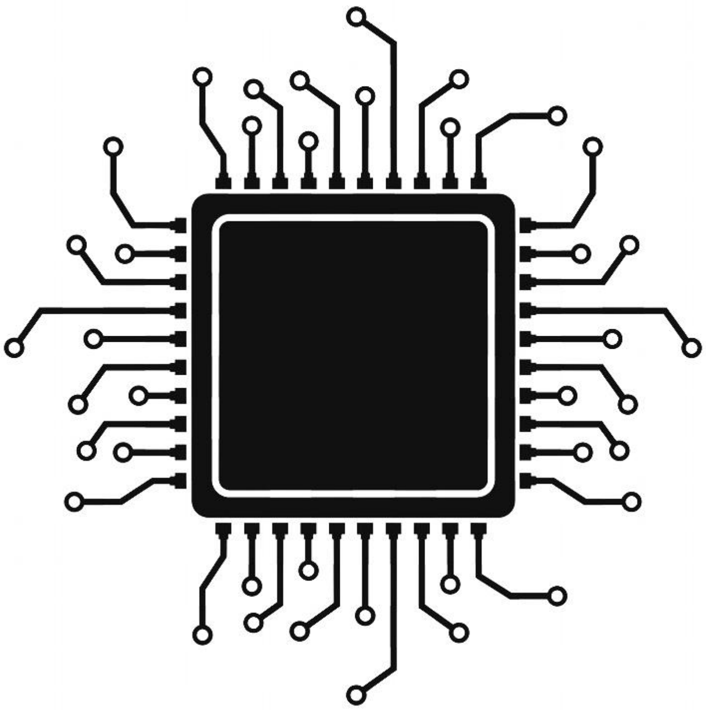

Figure 12: Microprocessor: how the brain looks like

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As opposed to conventional interactive systems…

For the time being, conventional method in creating input/output system relies on having a central processing board, as an external physical entity, to operate the computation on input and output signal. "Although it might be possible to route actuation signals and sensing information in and out of the material to where this information is processed centrally, this approach becomes increasingly difficult with both the required bandwidth and the number of sensors and actuators to be embedded." (McEvoy and Correl, 2015)

With advances in technology enabling us to have the computational power of 1990s super computers in a millimeter-scales chips, we are able to embed almost any macro-scale object with the same computational capability. More interesting is that fact that you can buy such microcomputers with the price range of cents to few dollars. This is the power of computation on a silver platter!

As opposed to re-active systems…

Embedded computing enables us to *program* the way that a system responds to external stimuli. Given a set of input data gathered through the sensors, embedded computation lets us to process this data with any desired level of computation, and define the way that the system responds to the stimuli based on the program burnt into the microprocessor. This capability opposes the notion of re-active systems, where the relationship between environmental stimuli and system's reaction is pre-determined. Material-based reactive systems, such as heat-responsive and humidity-responsive shape-changing materials and thermochromics inks are among the examples for reactive systems.

Programmability and Autonomy

A software program can be fused into a microprocessor, determining the way it processes the data and responds to different external stimuli. In theory, programmability does not have a time and trial limit: you can re-program a microprocessor as many times as you want. This translates into: you can change and determine the behavior of a physical system in as many ways as you want.

The other feature arising from embedded computation is allowing to create different levels of modules of the system. With embedded computation, alongside embedded sensors and actuator, a material module can act on its own and autonomously react to the external stimuli. This can help create a range of agent-based behavior and applications.

3. 4. 7. Connectivity and Communication

Embedding microcontroller and computation within the modules of material offers not only localized computation enabling programmability and autonomy, but also the ability to communicate information and data between different modules as well as an external computer.

Microcomputers can communicate with each other through various communication methods, including wired (i.e. Serial Communication, I2C Communication) and wireless (Bluetooth and Wi-Fi) protocols. Using processor-to-processor communication, we can create a pervasive system including local processors throughout a material system, and being able to communicate and correlate between them all. "Local computation becomes particularly interesting when individual processing nodes can access information from neighboring nodes via local communication." (McEvoy and Correl, 2015)

While local processing brings the opportunity to localize some computation within each module, having a central control over modules of a system is be favorable in some instances. For example, in a system, individual modules can localize the computation regarding sensing and actuation, but also listening to a central brain for more general commands such as *start* and *stop*. The communication between embedded microprocessor and a central computer replaces the usual central input/output control, which is highly limited by the number of input/output pins on a central microcontroller. This aspect of scalability becomes crucial if we ones to go beyond a handful number of input/outputs, and create a truly modular system that can increase in number of modules.

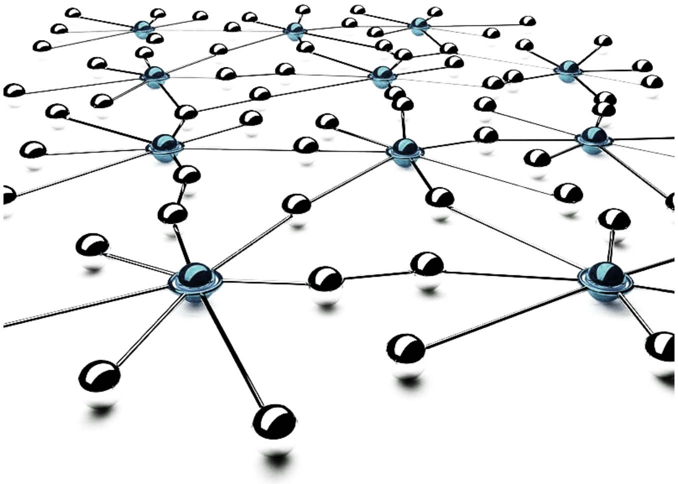

Figure 13: Conceptual drawing of a network communication between embedded microcomputers

4. Preliminary Case Study: Struct[k]it

Struct[k]it is a physical modeling toolkit for making, analyzing and learning structures. Focused on *intuitive and embodied knowledge acquisition* about structural analysis and behavior, I've created a modular strut-based toolkit that gives real-time feedback about the axial forces within each structural module to the user.

Struct[k]it helps designers make and learn structural systems through a hands-on engagement with a physical interface. Using Struct[k]it, the user incrementally assembles and refines a physical model augmented by real-time feedback about axial forces. This coupling of physical model making and the visual feedback on the otherwise abstract data builds a noble tangible interface which helps building an intuitive understanding about the structural analysis.

Each unit of Struct[k]it interface is embedded with Force sensors on both ends, length-long RGB LED strip for visualization of the force data, a computational brain and batteries. Through this integrated system, the data about the structural force in each structural member is directly extracted through the sensors, and is then mapped to the 256 bit RGB value of the embedded LEDs. Ranging in the color spectrum of Red to Blue, the colored light emitted from each member will represents the Tension to Compression stresses in each module.

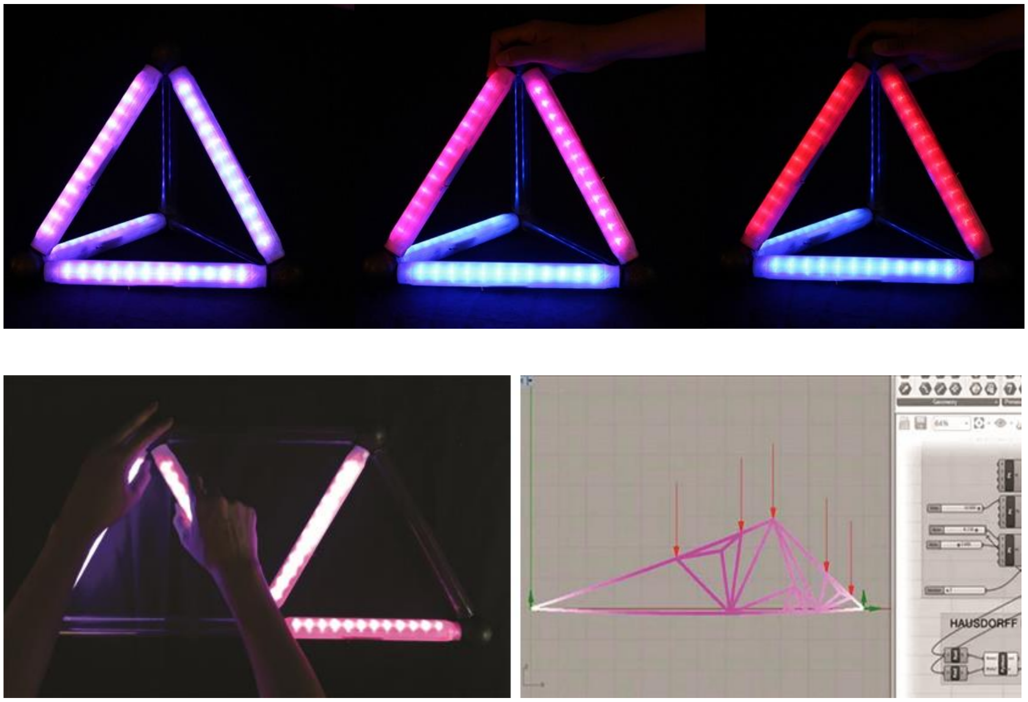

Figure 14: Struct[k]it Toolkit

4.1. Vision

Structural analysis is a central topic in architectural design and building construction, and gaining a profound understanding of the subject is critical for students in the fields of architecture and civil engineering. However, due to the computational and abstract nature of structural analysis, students and novices usually lack the intuitive understanding about the structural behavior. Traditionally, structural analysis is being taught as a pure mathematical calculation-based course dealing with numerous formulas and calculation of the forces and stresses within structural systems. More recently, Finite Element Modeling-based structural analysis software are being used by students and professionals for analyzing structural stability. While both of these methods provide accurate numerical measurements regarding structural analysis, they both lack the intuitive representation of structural behavior. Such representation is more critical for the students who are learning these concepts for the first time, as such knowledge will follow them throughout their career.

In Struct[k]it, the idea is to give a *tangible representation* to the forces within structural elements, which provides real feedback about the structural analysis to the designer. Struct[k]it is visualizing the forces and stresses within each structural module by changing its color. Following the familiar red-to-blue color coding for tension-compression stress representation used in the educational materials, each module of Struct[k]it emits colored light in the spectrum red to blue, representing axial stress in range of full compression to full tension within the module.

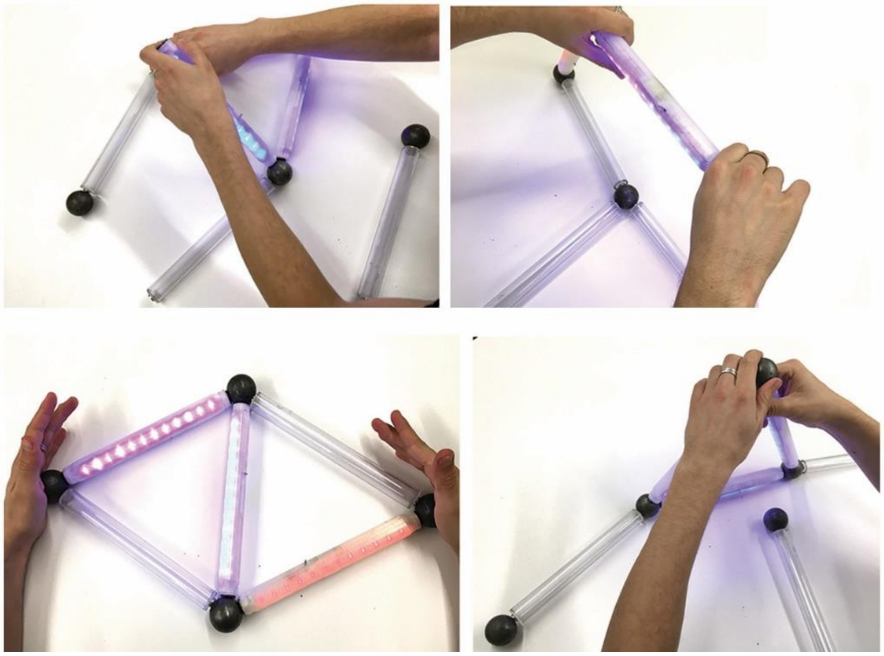

Figure 15: Struct[k]it Toolkit

4.2. Design

Following the guidelines of Augmented Materials, Struct[k]it is realized as a modular, LEGO-like system. Struct[k]it Modules can be assembled together in many ways, enabling designer to create complex structures. Anything constructed can then be taken apart again and the pieces being reused, enabling an iterative making process. Each module is designed as a strut, and assembled structures take shape in form of trusses and space frames. The modules are designed in CAD software, with details regarding location and housing of electrical components being specified in the CAD design.

