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[M]form:
Symbiotic Design and Fabrication for Casting of Modular Systems

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Abstract

[M]form: Symbiotic Design and Manufacturing for

Casting of Modular Systems

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Architecture

Me•cha•tron•ic

Adjective

A concurrent field blending mechanical (mecha) and electronics (tronics) engineering used for the development of interactive design and manufacturing.

Mechatronics opens a portal for information to flow between the digital and physical world the purpose of which is to control hybrid systems. This allows for input from one to generate output from another and vice versa. Symbiosis implies a mutually beneficial relationship between two entities whose performance dramatically increases as a result of this relationship. Essentially the action of one leads to the reaction of another in what can be described as an endless feedback loop. When the design and manufacturing of panels displaying highly complex smooth curvature are separated as two different processes the consequences are larger amounts of material waste, longer manufacturing times, and ultimately a more expensive outcome. Mechatronic forming, referred to here as [m]form, is associated with physical surfaces that are reconfigurable based on digital information. In this context [m]form is an additive casting machine that complements the contemporary disposition of architectural design and manufacturing as one symbiotic process that optimzes the production of pre-cast modular systems.

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Professor Kimo Griggs
Fellow MS Colleague Roark Congdon
Lecturer Jeff Hudak

Dedication

This project is dedicated to my parents Herb and Julia Ruthrauff who without their support the project would not have been possible. You have always pushed me to pursue my passions in life and I am forever indebted to you. May the encouragement that sparked this project lead to a more enjoyable design process and sustainable world.

Introduction

Interposing idea space and the physicality of body space lays a space of potentialities where design intent and the physical constraints of making come into dynamic relationship. This space can be thought of as the solution space or what has previously been referred to as “formation” space where complex representations of form interact with materiality, manufacturing techniques, and assembly logic.[1] It is in this solution space and the transfer of information from the digital realm to the physical one where intent can be lost or problematic due to the lack of a systematic approach. [M]form seeks to expand this solution space by advancing design toward a bottom-up coherent process that is driven by design intent as much as it is the tangible issues relevant to the production of variable forms. Specifically the focus of this thesis is an alternative to cast manufacturing tailored to generative design methodologies and the issues linked with manufacturing geometrically varying panels.

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1 Al-Haddad, Tristan, Vishwadeep Deo, and Ted Ullrich. Georgia Institute of Technology: Parametric Modulations in Masonry Systems. Tomorrow Lab: High Performance Concrete Systems. Web. 7 Jan. 2012. <http://tomorrow-lab.com/projects/project_4.php>.