In order to provide highest flexibility to the joints in terms of number of elements as well as the angle between them at each node, the joints are perfect spheres that accept connections equally throughout their surface area. The connection force between joints and struts are provided through *Magnetic force.* At each end, the struts are embedded with a high-pull Nickle-plated Neodymium[1]. Joints are pure steel spheres, which creates strong connection with the magnets at the two ends of struts.

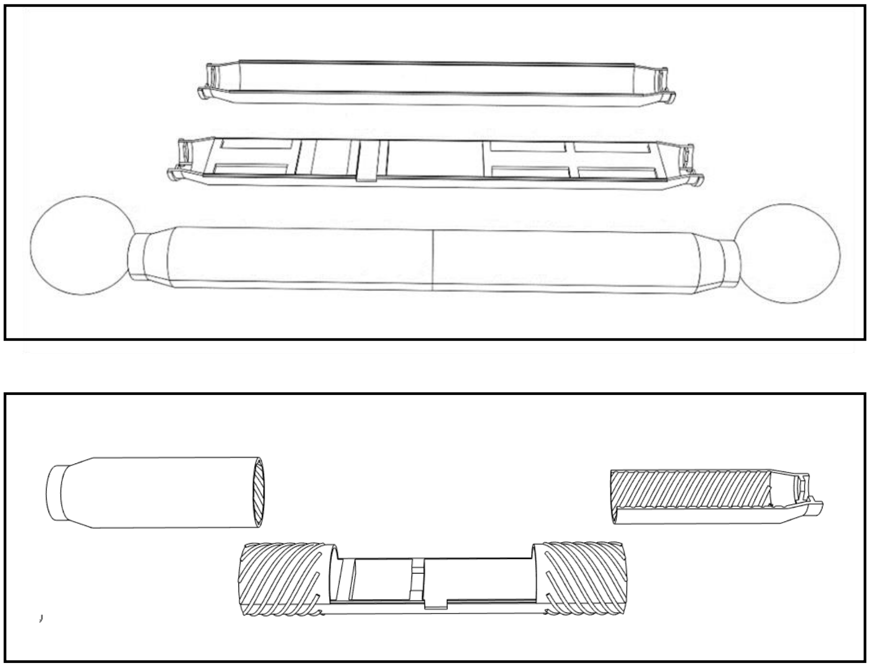

Figure 16: Top: Basic Struct[k]it Module, Bottom: Strut module with adjustable length

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[1] https://www.mcmaster.com/#magnets/=1ch35vf

4.3. Augmentation

Embedded computing and sensor technologies are the keys to creation of Struct[k]it. In sense[k]it, an augmentation within the strut modules have enabled them to *Sense* the axial stress, Analyze this data using *Micro-computer*, and outputting *Visual Feedback* about the structural state of each module through changing its color. In this section, I'll give a brief overview to the three main elements of sensing, computation, and actuation which construct this augmentation.

4.3.1 Sensing

Through embedding sensors within structural elements (struts), the measurement of axial stress can be directly extracted from physical material. This replaces the enormous computation that is needed for software simulation and structural analysis calculation. In order to extract the tension/compression data, I embedded Force-Sensitive Resistors (FSRs) at the two ends of each strut element which act as *force sensors*. Force-sensitive resistors consist of a conductive polymer material whose resistance changes when a force, pressure or mechanical stress is being applied to them. Through measuring the change in resistance, one can infer the amount of force being applied on the sensor. While change in resistance is not easily measurable using on-circuit components, this change can be translated to change in voltage using a simple *voltage-divider* schema in the circuit design. Variation in voltage can then be read by any microcontroller through *analog input*.

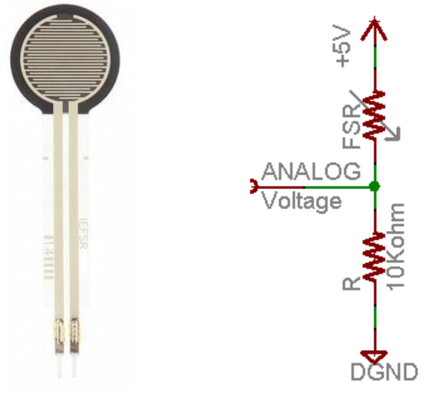

Figure 17. Left: FSR Sensor, Right: Voltage-divider circuitry for reading voltage from variable resistance

An issue with using FSRs for measuring axial stress (i.e. tension and compression) is that FSR sensors can only measure applied force in form of pressure (compression.) Here, In order to use the sensor for measuring *tension*, I have put the sensors in a pre-compressed state. In this way, having the strut in tension will decrease the amount of pre-compression at two ends, and having the element in compression will increase the pressure on the sensors. The pre-compression force has been provided through magnetic forces between strut and joint, with FSR sensor being critically placed in between magnets connected to the end of strut and spherical steel joints.

4.3.2. Embedded Computing

A microcontroller can read the voltage change through one of its Input pins. Either using a usual Arduino board or using a stand-alone microcontroller, the ADC (Analog to Digital conversion) input pins are easily found and addressable through software. After reading the raw voltage data through an input pin, this data will get calibrated and smoothed in order to give useable measurement of force input. At the final stage, the cleaned data gets remapped to 8-bit value (0-256) and gets represented through the coloring of RGB LED outputs.

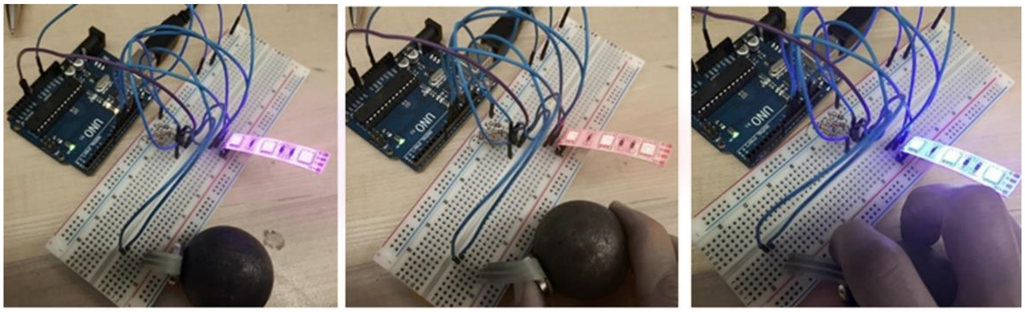

Figure 18: Demonstration of FSR Sensor situated between magnet (to be placed at the end of strut modules) and spherical steel joint.

Left: *In the neutral state, the sensor is in pre-compressed mode, and the purple output color represents the neutral state.*

Middle: *By increasing pressure between magnet and joint (representing compression mode), the amount of pressure on the sensor increases, which is shown by Red output color.*

Right: *By adding separating force between magnet and joint (representing tension mode), the amount of pressure on sensor decreases, which is shown by blue output color.*

4.3.3. Actuation

The variation in coloring of strut elements have been implemented through embedding a piece of RGB LED Strip within the semi-transparent plastic shell of the struts. The color of light emitted from RGB LEDs is determined by three 8-bit values representing the amount of RED, GREEN and BLUE light that is being emitted by LED. In Sense[k]it, the amount of Green color is always set to 0. The 8-bit values for RED and BLUE colors are directly provided by the microcontroller, which is the result of analysis stage based on the input data from Force-sensitive resistors. The more the element is under compression, the higher the value of RED and the lower the value of BLUE (element under compression gets more and more red). The opposite happens when the element goes under tension: the more tension the element is under, the more the BLUE hue gets dominant.

4.4. Fabrication

Integration of raw material and the elements of augmentation (i.e. Sensing, actuation and embedded computation) is enabled through embedding electrical components and circuitry within the physical modules, which can be done by employing digital fabrication technologies. In order to have the physical computing components as compact as possible, I designed and fabrication my own custom circuit boards. I designed my custom made PCD using Eagle PCB design and schematic Software[2], and fabricated the PCBs through milling copper boards using Roland Mill milling machine. For making the connections between sensors, LED strip and the main board, I hand-cut copper tape and soldered the ends to the components and the board for reliable connection. The casing has been designed using Rhino software, with the locations and housing of circuit board and other elements defined in the digital design. The casing has been 3D printed using semi-transparent filament on Makerbot3D printers.

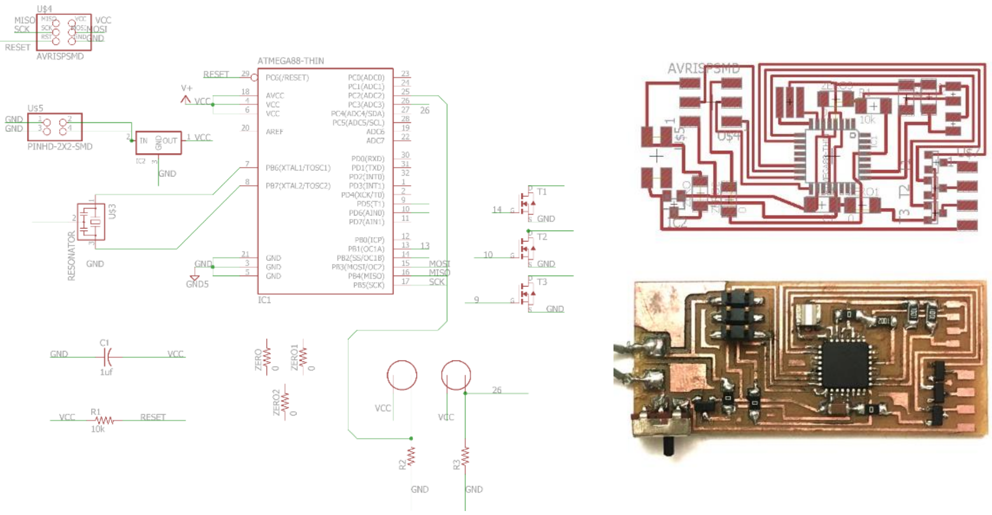

Figure 19: Left: Schematic drawn with Eagle Software, right: PCB Design and fabrication

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[2] https://www.autodesk.com/products/eagle/overview