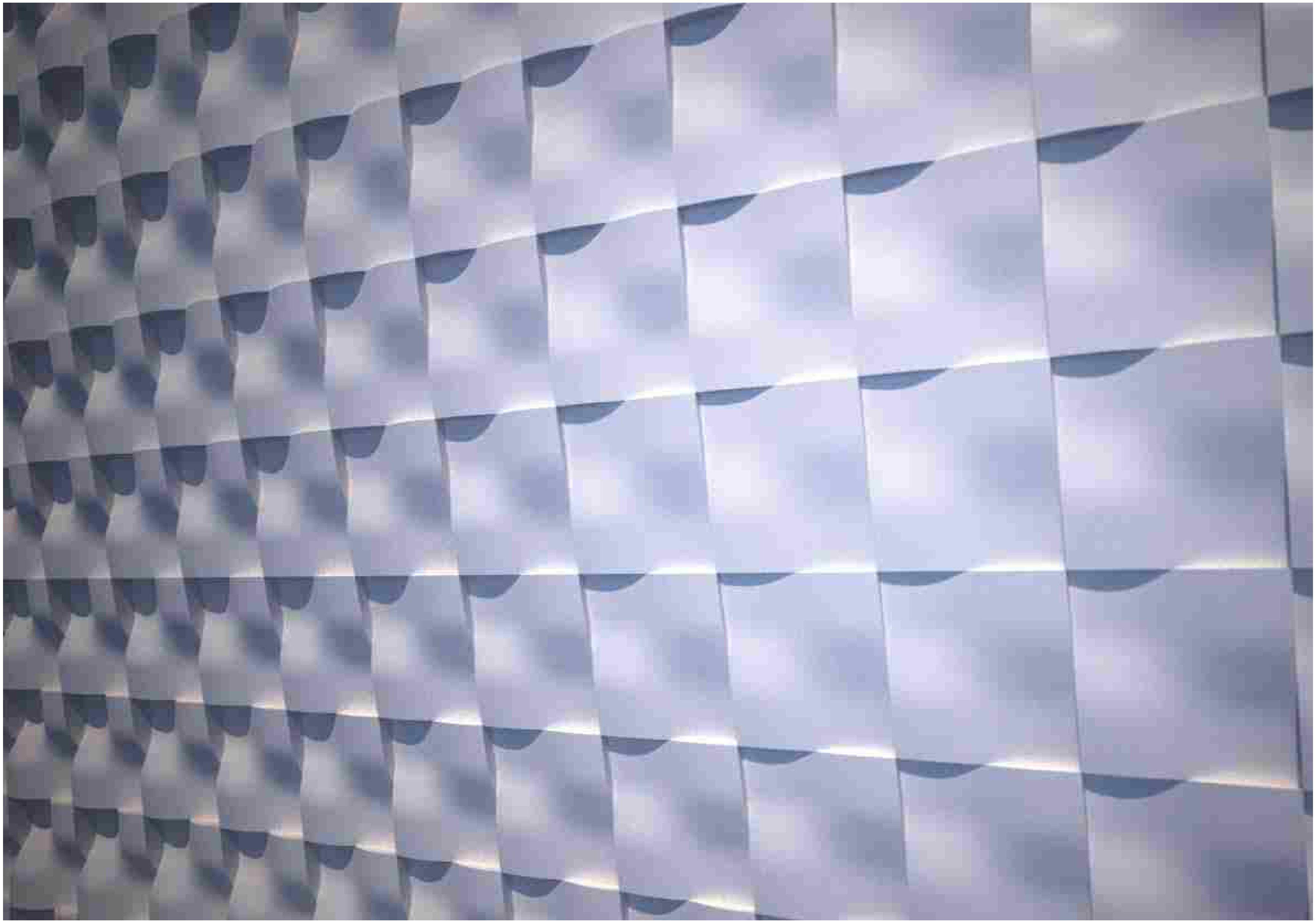

Figure 1: Rendering of case study produced via [m]form parameters

Motivation

Architecture is undergoing a transformation toward bottom-up design processes that promote variable form and modularity. This shift in process has been spurred on by advancements in fabrication technology and parametric design tools that enable architects to approach building design from opposing ends of the process spectrum simultaneously. Architectural design by its very nature is a top-down process where the bigger issues of site shape, area, program, code, climate, and so on act as constraining factors that shape the outer-most bounding mass of the building. This mass is then subdivided into the individual components such as structure, paneling, doors, windows, and then assembled in layers.

In contrast a bottom-up design process would start with a detailed description of modularity that weaves issues of structure, materiality, fabrication, infrastructure, and so forth in a way where each contributes toward effect. The resulting form's global mass is then difficult to control since its "growth" sequence depends solely on the distributed intelligence of the module but this intelligence can lead to a logical assembly that mimics mitosis more than the layered construction architects and builders traditionally employ. In summary, a top-down design strategy's global form exceeds the sum of its parts because it is the starting condition.

An example of a top-down design would be the Nordpark Cable Way stations designed by Zaha Hadid Architects in Innsbrook, Austria. The overall mass was formed and studied for its spatial qualities but it is quite obvious from observing the seam alignment of the panels that their division, dimensions, and individual shapes are derivatives of the larger scheme. As with the other three stations, the Hungerburg station has not one repeating panel. In this case each panel required its own computer numerically controlled (CNC) routed form work that was then used to thermo-form a standard sheet over it. Each adjacent panel's edge condition is just minutely different from its neighbor but very different over several making each panel's fabrication seem all the more tedious for just the smallest change in geometry. In this instance capturing the plastic fluid-like global form for the project took priority over the tectonics of the panels.

While exuberant in form and innovative in its fabrication

Figure 2: Example of top-down design project by Zaha Hadid Architects/ Photo by Zaha Hadid Architects

Figure 3: Example of top-down design process

from a traditional architectural perspective, the layered construction of this project conflicts with the intention to produce a smooth object because the steel ship-like frame beneath is fabricated from stock materials that have different dimensions and cross sections than the panels. Therefore, panels that display smooth double curvature resulting from a top-down design process will inevitably be problematic in their fabrication and assembly unlike bottom-up strategies that integrate these issues early in the process.

Of late biology has been the lens by which designers have drawn inspiration for bottom-up design logic, not only for formal inspiration but more importantly as a model for assembly and construction. This can be attributed to the fact that organisms align aesthetic, performance, function, and growth in a manner that is unparalleled to artificial processes, and while computation is advancing us closer to mimicking these processes in architectural design we are largely at the mercy of current fabrication tools. Generative design has recently gained popularity in the realm of architecture and is affiliated with bottom-up processes in biology such as morphogenesis. This denotes form that is "constructed" in chunk-like modules that have subtle morphological differences between neighbors but lead to a form that is strictly governed by its component pieces. One could say its geometry and relationship to its neighbor is "programmed" into its physical composition.[2] This strategy begins with defining a module in a bottom-up system where the overall form does not exceed the sum of its parts because it is dictated by the module's relationship to its neighbor.

An example of a generative project that utilizes a bottom-up design process would be the tessellated concept model in figure 2 which was a product from the University of Washington's Department of Architecture design-build studio entitled Collab/Fab. In this case one module was first designed with a specific range of angles that neighboring modules could connect at. Material efficiency and "sameness" of module were key parameters driving the overall system and allowed for the modules to be tightly nested on the stock sheet resulting in a highly material efficient fabrication process. Each module folds in on itself ensuring that when flaps

2 Tibbits, Skylar. "Logic Matter." Web log post. SJET. 2010. Web. 15 Feb. 2012. <http://www.sjet.us/MIT_LOGICMATTER.html>.

Figure 4: Example of bottom-up design project.