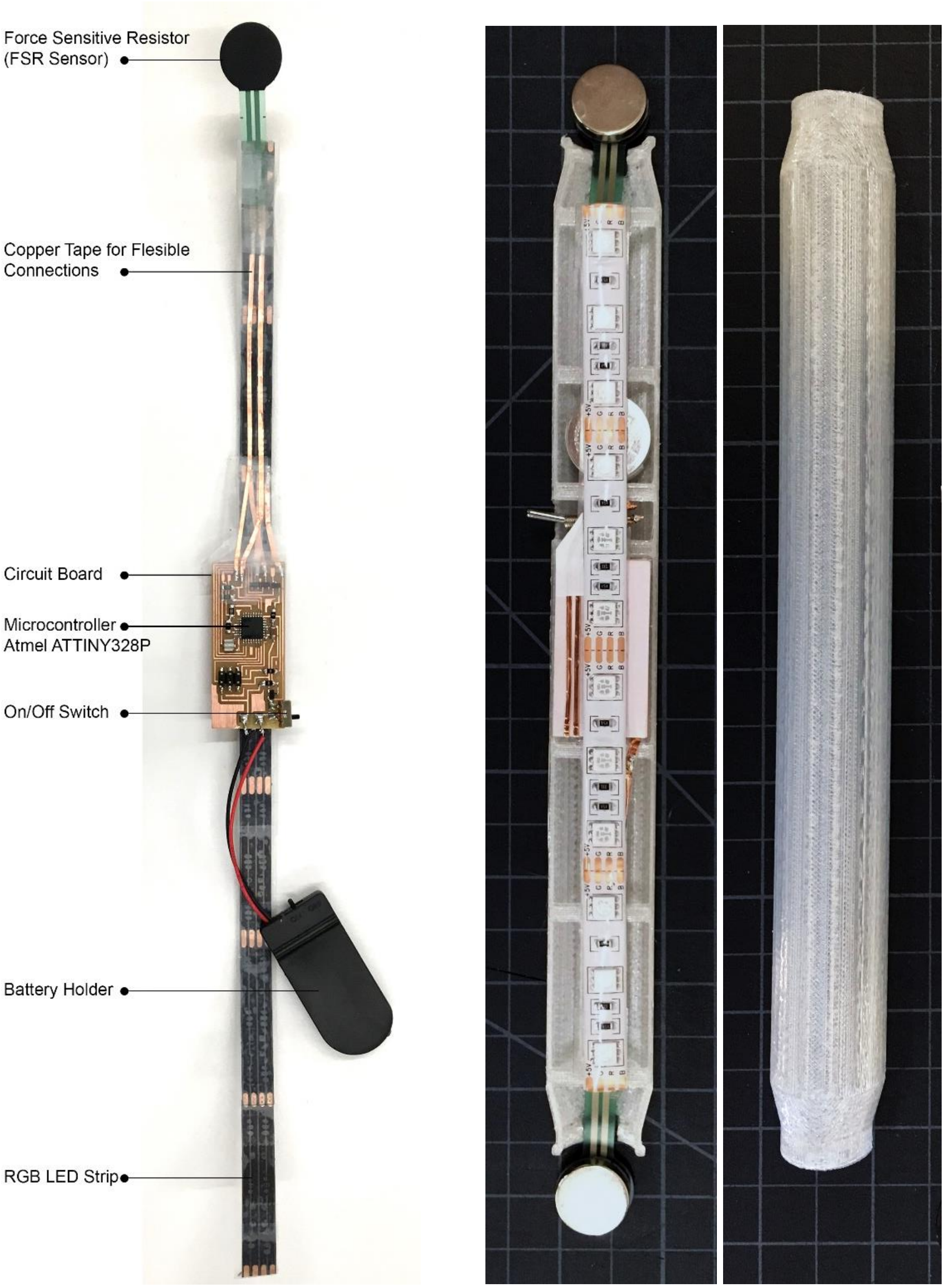

Figure 20: Fabrication of Struct[k]it Module

4.5. Extended Application

While the main incentive behind Struct[k]it project is to create a toolkit to be used by designers during early stages of design, making and learning, there is no technical barrier in scaling up the technology and implementing it in full-scale architectural components. Here, my goal is to emphasize on the scalability of the system, and to propose potential implementations of Struct[k]it. Either as an installation or as a part of interior or exterior architecture, Struct[k]it can be an artistic representation of forces within a structure. A large scale implementation of Struct[k]it combines the concept of illumination with the visualization of digital data, which can act as a playful and informative piece in public spaces.

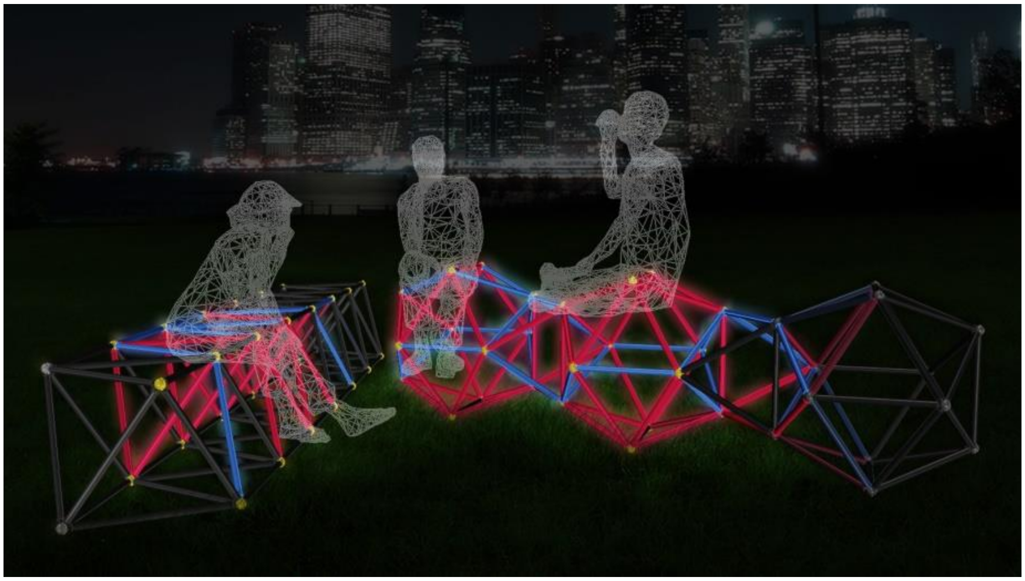

Figure 21: Demonstration of large-scale implementation on Struct[k]it

5. Case Study: NURBSforms

5. 1. Vision

Today, CAD software has made it possible to create digital models of free-form curves and surfaces quickly and easily. In NURBS-based software, such as Rhino, this task can be done as easily as drawing lines and surfaces and manipulating their curvature by moving their control points. This gives designer the ability to quickly iterate on their design and explore design space. Doing the same task in physical world (making) requires a high-level mastery in model making, and requires significant amount of time and resources, which makes it impossible to iterate on design as easily and freely as one does using digital tools. On the other hand, the richness of multi-sensory interaction with material is itself a source of embodied design knowledge that enhances design process and creativity.

> My goal is to create a novel interface that bridges between digital and manual model making. I've created NURBSforms, a shape-changing interface that lets designers create and manipulate *curves and free form surfaces* in a physical form, just as easily as they do in Computer-aided design software.

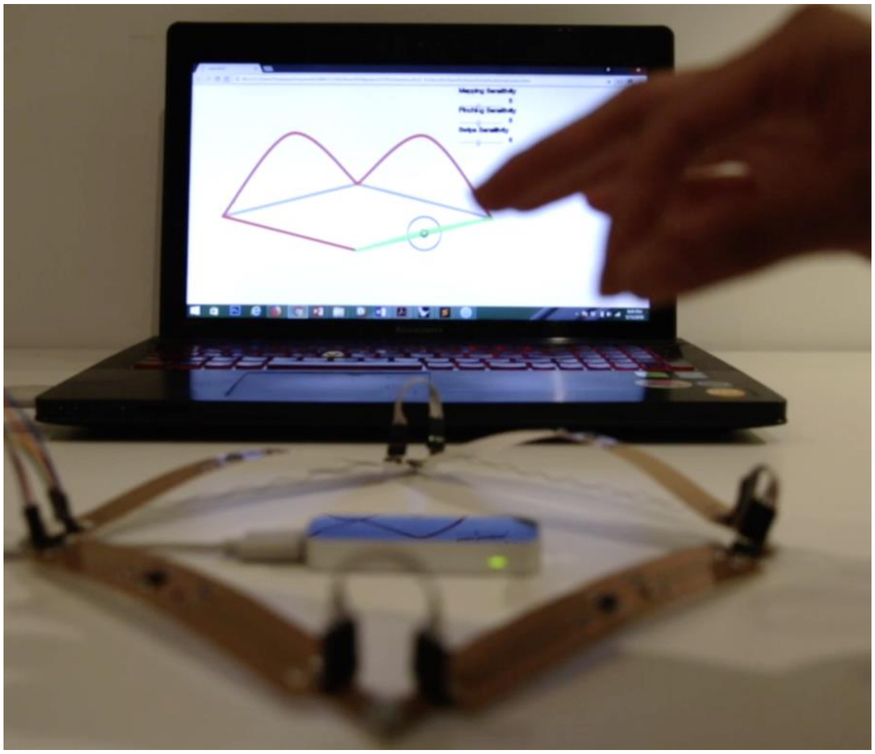

Figure 22: NURBSforms Interface

5. 2. NURBSforms interface

NURBSforms is a modular shape-changing interface that lets designers create and manipulate curves in physical form, just as easily as they do in CAD software. Each module of NURBSforms represents a *base curve* with one *control point* on its midpoint, which determines its amount of curvature. Similar to NURBS-based software such as Rhino, user can manipulate and control the curvature by moving the control points. By connecting multiple base-curves together, the designer can create more complex curves and surfaces in 2D or 3D space. Physical connection between modules is provided by magnets at the two ends of the module, and electric connection is provided through male-female 4-PIN headers.

NURBSforms bridges between digital and physical model making by bringing digital capabilities such as such as transformation, programmability, repeatability and reversibility to the physical material. Through embedding *sensors, actuators and computation* directly within physical modules, I have created an augmented material that senses user interaction, performs computational processing, and represents digital data and computational processes through transformation in its physical modules. This transformation directly represents the shape of curves designed by the user.

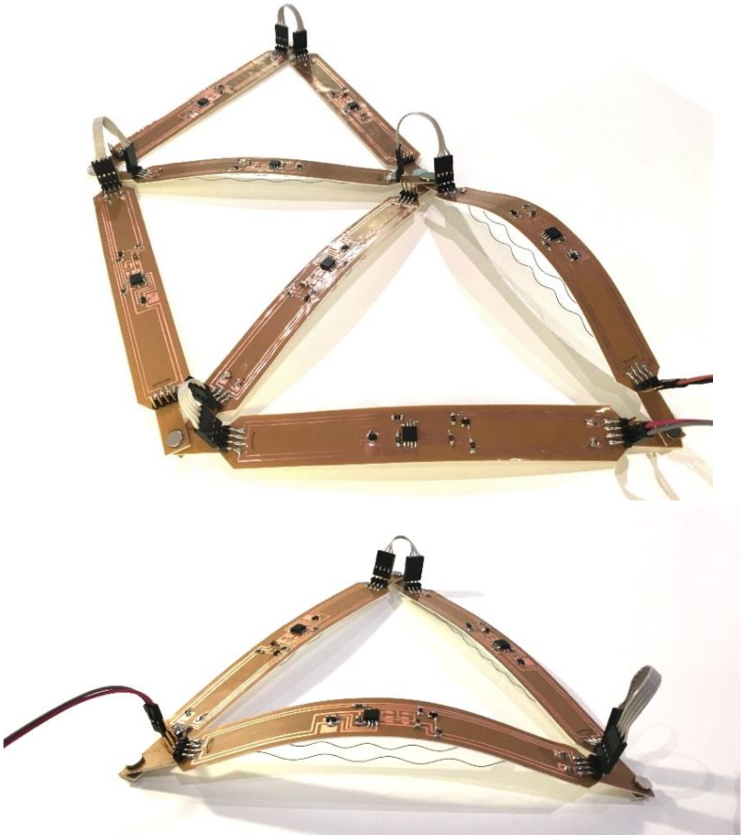

Figure 23: NURBSforms modules aggregation

5. 3. NURBSforms Module

The base NURBSforms module is an augmented material that is embedded with sensor, actuator, microprocessor, and flexible circuitry directly on its surface. This enables a module to sense user interaction, process input data, change its shape, and act as an agent in an aggregation of modules shaping a designed NURBS curve or surface.