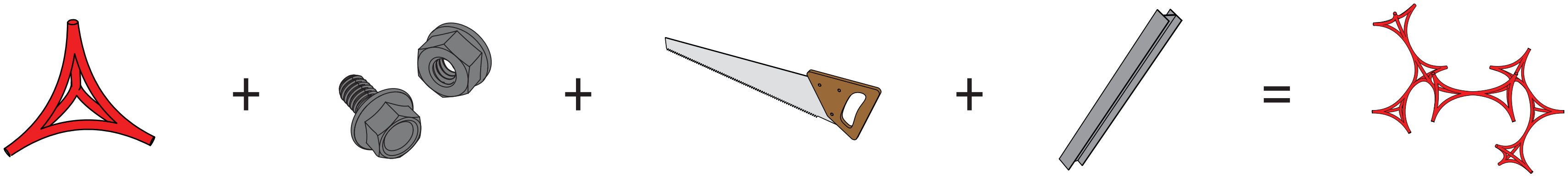

Figure 5: Example of bottom-up design process.

align with designated edges and apertures it automatically assumes the correct angle relative to its neighbors leading to an easy assembly process. In this scenario there was no preconceived mass that would drive the overall design. Each module has the exact same perimeter when flat but differs in how the laser cutter scores it subsequently restraining its folded condition. The ensuing direction that the design is capable of is inherently diagonal/ spiral due to its modules which are diamond shaped. It is an example of a systematic process where issues of effect like aperture, shadow and texture intertwine with fabrication and assembly logic each of which are governing parameters of the system.

Typical parameters that drive a bottom-up design process are the varying change of a form's mass or the components that define it such as size and geometry. Size can address depth, height, and width while geometry can define surface shape, cross section, or even voids. Currently forming methods such as vacuum or thermo excel at quickly deforming standard shaped panels to fit a form, but integrating a varying thickness in cross section is something that is best captured by casting an object and one of the primary reasons why this exploration will be focusing on reconfigurable molds for cast fabrication. Many designers have been halted in their tracks from moving beyond the digital world primarily because of the cost of producing variation at any scale. The ones that do implement a high degree of variation in their designs have developed fabrication technologies and design strategies that consider material properties and fabrication technique as another parameter that governs the dynamical system, and hence the cost is factored in early in the process.[3]

The second and most important motivation for this study is to create a mechanism that works seamlessly in conjunction with the design process itself where the machine's actuation and material properties are accounted for as factors that are fed back into the system and design intent is framed by these factors in what is an ever evolving feedback loop between designer and computer. The concept of a feedback loop between machine and user is a common denominator especially amongst architects that have engineered

3 Spuybroek, Lars. "Ali Rahim: Uniformity and Variability in Architectural Practice." Research & Design: the Architecture of Variation. New York: Thames & Hudson, 2009. 41-47. Print.

reconfigurable molds due to the attraction of variable form. It stands in stark contrast to the unidirectional process of using a CNC cutting device specifically in how information is produced. The difference between a unidirectional and bidirectional approach boils down to interactivity versus automation. Interactive systems dynamically produce numeric information through the exchange of feedback between designer and computer whereas in automated systems similar data is the product of algorithmic tasks based on representations.[4]

The development of [m]form can be broken down into two categories: mechanics and computation. From a process stand point this can be understood as two exchange points where information is transferred from user to computer and then computer to user. Time and resources invested into the development of [m] form were spent primarily focusing on this first exchange point and therefore the mechanics of the machine. In stating this there is a clear acknowledgement that the second exchange point and feedback loop still require development in order to make [m]form a truly symbiotic design process.

4 Kahn, Omar. “Reconfigurable Molds as Architecture Machines.” ACADIA 08: Silicon + Skin : Biological Processes and Computation : Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) : October 13-19, 2008. University of Minnesota, Minneapolis. [United States]: Association for Computer-Aided Design in Architecture, 2008. 286-91. Print.

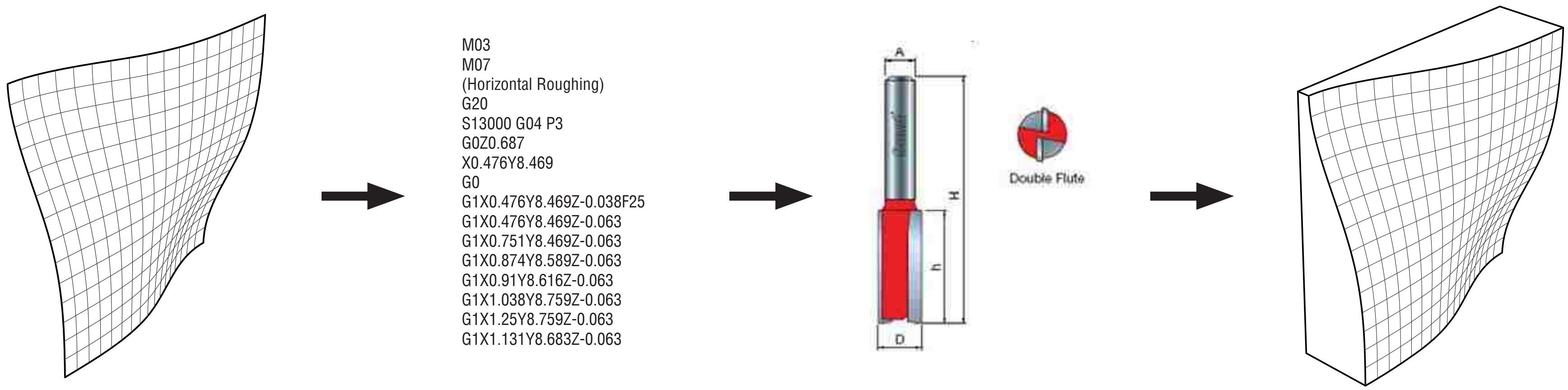

Figure 6: Manufacturing process via CNC router: CAD, CAM, routing, and the final mold.

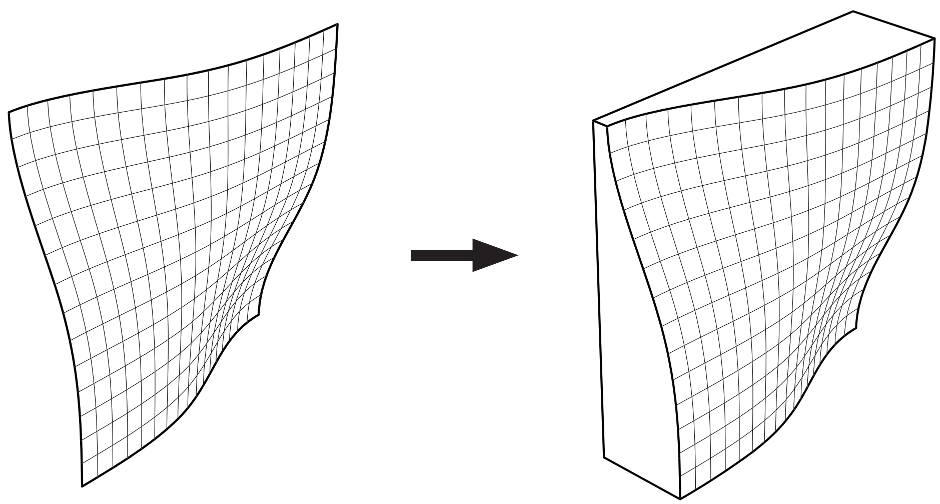

Figure 7: Manufacturing process via [m]form: CAD & final mold.

Sustainability

Architecture 2030 challenges architects to design buildings that operate with carbon neutrality within 18 years[5], but it has since expanded its scope to address the way we make buildings proposing a 50% reduction in the total embodied energy used in architectural manufacturing within the same time frame. The challenge was initially proposed by architect Edward Mazria in 2003 to address the emissions produced by the building industry which is responsible for 48% of the green house gas (GHG) emitted each year. The 2030 Challenge has been widely adopted throughout the building industry in an effort to achieve a dramatic reduction in the amount of climate-change-causing GHG emissions produced as a result of the building sector.

Manually or CNC routed molds are both subtractive fabrication methods where stock material is cut away to reveal the final part. Often waste is collected and recycled but it is rarely used to be reformed into the same stock material. [M]form's process goes directly to the negative to reveal the final positive removing an entire step that has been used in mold making. While [m]form's primary objective is to link design and manufacturing as one process it also reduces material waste because it's an additive fabrication technique that eliminates the process of producing a mold from stock material ultimately lowering the amount of embodied energy involved in the fabrication process.

5 Mazria, Edward. "2030 Challenge for Products: Critical Points." Architecture 2030: Publications. 2011. Web. 20 Feb. 2012. <http://architecture2030.org/files/2030products_cp.pdf>.

Figure 8: Stock material prior to CNC routing

Figure 9: Part and resulting waste after CNC routing

Figure 10: One-off foam molds used to form concrete ceiling/ Photo by Caliper Studio

Pre-Cast Architecture

Prior to the digital era in architecture pre-cast modules typically achieved variation in design by shifting orientation and adding voids. This was due to the tedious nature of drawing variation at the time much less manufacturing it. Frank Lloyd Wright produced many pre-cast concrete structures through the 1920's including the Imperial Hotel in Tokyo, Japan and the four Southern Californian concrete block textiles homes. The Ennis House, figure 11, is one example of how variation was handled before computation became a regular part of architectural practice. Notice that there is only one type of relief block and this module repeats across the facade in between blank ones yet the design is not overwhelmingly repetitive due to its subtle variance. In this case variation is controlled by rotation and the addition of a void space within the block. These modules were then rotated and organized as groups into horizontal or vertical bands resulting in varying types of the same species.

Fast forward to modern times where computation has enabled architects to quickly and effectively change size and most importantly geometry of complex assemblies digitally and manufacture them with great precision and accuracy. Parametric design tools (e.g. Rhino 3-D's Grasshopper) and building information models (BIM) such as AutoDesk's Revit even permit shop drawing updates when the three-dimensional model changes as seen in LMN's design for the Cleveland Medical Mart, figures 12 and 13. In this project the facade elements were all fabricated from one high density foam master mold that was routed via CNC and lined with rubber. The variation in panel size and geometry is controlled by how much material is poured and what portions of the master mold are sectioned off. Geometrically each facade panel has the same maximum relief depth and ribbed condition governed by material stock dimensions and effect.