- **Transformation:** The base module is *actuated*, which enables its real-time transformation from flat to curved state. The amount of curvature is determined by the amount of current flowing through the actuator.
- **Embedded Sensing:** The embedded sensors enables direct manipulation from user to control the curvature.
- **Embedded Computation:** Embedded computation enables module to process information locally, as well as enabling communication with other modules as well as an external computer.
- **Communication:** Each module is tagged with a *unique address*, which makes it possible to be recognized and addressed via other modules or a computer, regardless of overall configuration of all modules.

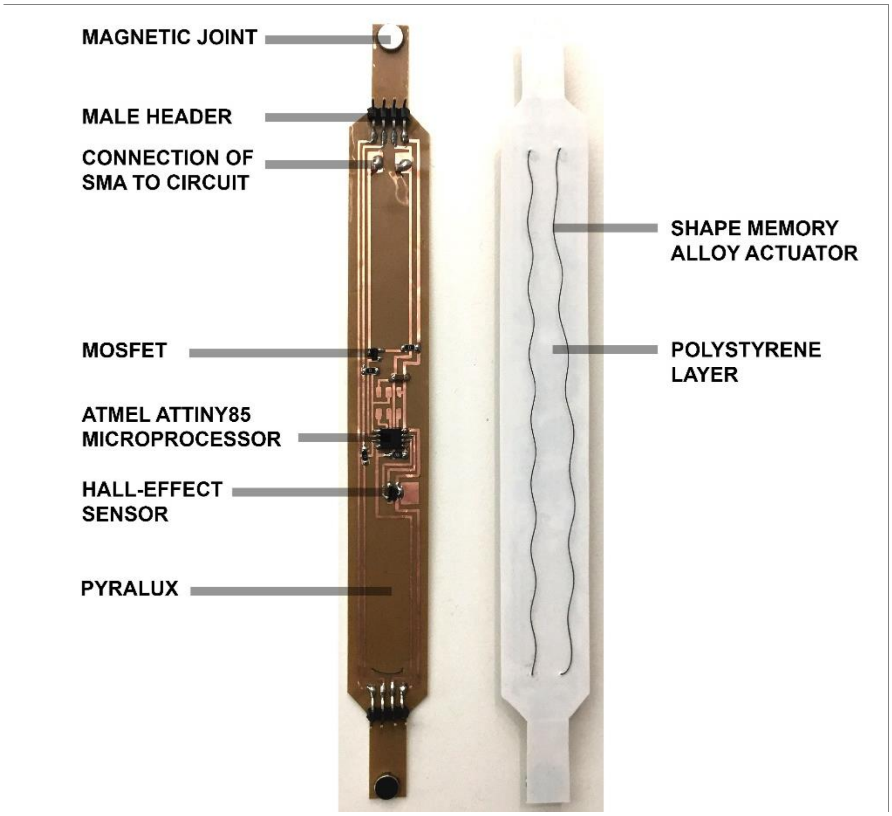

Figure 24: NURBSforms Base Module

5. 3. 1. Transformation

Each NURBSforms module is embedded with Nitinol Shape-memory Alloy actuator. “A Shape Memory Alloy (SMA) is an alloy that is able to “memorize” and “recover” its original shape after it has been deformed, via heating over its transformation temperature.”(Huang, 1998). When a shape-memory alloy is in its cold state, the metal is malleable and can be bent or stretched and will hold those shapes until heated above the transition temperature. Upon heating, the shape changes to its original “memorized” state.

I have executed the shape-memory property of Nitinol SMA Wire to control bending curvature of NURBSform module. In its cold state, the elasticity of the Polystyrene strip stretches the Nitinol wire and straightens it. When being heated, the wire transitions to its memorized state to the form of a *spring.* This applied a pulling force on the two ends of the strip and bends it towards the opposite direction.

Figure 25: SMA Actuator providing controllable curvature

While generic form of shape memory alloys- known under the name of Muscle Wires- shrinks for around 10% of its length when getting heated, *training* SMA provides an opportunity to bring larger transformations. Training refers to the process by which material "memorizes" a new state as an original state. In this project, I have trained nitinol into the shape of spring, which provides large amount of change in length when transitioning between states.

In this project, the heat needed for shape transition in Nitinol is provided by Joules heating, which is generated by applying electric current through Nitinol wire. The amount of shape-change corresponds to the amount of voltage applied to the two ends of actuator. This voltage is controlled by embedded microprocessor via Pulse-width modulation.

Figure 26: SMA Actuator creating variable curvature

5. 3. 2. Embedded Sensing

Each NURBSforms module is embedded with a Hall-effect sensor, which enables user's interaction via direct manipulation. As we will see in section ……, NURBSforms interface can be interacted with via a centralized sensor such as a Leap Motion or video-based processing. However, an embedded sensor can be taken advantage of when a central control is not desired.

In such condition, a module will act as an *autonomous agent*, which react to user interaction individually via its internal sensing and computation capability. This behavior resembles the simple biological systems that integrate sensing, computation and actuator to interact with their environment.

A Hall-Effect sensor is a transducer that varies its output voltage in response to a magnetic field. In other words, a Hall-effect sensor detects the direction and magnitude of magnetic field, induced by proximity of a magnet to the sensor.

The choice of Hall-effect sensor is a response to the requirement for control signal in NURBSforms module: In order to have full control over the curvature, two values of *direction* and *magnitude* is needed. A magnetic field can represent both values: positive or negative polarity of magnetic field determines the direction, and the intensity of magnetic field determine the magnitude of shape-change. While Hall-effect sensor may not seem as the first choice for a user interface, its extreme compactness, as well as its low price, makes it a perfect fit for embedded sensor in NURBSform module. The only downside is that in order to interact with modules, the user needs to hold a piece of magnet in hand, or to attach it on her fingertips.

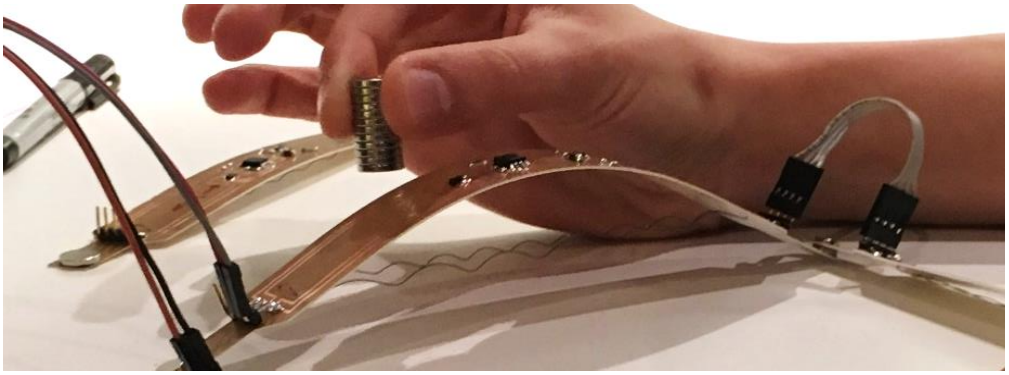

Figure 27: Magnet-induced control over curvature

5. 3. 3. Embedded Computation

Each NURBSforms module is embedded with an Atmel ATTINY85 microprocessor. This simple microprocessor with 4 I/O pins localizes a part of computation as well as facilitates the communication between modules. Each module is *tagged with a unique address* specified by the code burnt in the microprocessor. This enables each modules to be *individually addressesable* in a network of communication, for example, when an external central computer is controlling the curvature of interface. A module works in two modes of Autonomous and Synchronized:

Autonomous mode:

In autonomous mode, each module reads the data from embedded sensor, and responds to it with mapping the input data to output value for actuating Shape Memory Alloy. This computation if fully internalized and autonomous, and the microcontroller is responsible for adapting the output voltage in response to the *Direction, intensity and duration* of magnetic field. In Autonomous mode, these is no exchange of data between modules. In order for a module to work in Autonomous mode, it only needs to connect to the power source via its GND and 5V header pins attached at the two ends of the modules.

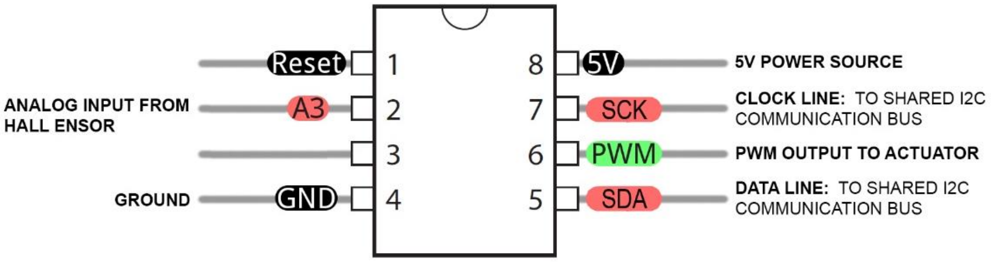

Figure 28: ATTINY85 pinout and pin assignment in NURBSforms Module

Synchronized mode:

In Synchronized mode, each module listens to the incoming data from a central computer (Master) via its Data Line (SDA) pin, and matches the output value for controlling actuator in response to the incoming data.

5. 3. 4. Data Communication

Communication between modules and a central computer (I.e. Arduino board) is established through I2C protocol. I2C protocol is an efficient communication protocol suitable for data transfer between microprocessor. The communication can be established between all the modules through 2 shared bus lines of SCA and SDK (in addition to shared VCC and GND). Each microprocessor is known and addressed by the unique tag specified in its embedded program. Using this unique address, the central computer (Master) can control all the modules individually using the same shared bus.

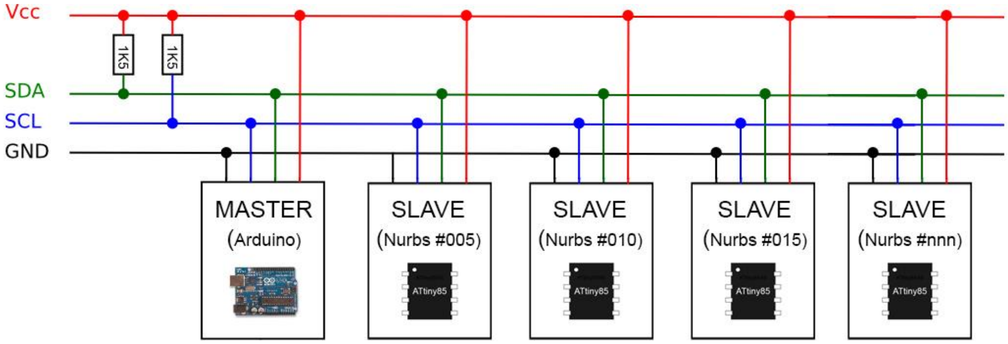

Figure 29: I2C Communication Diagram

5. 3. 5. Fabrication

The body of NURBSforms module is itself a spread flexible circuit board that places functional components at their allocated positions throughout the surface area. The base material for flexible circuit is DuPont *Pyralux®* copper clad laminates[3]. In order to increase stiffness and elasticity of the base module, a layer of Polystyrene (0.3mm thickness) is adhered to the back of Pyralux. Together, the two layers create the body of shape-changing modules. The Shape-Memory Nitinol wire is placed on the back of the strip, with its two ends going through the Pyralux and Polystyrene layers, and getting connected on soldered on the circuit board surface. At the two ends of module, two 4-pin male headers enable the electrical joint between modules. Two disk magnets create the mechanical joint, which gives freedom in number of modules as well as angling between the modules connecting at each joint. Following, I will give a short overview of two challenging aspects of fabrication of NURBSforms modules.