Looking back, the process of integrating variation into the facade of LMN's Medical Mart building is similar to Frank Lloyd Wright's textile block projects where orientation (e.g. rotation, mirroring, etc.) is the controlling factor, but the difference here is the production of the master mold is automated rather than manually produced. This is due largely to the cost of CNC routing unique master molds for each varying panel. While the file-to-factory method has greatly improved the work flow from digital model to

Figure 11: Ennis House by Frank Lloyd Wright/ Photo by Hunter Ruthrauff

physical representation, production remains expensive as a result of the material used and the machining necessary to produce variability. This is due primarily to the fact that manufacturing in the building industry is dominated by CNC machines which is a subtractive method. Variably shaped pre-cast forms require a unique mold meaning each slightly different mold must be milled from a larger stock material that contains the part within. Time and material are two factors that largely dictate how much variation can be injected into a project.

If the building industry is to fully embrace generative design and commit to building variably shaped casts it must consider design and manufacturing as one process. This implies that designers have a thorough understanding of how molds are made and incorporate these factors as parameters that govern the system. Variably shaped mold production requires us to rethink manufacturing as having input on the overall direction of the design from the beginning. Fundamentally CNC routing is not a specialized tool. In essence it removes material with a piece of sharpened metal just as a manually controlled one would the difference being its capabilities and the type of forms it can produce broaden with numeric control.

One can also think of the way we manufacture complex curvature in casting as fostering a top-down rationale due to the seemingly infinite types of objects that stock material can yield. It is the un-specialized nature of routing that gives it a much broader range of the types of forms and operations that it is capable of. In contrast [m]form is a specialized machine whose capabilities are less broad, but whose interactivity is anchored in a parametric design tool making it a tool for design.

Figure 12: Actual Panels for Cleveland Medical Mart/ Photo by LMN Architects

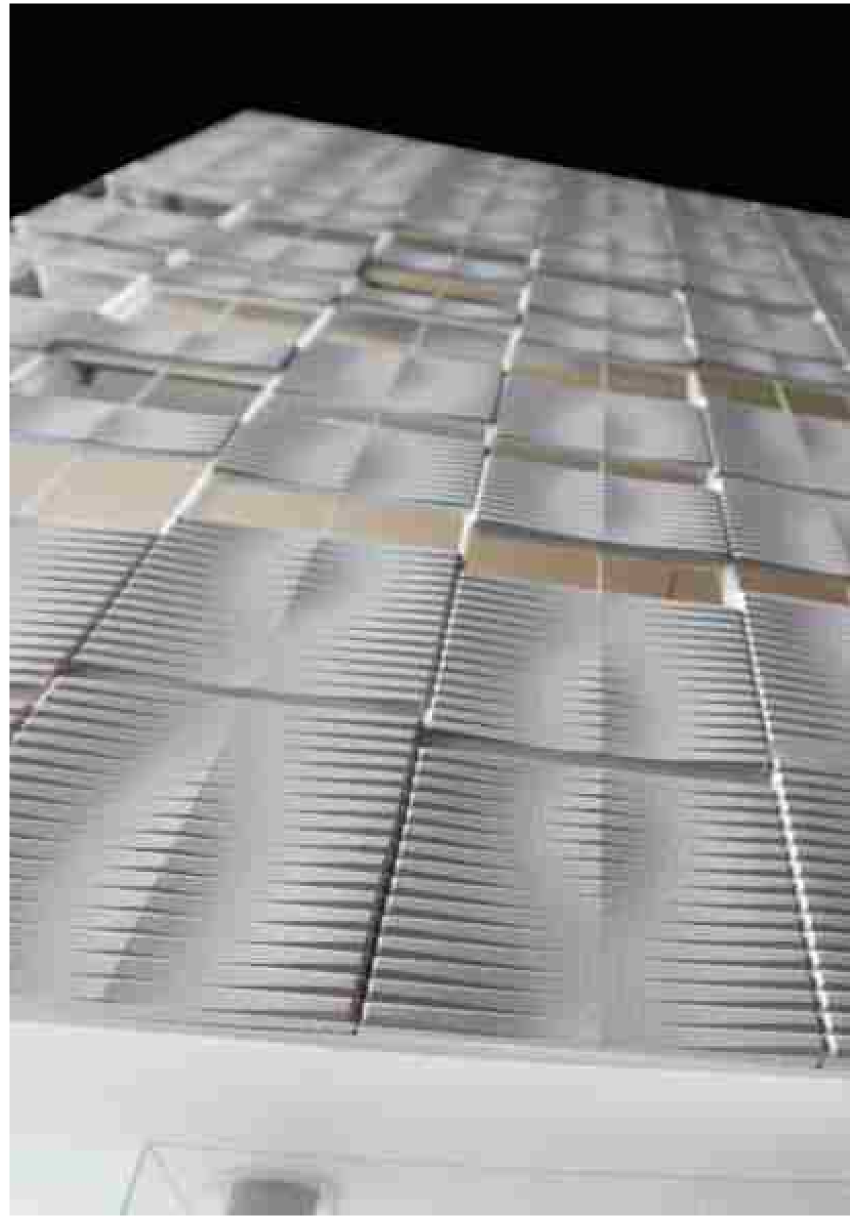

Figure 13: Scale model of Cleveland Medical Mart/ Photo by LMN Architecs

Point Forming Background

Conceptually pin-point forming is a fabrication technique that works similar to a pin-art toy, figure 14, where an object is inserted on one side and its form is approximated as a height-field on the opposing side. The history of pin-point forming as a manufacturing method stretches as far back as 1923 when Williams and Skinner were granted a patent for a two-dimensional former used to produce automobile leaf springs that were manually adjustable.[6] Some twenty years later the method was expanded into three dimensions by adding multiple rows with the intent of forming sheet metal.[7] These types of forming devices are referred to as reconfigurable discrete dies and did not become digitally actuated until the mid-Seventies with the work done by Mechanical Engineering Professor David Hardt at the Massachusetts Institute of Technology (MIT).[8]

Professor Hardt's original design was a press that configured itself by adjusting a matrix of densely packed quarter inch pins with rounded heads via servo actuators. The problem from the beginning was how to ensure that the rods did not move once they experienced pressure from the forming process and how to smooth out the dimples caused by the pin heads. Some thirty years later in February of 2002 John Papazian of Northrup Grumman's Integrated Systems Sector sought to perfect the model by rectifying these two issues.[9] His goal was 1) to make the machine robust enough to withstand a shop environment and 2) find a proper forming material that was stiff enough to resist dimpling but malleable enough to assume the die's configuration.

The solution to making the machine more durable was to replace the rod and servo motor with threaded rods and stepper motors because thread helps to ensure that when the machine is turned off the rod will not slide out of position caused by the pressure pushing back from the material being formed. Existing digitally reconfigurable forming machines have proven useful mainly in the aerospace industry and on a case by case basis for architecture but for very different reasons. For aerospace it means

6 C.J. Williams and T. Skinner, "Spring-Forming Device," US Patent no. 1465152, issued Aug. 14, 1923.

7 T. Walters, "Press," US Patent no, 2334520, issued Nov. 16, 1943.

8 Walczyk, Daniel F., and David Hardt. "Design and Analysis of Reconfigurable Discrete Dies for Sheet Metal Forming." Journal of Manufacturing Systems 17.6 (1998): 436-54. Print.

9 Papazian, John M. "Tools of Change." Mechanical Engineering Feb.-Mar. 2002. Web.

Figure 14: Pin-Art Toy/ Photo by Westminster

not having to keep a library of forming dies for every product they produce and for architects it enables variable design practices.

Pin-point forming is not a replacement for CNC routing technology because there are simply operations and forms that a router is capable of that this strategy is not. CNC operations in general are a subtractive method of fabrication meaning a sheet or block of stock material is cut or milled to reveal the part. Its precision is largely due to the amount of step over per pass relative to its diameter and shape. The smaller the step over the more precise and accurate the shape is to its digital self. Pin density is dictated by the actuation mechanism and rod dimension. Forming rod length is dictated by its diameter as the further it extends past the origin plane the easier it is to bend the rod. These specifications in turn affect the type and size of the actuation mechanism as the amount of torque required to turn the rod increases with size. The trade off with a reconfigurable die is that the shape will never achieve the extreme precision that a CNC router is capable of but it will produce an array of approximated shapes in a fraction of the time.

Steep shifts in the topography of a form are possible with a CNC mill so long as the Z-axis movement has the range and the routing bit is long enough. As neighboring pins move further and further away from each other the more approximated the part becomes thus steep topographical change in shape via a pin-point forming process can only be achieved over several pins or several panels linked together ultimately limiting the forms it can produce based on the scale of a project. In order to produce steep changes in form within one panel the designer must consider the lowest and highest quadrants of the surface and center these over a pin's location.

This type of thinking follows a top-down rationale and typically yields undesirable results as aligning quadrants of a digital surface that was formed without considering pin location or density is nearly impossible. For this reason, specifically with a pin-point forming method of manufacturing, one must begin by identifying a shape that satisfies the design and recording the location of pins within the matrix to further refine the surface shape into the desired geometry. [M]form products are poured rather than layered,

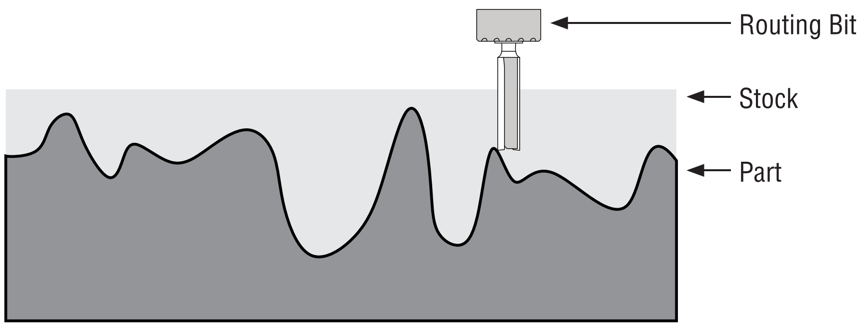

Figure 15: Complexly curved mold produced via CNC Router

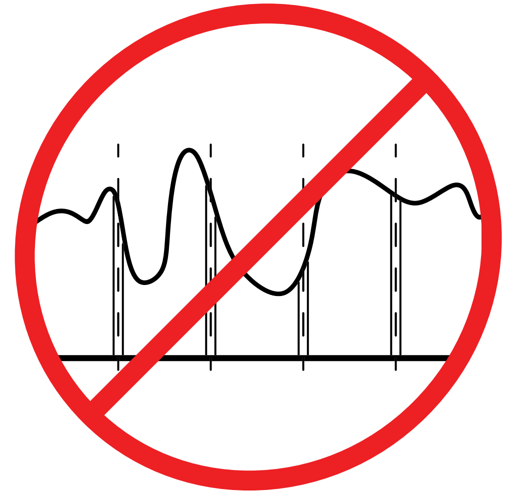

Figure 16: Same mold produced via pin-point forming showing misalignment of pins with quadrants of surface