Flexible Circuit Production

For fabricating flexible circuit boards, I followed 4 main steps:

1. Creating a circuit board design with an image format
2. Transferring the circuit design on the Pyralux to act as a mask
3. Chemical etching to remove the excess copper from unmasked area
4. Removing the residue of mask to expose the copper traces

Among these steps, the first and the last are straightforward: after creating the circuit design in any CAD software, the traces can be exported in .png format. The image file is then used for creating the mask to be transferred on Pyralux.

Two usual methods for transferring the circuit design on Pyralux include 1) Direct printing on Pyralux using a Solid-Ink Printer, and 2) Applying Toner Transfer Method. Direct printing is be the most efficient way to transfer the circuit design and create the masks. However, I did not have access to a Solid Ink Printer. Toner Transfer technique is less reliable and more prone to miss traces. It can work well for small circuits, however, I couldn’t make it work for my scattered circuits. This led me to get creative: I attached a layer of Vinyl sticker on copper side of the Pyralux, and used a desktop Vinyl Cutter to cut the traces on the sticker. I then removed all the vinyl sticker except from the traces areas, leaving a nice and clean mask behind.

I used Ferric Chloride as chemical etchant for removing the excess copper. Ferric Chloride is not an environmental friendly chemical, but it works very well for delicate

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[3] http://www.dupont.com/products-and-services/electronic-electrical-materials/flexible-rigidflex-circuit-materials/brands/pyralux-flexible-circuit.html

circuit boards. I kept the solution in a closed container, and re-used it for making all of my circuit boards. For etching the circuit boards, I put the masked Pyralux inside of the closed container, hardly agitated it for 7-10 minutes, and then removed it from the solution and washed it with water. In this stage, all the copper is removed from the Pyralux except for the areas under vinyl. Lastly, I removed the vinyl traces, leaving the copper exposed and ready for soldering electronic components.

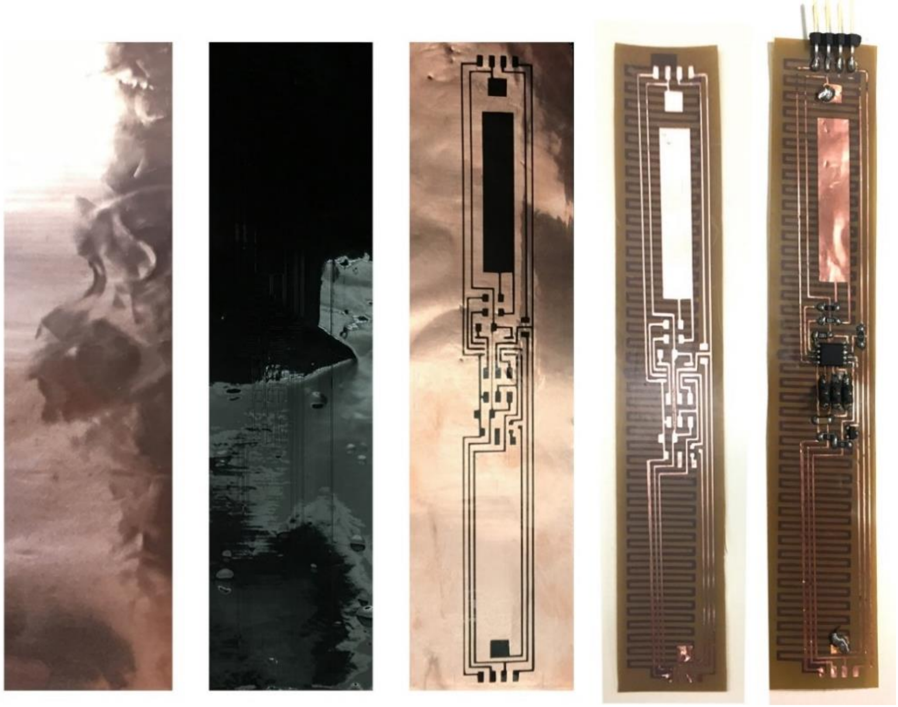

Figure 30: Flexible circuit fabrication

Customized Nitinol Training:

In order to achieve maximum deformation through Shape Memory Nitinol Actuators, I custom-trained Nitinol wires to have the shape of a spring as their *memorized* state. I Followed Marcelo Coelho's instructions (Coelho, 2008) for training Nitinol. This included 1) Restricting the nitinol wire to the desired shape, 2) heating it above 550 Celsius degrees for 13 minutes, and 3) quickly reducing its temperature by putting it into cold water. Following this process, the nitinol will shape into its trained state whenever it gets heated above its transformation temperatu 70 to 90 Celsius degrees.

Figure 31: SMA Training

5. 4. Interaction with NURBSforms

I have implemented two modalities for interacting with NURBSforms shape-changing interface: *Direct Manipulation* using embedded sensors, and *Gestural Control* using Leap motion sensor. Following, I will first introduce each method, and then show the results of two user experiments comparing the two interaction methods.

5. 4. 1. Direct Manipulation

Direct manipulation with NURBSforms module facilitates the embedded Hall-effect sensors and Autonomous control of modules. In order to interact with the interface, user can attach pieces of magnet to her fingers and touch the sensor area on modules. Depending on the polarity of magnet directed towards the sensor, the curvature would increase or decrease.

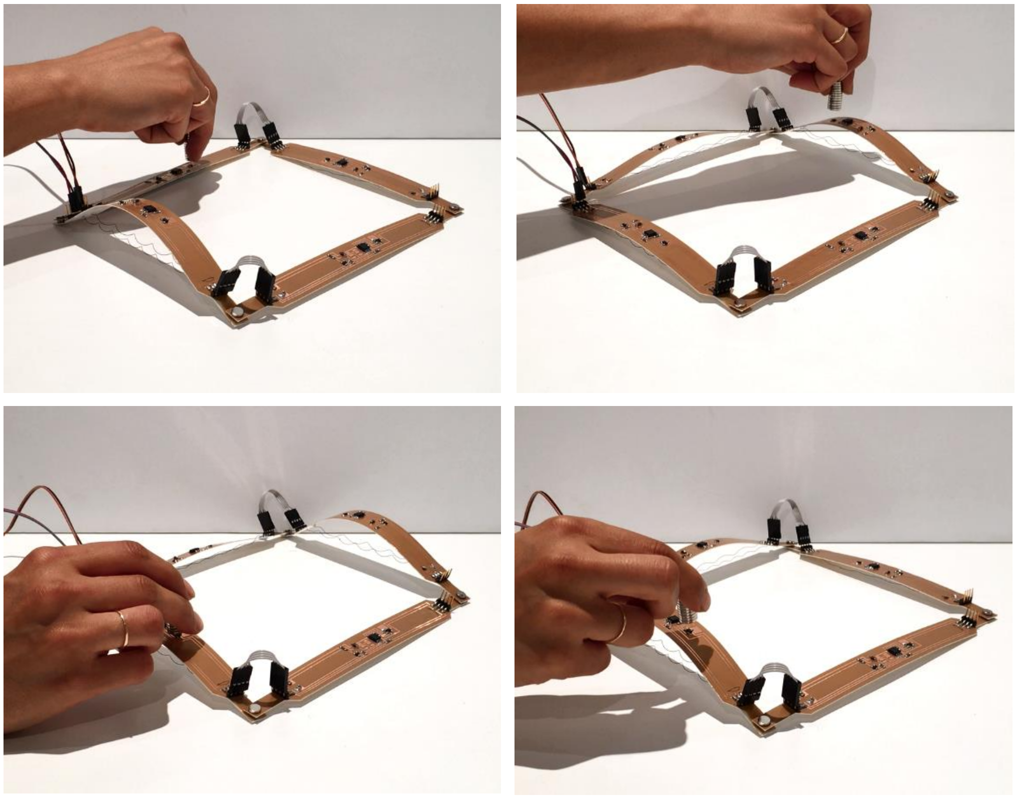

Figure 32: Direct Manipulation using Magnets

Extended Functions:

While direct manipulation provides a hands-on embodied modality to control the curvature of NURBSmodules, expanding functions of the system beyond curve manipulation is highly challenging. Because there is no centralized interface for the system, adding any extra functions, such as Save, Load and Reset, requires its own external interface. In the first prototype of NURBSforms, I implemented this interface in from of a button based pad with dedicated button for each additional functions of Save, Load, and Reset. Such external interface not only decreases the intuitiveness of the whole interface, it poses high degree of limitation in expanding the functions, As the complexity and the number of buttons can reach the point of making the interface unusable. I solved this problem by creating a central interface based on Gestural Control which I will introduce shortly.

Figure 33: Gestural Interaction

5. 4. 2. Gestural Interaction

Gestural control provides a natural way for interacting with NURBSforms interface. Using intuitive gestures such as pinching, a user can hover their hand over NURBS modules, grab their control point, and adjust the height of each curve. I have used Leap Motion sensor for detecting user's hand, and I have developed a JAVAScript code that works as central brain to detect hand motions and recognize gestures. The central system then sends controlling signals to the individual modules via an Arduino Uno.

In addition to the intuitive interaction provided by gestural control, having a central system has enabled me to easily extend the functions of the interface. Using gestural interface, implementing any additional functions such as Save, Load, and Reset is as easy as assigning different recognizable gestures to the system.

In the next section, I will describe the Gestural NURBSforms interface. To simplify, I have implemented the interface on a 4-moduled rectangular configuration.

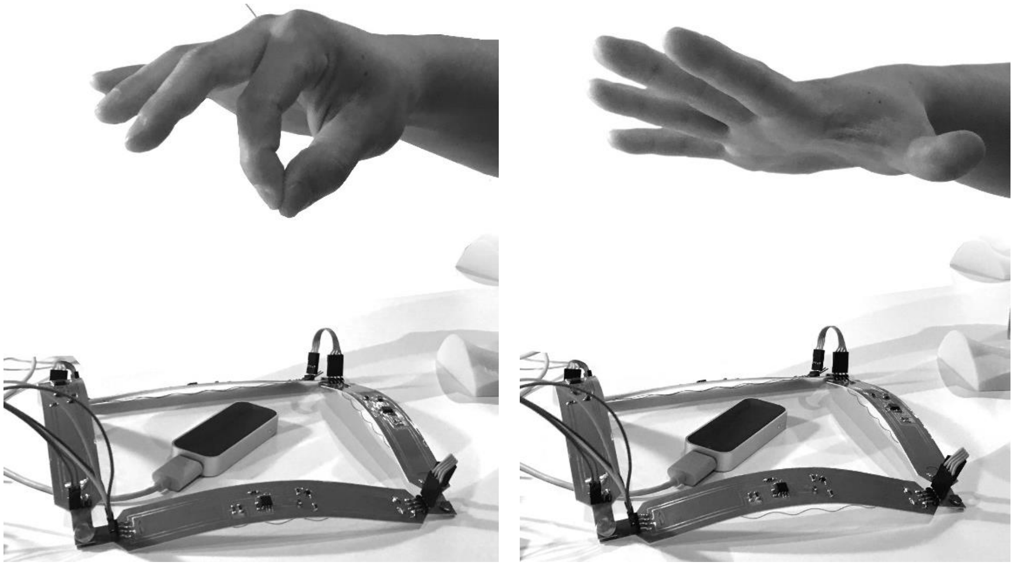

Figure 34: Gestural Interaction using Leap Motion sensor

System Components[4] :

NURBSforms Gestural Interface consists of three main components:

- NURBSforms modules connected to Arduino via I2C Bus
- Gestural interaction enabled by Leap Motion sensor
- Graphical User Interface

The Leap motion sensor measures the three dimensional position of the hand. The planar position of the hand is used from Leap Motion SDK to identify which curve to manipulate. I have used standard gestures such as pinch, grab and swipe from the SDK to trigger different functions in the system. To make simple visual interface for the interface, I've used P5.js Javascript library. P5.serialport is a serial Port API for p5.js to send serial data from the computer to Arduino. When the Arduino receives the serial data, it sends the data via I2C communication to NURBSforms modules.

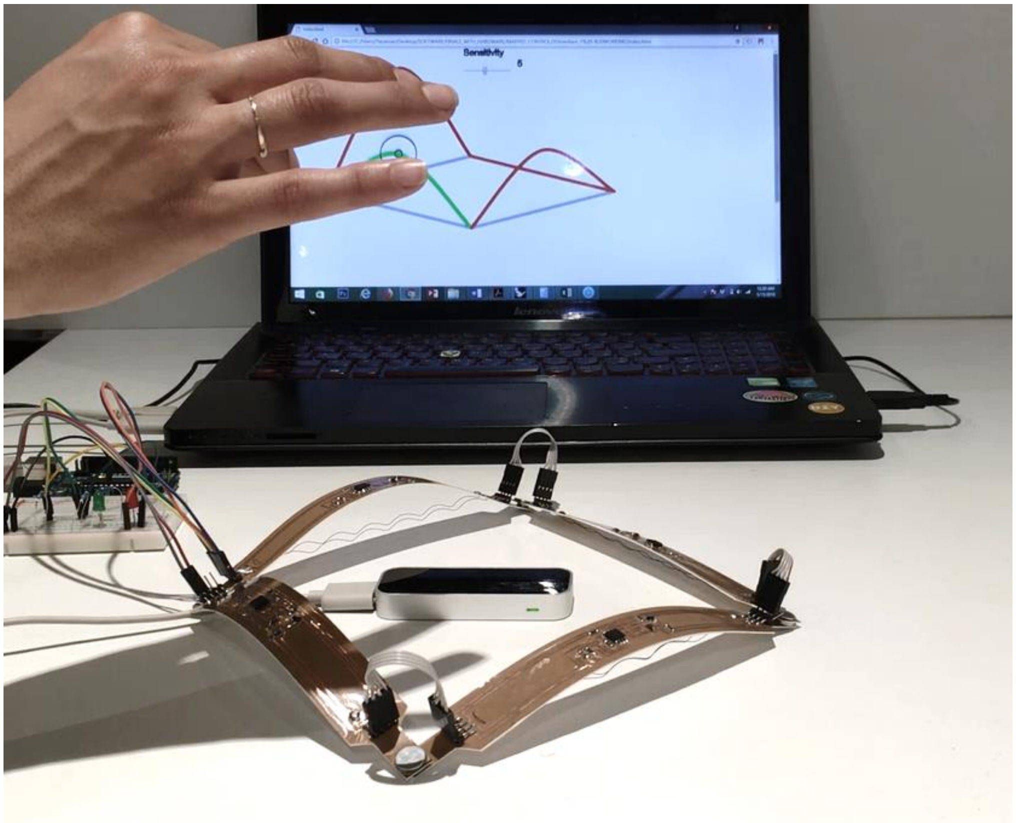

Figure 35: NURBSforms Gestural Interface

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[4] **Gestural Interface have been developed in collaboration with Hunmin Koh. Developing Graphical User Interface has been mainly Hunmin's individual contribution.*

Extended Functions:

SELECT

The user can hover her the above the physical interface to select a curve to manipulate. The actuator configuration is manually aligned with the visualization in the screen, so that the user can have more intuitive understanding of the selection and naturally understand its relationship with the visualization on the screen. The planar position of the hand is used to determine the curve that user wants to manipulate. When position above a desired curve, the selected curve is highlighted in the virtual model of our physical device in the computer.

Curve Manipulation (Pinching Gesture)

When the user PINCHES selected curve, the curve become activated and changes its curvature according to the relative vertical height of the hand. User can change and manipulate the curvature by moving their hand up or down as long as they keep the pinching gesture. When user is satisfied with the curvature, they can fix the position of the curve by releasing the pinch. The curvature of module will stay the same until the user selects, pinches, and manipulates the curvature in another cycle.

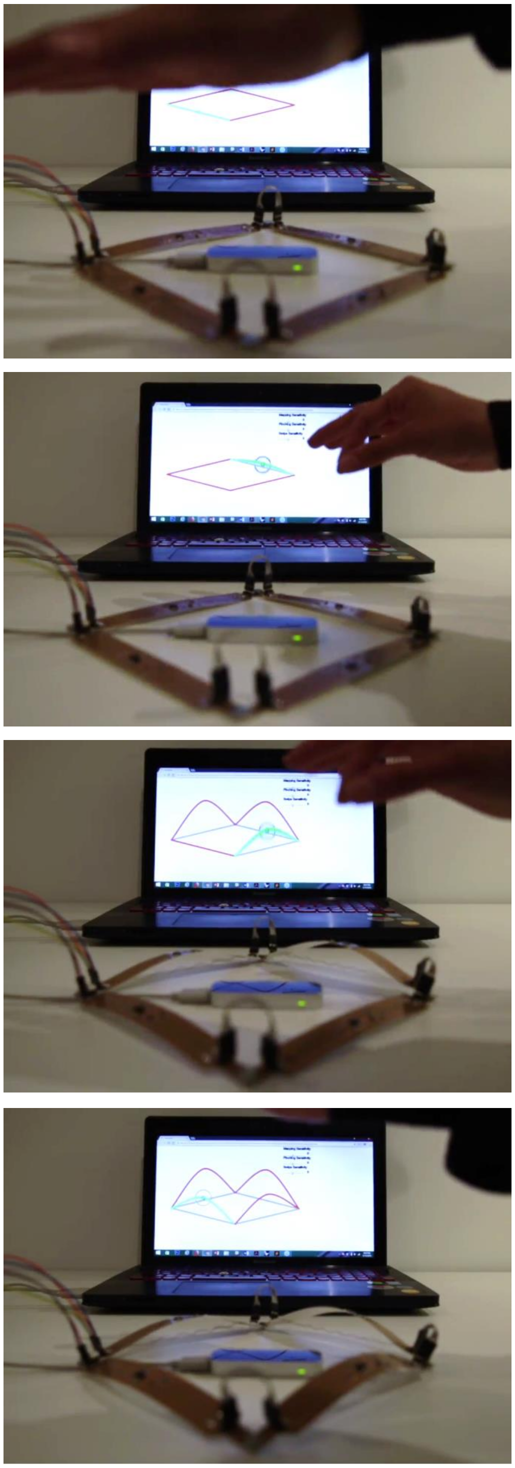

Figure 36: Gestural Interface. From top:
1: Curve Selection via Hovering,
2, 3, 4: Curve Manipulations via Pinching and pulling

SAVE
(Grabbing Gesture)

To save current shape, the user grabs the hand.By doing so, the position of control points of the curves are saved in the memory.

RESET
(Swiping Gesture)

To bringing all the modules back to the original state, the user swipes the hand over the leap motion.

LOAD
(Circle Gesture)

To load the saved design, the user draws a circle with an open palm over the Leap Motion. Save and Load functions are specifically useful when the user accidentally erases her design.

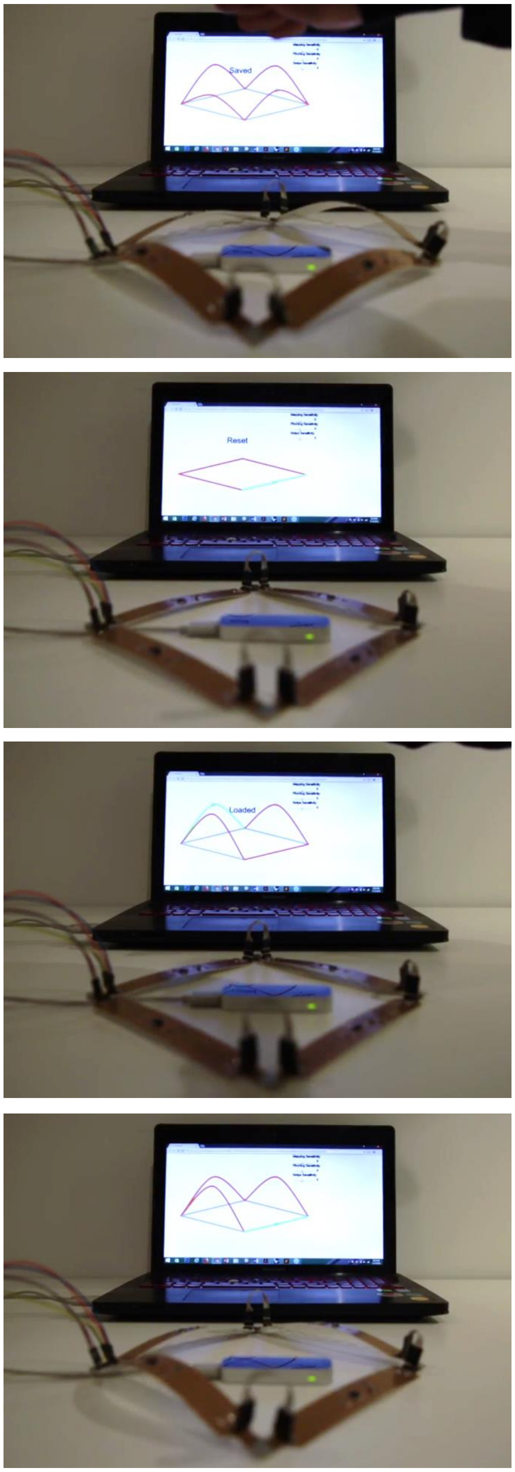

Figure 37: Gestural Interface. From top:
1: Saving via Grabbing Gesture,
2: Resetting via Swiping Gesture,
3: Loading via Circle gesture,
4: Loaded Model

5. 5. Evaluation: User Studies

In designing the user study, I focused on comparing the gestural interface with the button-based interface for controlling and manipulating the NURBSforms curves. The user experiment included two stages: first stage was aimed to evaluate the learnability of the interfaces, and the goal of second stage was to evaluate users' success rate in performing a specific task.

In the first stage, the users were handed a written manual of the interface, and were asked to start working with simple one-moduled interface and try to control its curvature. I asked users to self-report the moment they felt comfortable with controlling the curvature. Overall, in the first stage, users performed better with gestural interface. As opposed to Button based interface, all the participants succeeded to use gestural interface and control the curvature without asking any further question about the user manual. The time that took users to feel comfortable with Gestural interface was in average one/third of the time needed for the button based interface. From five participants, one was unable to work with Button-based until I performed the task and showed him how to use the magnet and sensor.

In the second stage, participant were asked to perform a simple modeling task using the four-actuator quadric configuration. The users were given a 3d printed model of a free-form surface, and were asked to replicate the shape using the NURBSform interface. Once the test was over, the participants were asked to fill out a questionnaire with 15 Likert questions and 3 open-ended questions

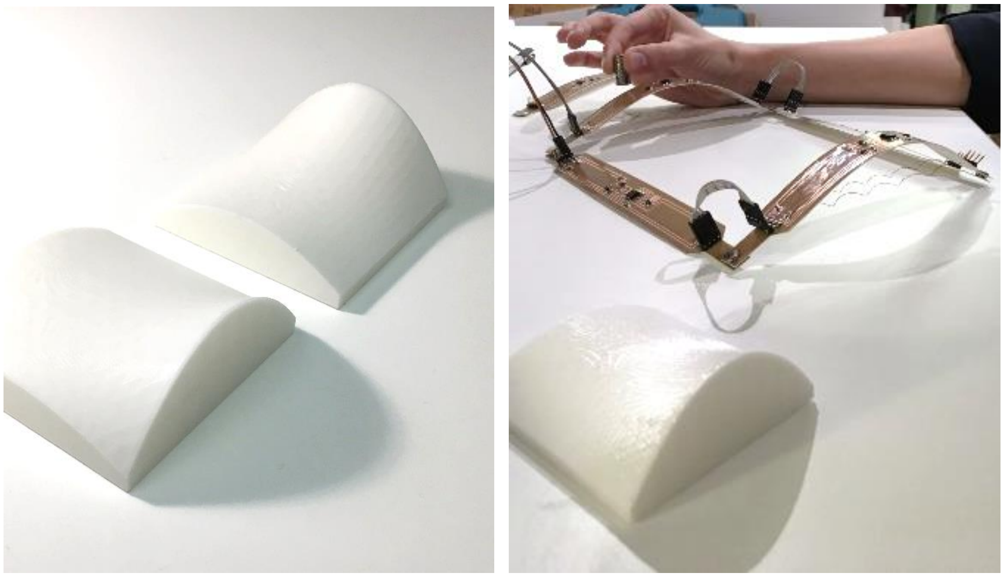

Figure 38: User Experiments

While both groups succeeded in replicating the reference object, the users were in general more satisfied with the experience of working with gestural interface. The main reason was that they found gestural interface more *intuitive*, *natural*, and *pleasurable* to work with. However, some users reported that they felt more *precise control* over direct-manipulation interface rather than gestural interface.