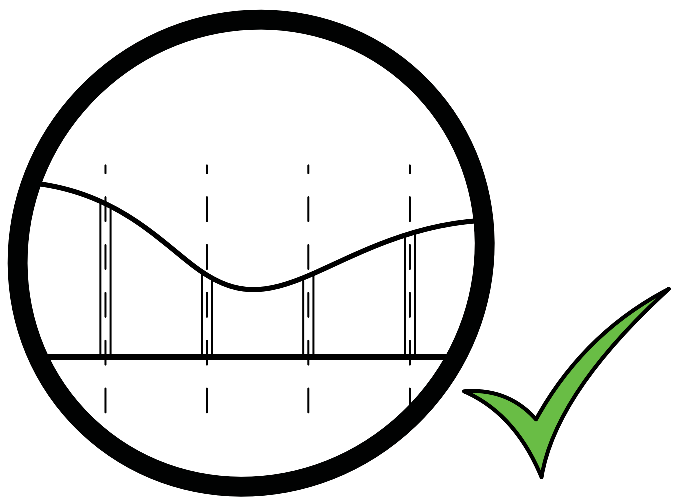

Figure 17: Subtly curved mold produced via pin-point forming

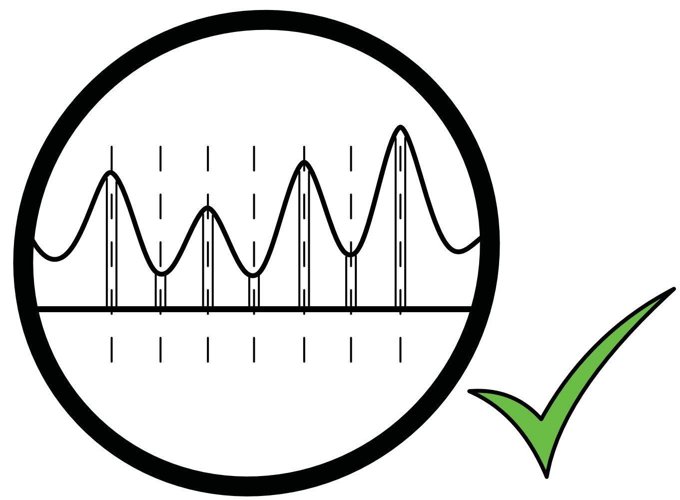

Figure 18: Complexly curved mold produced via pin-point forming showing alignment of quadrants with center line of pins

formed, or extruded so they have the potential to incorporate tension members for added structural strength. However, the goal of this exploration is the production of variably shaped non-structural panels that in a given project attach to simple structure so that the intricacy of the connecting hardware is not exacerbated.

The defining difference between [m]form and its predecessors is that it is a reconfigurable mold for cast fabrication and features a flexible membrane that attaches to the pins allowing the machine to form two opposing faces of an object for variable thickness in cross section. This option gives designers another parameter that can be input into the dynamic system and can affect variability of form beyond size and geometry. Second, it allows for panels to have a degree of structural robustness since thin surfaces can then morph to incorporate thicker cross sections providing areas of high and low rigidity.

Symbiotic Design

Symbiosis in the natural world implies a mutually beneficial relationship between two different organisms. Bromeliads for instance, are epiphytic plants that attach to large tree hosts in wet forest ecosystems. They soar into their host's canopies so they can receive the maximum amount of sunlight which gives them an advantage over floor dwelling plants. In return the bromeliads increase the amount of water available to the tree by absorbing cloud moisture and collecting rain. Alone neither organism would be as effective or efficient a survivor. Up to this point the design and manufacturing process between man and machine has been unidirectional resembling automation rather than interactivity resulting in a suboptimal use of material and time.

Symbiotic design and manufacturing implies that neither step in the process takes priority over the other and that the design must undergo several cycles before being considered a finished product. Unifying design and fabrication as one coherent process promotes bottom-up design methodologies because tangible issues related to making play a major role in the outcome of formal resolutions. This can be problematic since architectural design is a top-down process but the outcome does not necessarily have to be one hundred percent top-down or bottom-up. In fact it can become a hybrid condition where the two meet at an opportunistic juncture. The facilitator here is parametric design because it enables designers to shape a bounding mass that is informed by the larger ideas of site and context while developing detailed features that address modularity, fabrication, and assembly.

Firgure 19 summarizes the symbiotic relationship between design and manufacturing, user and computer, and the top-down and the bottom-up. The realization of a physical artifact via [m]form can be divided into three spaces: idea, solution, and body. There are then quadrants that divide them further: 3-D CAD, parametric design, programming, and actuation. In each succeeding quadrant the user's input is reduced as the machine's increases. Idea space is dominated by the user and the original design intent which may very well begin without any regard to the capabilities of the machine. The only influence that the computer has on the process at this point are the capabilities of the CAD software (Rhino, Sketch-Up, etc.) used and the manner in which surfaces are created (e.g.