The other finding the user study was that the users found Graphical interface feedback very helpful, because it makes up for the latency that is natural to the physical actuators, and informs them about final state of the physical interface after ~second latency. As one participant stated: *"Precise + predictive feedback on the screen helped me understand what I was doing, since the time lag impacted physical feedback"*

Figure 39: User Experiments: Gestural Interface

… A few answers to open-ended questions from participants…

"Immediate, intuitive gesture felt good"

"In Gestural interface, the natural way of interaction is very comprehensive without requiring a lot of explanation."

"I felt more in control when manipulating with button. Physical attractors/magnets are always fun to work with! "

"(In gestural interface) the selection based control made it easier to switch between actuators. "

"It was easier to understand the physics behind the system and made it more logical in a mechanical sense, (maybe because I am familiar with electromagnetic field."

"Intuitive gesture was really nice, it translated a "natural" motion/activity into a gesture that performs a correlating task."

5. 6. Pilot Study

Identifying *embodied design knowledge* using NURBSforms Interface

> *"Design knowledge is knowing in action… It is mainly tacit, in several senses of the world: designers know more than they can say, and can best (or only) gain access to their knowing in action by putting themselves into the mode of doing."*
>
> *Donald Schon, 1987*

This thesis has been founded on the hypothesis of *embodied design knowledge*, defined as a tacit knowledge that exists within the harmony mind and hand, and is achieved through direct interaction between designer and physical material during the process of making. The notion of embodied design knowledge is theocratized within the fields of design, cognitive psychology, and computational fabrication, and can be further studied through quantitative and qualitative user studies.

In the context of digital design tools, we can identify embodied design knowledge by means of a user study that compares manual and digital model making. However, comparing the two is highly challenging, because their substantial disparities -such as ease, speed, and precision of modeling- makes any comparison between the two unjustified. Augmented Materials can be used to overcome the disparities between physical and digital, while keeping the essence of interaction modality intact.

In this section, I present a pilot study to evaluate *design knowledge in making* by means of NURBSforms interface, which allows me to compare digital and physical model making in a controlled manner.

To set up the study, I have defined three modalities of PHYSICAL, DIGITAL, and HYBRID interaction, each enabled by a simplified and/or modified version of NURBSforms Interface:

- **PHYSICAL** interface is based on Direct Manipulation mode of interaction with NURBSforms modules; it uses embedded sensors on the modules to sense user interaction, and the users control the curves via direct touch using magnets.
- **DIGITAL** interface employs Rhino CAD software to simulate NURBSforms modules in digital modality. The curve manipulation is enabled by selecting and moving midpoints of virtual curves.
- **HYBRID** interface is based on Gestural Control over NURBSforms modules; it couples physical interface with digital representation of curves on a display, and facilitates gestural control as the mode of interaction.

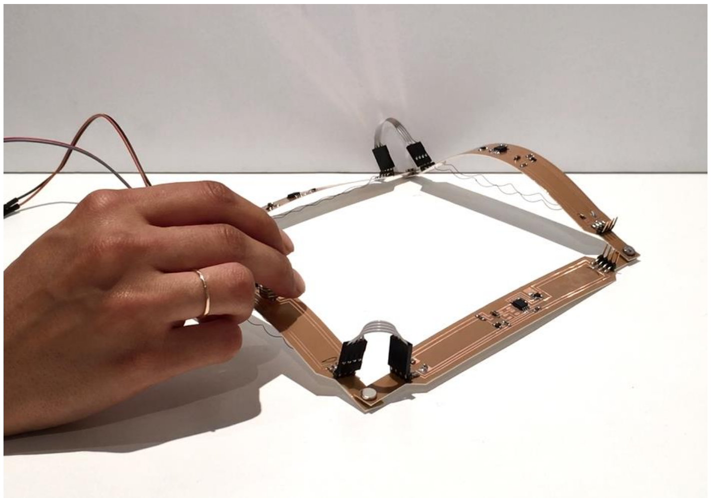

Figure 40: Physical Interface using direct manipulation with NURBSforms Modules

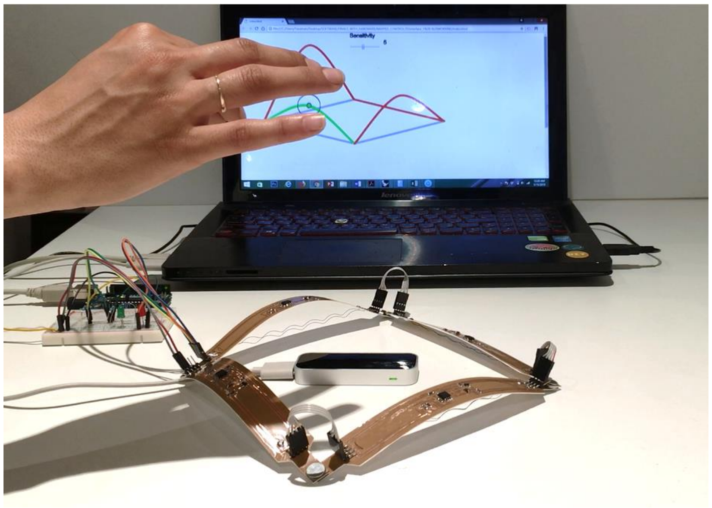

Figure 41: Hybrid Interface based on Gestural Interaction with NURBSforms Modules

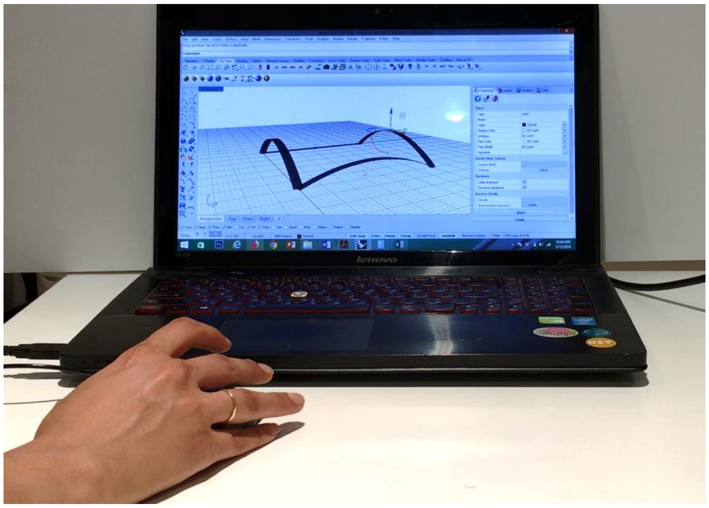

Figure 42: Digital Interface using Rhino software and a parametric model that simulates NURBSforms

5. 6. 1. The Experiment

Participants, divided in three groups, were each assigned to one interface. After getting comfortable with working with the interface, they were asked to perform modeling task, which is to replicate a 3D printed model of a free-form surface consisted of 4 edge curves. The **duration of their performance** until finishing the task, as well as **dimensions and proportions of their created model** have been recorded. After finishing the task, they were asked to write down their ***design story***.

I have used "The Strong Story Hypothesis"(Winston, 2011) as my theoretical framework to evaluate embodied design knowledge based on users' written stories. According to Strong Story Hypothesis, intelligible stories are indicators of high-level knowledge and intelligence. In the context of this study, I argue that the written stories are designer's self-reflection about their own thought and actions during design process, and coherent stories indicate richer design knowledge in process. I judged the written stories based on parameters such as the amount of detailed descriptions, sequence indications, causal statements, planning, and spatial and relational indicators.

Tell me your design story!

"You are to tell another designer exactly what you did, so that they can replicate your design process from the beginning to the end. Give them ***a step by step recipe of your thoughts and your actions.*** *Try to be as detailed as possible!"*

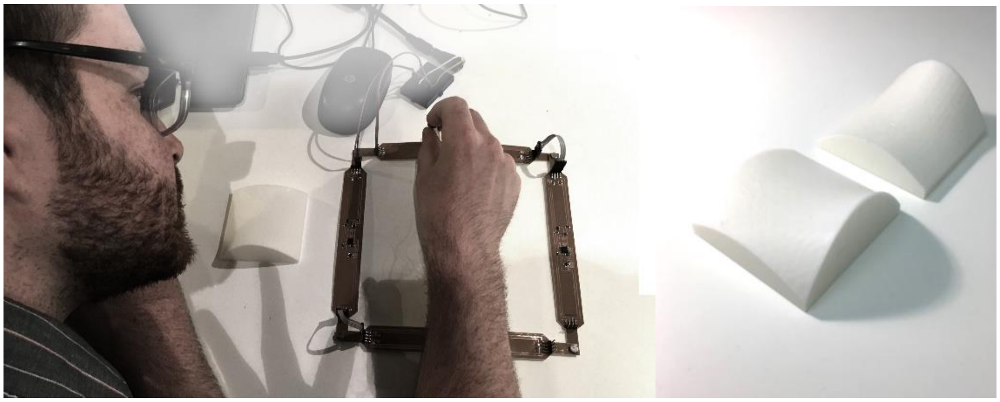

Figure 43: Pilot Study Setup

5. 6. 2. Results

Scale and Proportions:

After each user finished making their model, I documented the dimensions and proportions of their model based on height of each curve. The proportions of models created by three groups were compared with the proportions of reference model, and are represented in the following graph.

Both PHYSICAL and HYBRID groups succeeded in replicating models with satisfactory proportions. However, the DIGITAL group performed considerably weakly in keeping the scale and proportions of the reference object. The results of comparing proportions between the three modalities show how deceptive the on-screen 2D visualization of 3D models can be. These results also provide a quantitative proof of enhanced spatial cognition that results from *multi-sensory interaction and physical representation.*

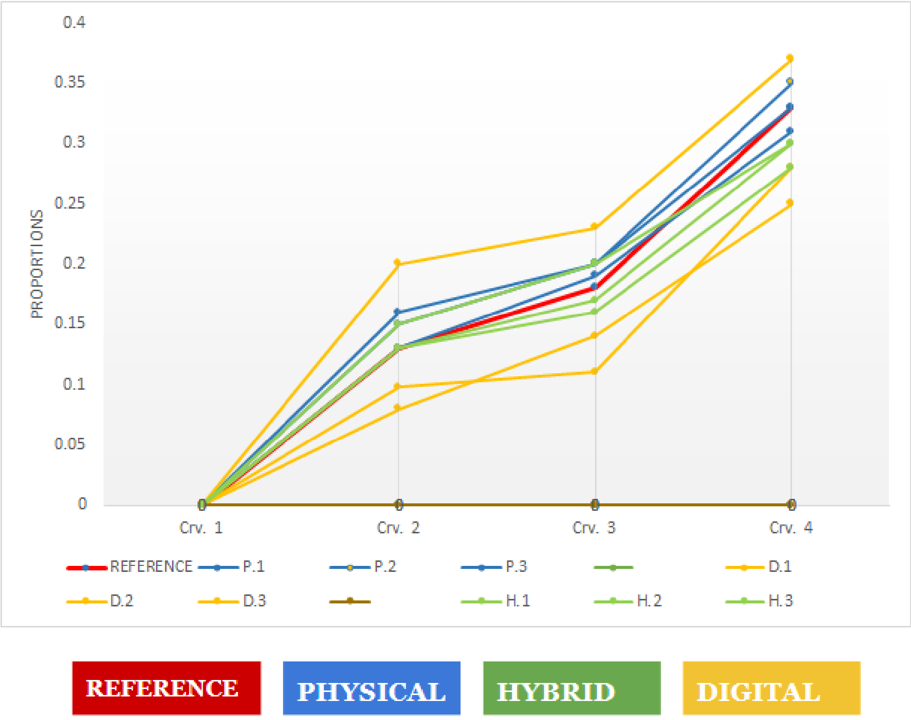

Figure 44: Scale and Proportion comparison graph

Time:

In average, DIGITAL and HYBRID group finished the task in 40 to 60 seconds. This duration was extended to 90-120 second in PHYSICAL group. The curious notion here is to remember that there is no actual, physical difference between the PHYSCAL and the HYBRID interfaces: they both work with the exact same hardware with the same response time of actuators. Thus, the longer duration of design process using PHYSICAL interface is only a result of interaction modality.

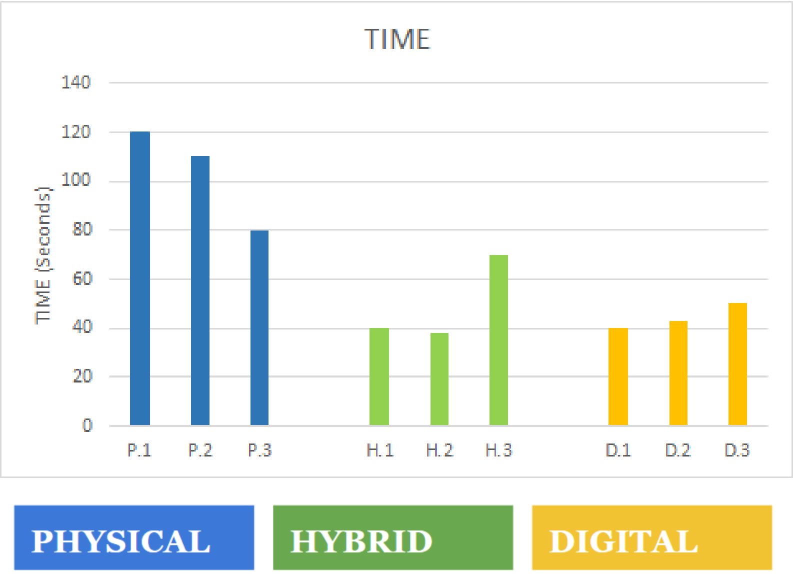

Figure 45: Comparison between duration of modeling using the three interfaces

Stories:

The comparison of stories between three groups sheds light on the timing graph: the stories of PHYSICAL group is significantly longer than the other two groups: The average word count of PHYSICAL stories is 112, for the HYBRID group it is 65, and for the DIGITAL group it is 58. Such pattern also shows up in comparing the number of steps that each user included in their story: in average, PHYSICAL stories include 6 steps, HYBRID stories include 5 steps, and DIGITAL stories include 3 steps.

By further analyzing the stories, I observed that the PHYSICAL stories have significantly higher amount of *detailed description, indications of spatial relationships, causal relationships, and planning*. Based on Strong-story hypothesis, these are the direct indication of an underlying intelligence, one that is unique to the group that directly interacted with physical material. Following are some of the examples from written stories by participants:

…

2. Start making from the curve on the opposite side of flat side - which does not need to change. Compare the height with the original shape.

3. Once the first side looks acceptable, start working on the side next to it with middle height. Try to make it higher than the previous one, but not too high. Keep comparing the two curves against the original shape.

Detail, Spatial Relationships, Reasoning

…

Start with the side that has least degree of curve, so that you can make sure of the stability of design.

…

Then, adjust the second highest curve to around ¾ of max height.

…

Planning ahead, Causal Reasoning, Spatial Relations

1. Lift the largest curved edge until desired height reached. Release.

2. Move to the adjacent "elevated" side and lift until height was about ½ of the side elevated before. Release.

3. Finally move to the last elevated curve, lift until slightly more elevated than step 2.

Missing Steps | Relationships, Detail

1. Study the geometry.

2. Study the features.

3. Start with the highest curve, adjust the others based on that.

4. Rotate the model to observe from 4 sides.

Lack of Details, Lack of sequencing, Missing Steps

…

I made three steps starting from the highest curve to the lowest one. I brought the midpoint to the height that corresponds the most to the requested 3D shape.

… How??

5. 6. 3. Conclusions

I emphasize that this work has been a pilot study, and further user experiments are needed to gather more data points and make more credible conclusions. However, as a pilot study, it is presenting promising results, which itself is the reason and motivation for future developments of this study.

The results of this pilot study provides evidence for the hypothesis on which I based this thesis: Physical interaction with material is a source of *embodied design knowledge*, a knowledge that is achieved through multi-sensory interaction with physical material, and is reflected both through the end-result of the design process, as well as designer's self-reflection on their own actions and thoughts.

Based on *analyzing proportions graph*, I conclude that multi-sensory interaction and physical representation enhance spatial cognition, and give designers superior sense of scale and proportions.

Based on *analyzing the stories*, I conclude that direct physical interaction enhances design knowledge in process. Users that work with PHYSICAL interface:

- They often don't miss steps, and their sequencing of actions are clear.
- They have better recollection of their own actions and thoughts during design process.
- They tend to make more spatial comparisons and relationships between different elements of designs, which helps them create more accurate models.
- They tend to follow sequential, causal and inferential process while creating a model, which shows coherency in their thoughts and actions during modeling.
- They tend to plan ahead their future actions, and act accordingly.

Based on comparing results of proportions graph, timing graph and story analysis, HYBRID interfaces can be considered as most efficient interfaces: In keeping scale/proportion, their performance level is similar to the one of PHYSICAL group, while they achieve this performance within the same time as DIGITAL group. However, in comparing design stories, their performance is weaker than PHYSICAL group, which emphasizes the effect of direct physical interaction on embodied design knowledge.

6. Conclusions

6. 1. Conclusion

In this thesis, I addressed the issue of separation of design and making in the context of computer-aided design tools. I explored this issue through the lens of Human-Computer interaction, and argued that *making* can be contextualized within HCI research by focusing on multi-sensory and tangible modalities of interaction. I then argued that if we want to enable physical interaction with computer-aided design tools, the material itself should become the interface between designer and computer.

By having material as interface, while the user interacts with material with their hands and body, they are reaching into, and interacting with, the underlying computation. I called such interface Augmented Material, and defined it as physical material that is augmented with digital capabilities such as sensing, computation, and actuation. These capabilities are enabled by embedding functional electrical components such as sensors, actuators, and microprocessors, directly within material system.

During development of this thesis, I explored parallel realms of *Bits and Atoms*, *Mind and Hand*, and *Design and Making.* As I progressed, the three domains got more and more intertwined, until getting united under the notion of Augmented Materials, where bits and atoms get integrated in order to reconnect mind and hand, and design and making.

I then presented NURBSforms as the proof of concept for Augmented Materials thesis. NURBSforms is an attempt to create a transformable matter that changes its physical form in response to the underlying bits, and offers an interface to designers for creating physical models that are connected and controlled by digital bits.

NURBSforms is a modular shape-changing interface that lets designers create curves and free-form surfaces in a physical form. Each module of NURBSforms represents a base curve with variable curvature, with the amount of its curvature being controlled by the designer, and represented through real-time actuation of material. NURBSforms bridges between digital and physical model making by bringing computational capabilities such as real-time transformation, programmability, repeatability and reversibility to the physical modality. The designer can control NURBSforms modules via direct manipulation or gestural interaction, and can take advantage of functions usually found in computer-aided design tools such as Save, Load, and Reset.

I concluded this thesis by conducting two sets of user experiments. The first experiment was aimed to evaluate the usability of NURBSforms as a design interface: participants from different backgrounds succeeded to work with the interface and to perform a simple modeling task including replicating a free-form surface. Alongside the selfreported satisfaction level of participants, this study indicated the successful implementation of the NURBSforms, as well as its naturalness and usability as a design interface.

Based on the promising results from the first experiment, I used NURBSforms interface to conduct a pilot study for evaluating the effect of physical interaction on design knowledge and process. The striking results of this study provides quantitative evidence for the hypothesis on which I had based this thesis: physical interaction significantly enhances spatial cognition, and is a source of embodied design knowledge, reflected both through the end-result of design process, as well as designer's self-reflection on their own actions and thoughts during design process.

While NURBSforms is far away from becoming a comprehensive design tool comparable to current CAD software, it is a proof of concept for Augmented Materials: a vision for interfaces that enhance embodied design knowledge by reconnecting design and making.

6. 2. Contributions

My contributions to the fields of Design and Computation as well as Human-Computer are as follows:

I framed the issue of separation of design and making in the context of CAD/CAM tools through the lens of Human Computer Interaction. Through this discussion, I draw a focus towards multi-sensory and physical interaction in designing user interface, and emphasized on its necessity to be the core element for interfaces between designers and digital design tools.

I introduced Augmented Materials as a framework for creating interfaces that bridge between digital and physical modality and connect designs and making. I identified the properties of augmented materials, and provided gridlines and suggestions for further development of interfaces.

I designed and implemented NURBSforms as a proof of concept for Augmented Materials, and consolidates its hardware and software implementation so that it can be used as a usable, reliable design interface as well as a tool for further user studies in computational making.

In creating NURBSforms interface, I developed innovative solutions for creating integrated system, for which I combined software, hardware, and fabrication techniques. These solutions, such as the NURBSforms actuated modules, can be further developed and used in the fields of architecture, product design, and human computer interaction.

6. 3. Future Work

Augmented Materials is a vision towards the future of Human Computer Intercation, where physical and digital components become merged together to create new amalgams with extraordinary capabilities. Advances in science and technolgy in the fields of material science, electrical engineering, computer science, and digital fabrication, will provide new opportunities to create novel Augmented Material systems with enhanced performance. Thus, I see this the main vision of this thesis as an ongoing process that develops as technology advances.

Specifica to the NURBSforms project, more immediate work can be done to develop the system:

- NURBSforms module can be further enhanced by adding a PID control loop, which will decrease the actuation time, and better syncronizes digital representation with actuated physical modules.
- Decreasing the size and expanding the number of modules will broaden the design space, and allow designers to create more complex models.
- A revised joint system, followed by strengtening the modules, will provide an opportunity to create 3D spatial structures.

Gestural NURBSforms interface can be further enhanced by:

- Enabling additional function, such as Copy, Scale, Snapping, etc. These functions can be added by using other recognizable gestures, or by using different interaction modalities such as voice commands.

- Graphical User Interface should be further developed to have flexibility over the number and arrangement of modules. This arrangement can be manually determined by the user, or be automatically generated based on physical interface.

- Ideally, a computer vision system should be added to automatically detect and recognize the configuration of physical modules, and to match the graphical user interface accordingly in real-time. Detection of the unique ID number of physical modules can happen by adding a visual barcode on their surface.

The pilot study presented at the end of fifth chapter should be further developed, and new experiments should be done to gather more data points and improve the credibility of the results. However, the pilot study proved NURBSforms to be a promising tool for developing further user studies that quantifies embodied design knowledge and design process.

7. List of Figures

8. References

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