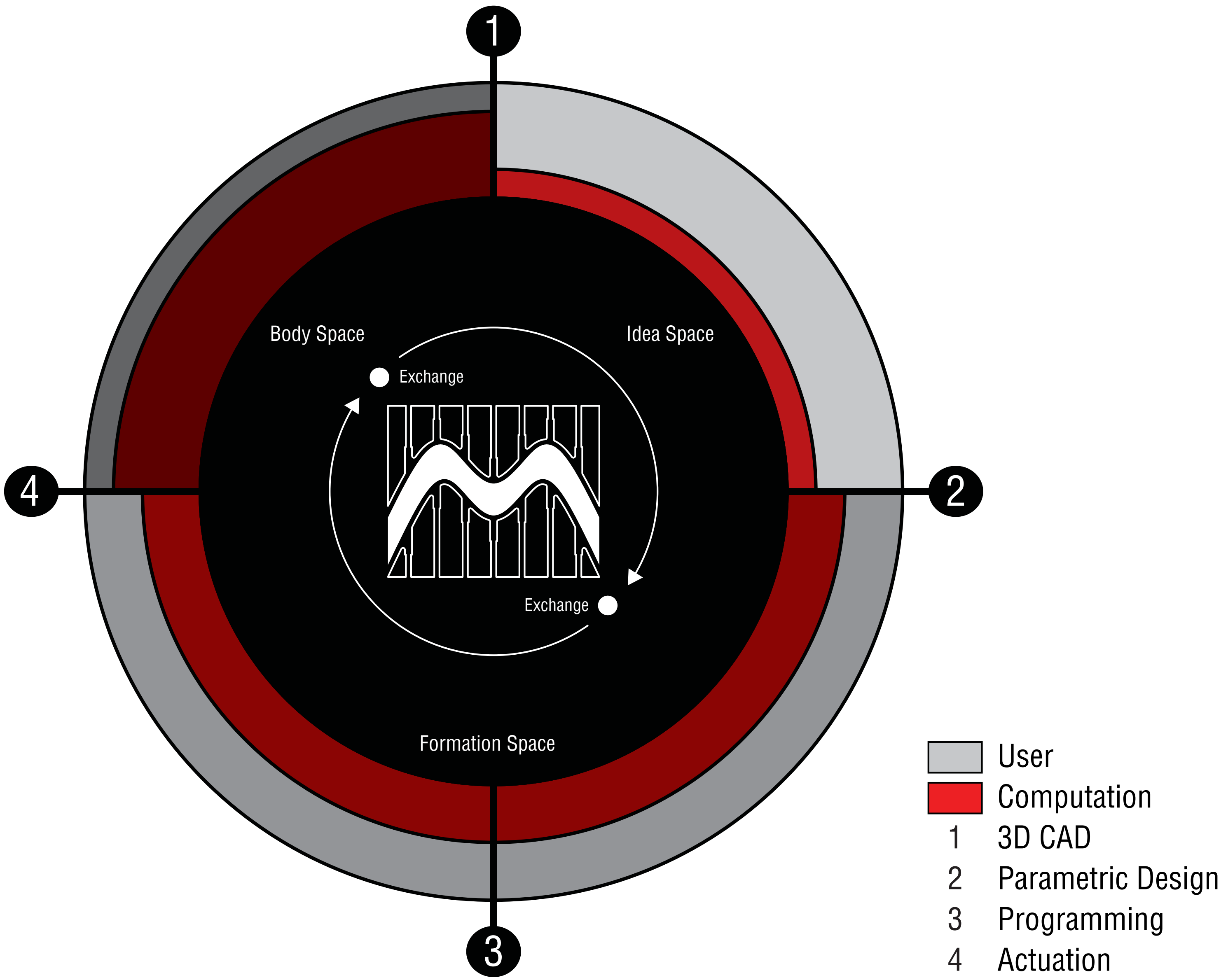

Figure 19: Symbiotic design and manufacturing process

sweeping, extrusion, primitives, etc.).

The first quadrant of solution space begins when the driving surface is imported into the parametric design tool (Grasshopper, Generative Components, etc.). It is important to note that since [m]form is capable of forming two faces of a panel the surface that gets parameterized must have a thickness. Once the bounding mass or surface is modeled three-dimensionally in CAD it is then parameterized meaning that the surface is divided into smaller iso-surfaces which are then tied to their own individual height fields. The profile of the panel and spacing of height field lines all correspond to physical attributes of the machine itself. The more pins that are available in the UV directions on the machine the fewer surfaces that the original surface must be divided into. Of course the size of the subdivision of the bounding surface is also a matter of design in and of itself.

This quadrant is particularly important because it contains one of the two points where information is exchanged between user and computer. The amount is dependent on how closely the user wants the physical artifact to resemble the digitally derived bounding surface, and because operability is rooted in a parametric system direct manipulation of the pin-point forming process is possible.

Take the example on the following page, figures 22 and 23, a bounding surface is brought into Rhino 3-D's parametric modeler Grasshopper and subdivided into panels. Each panel contains sixteen height field lines anchored to their respective planes on both sides of the surface. Each height field consists of four lines in the UV directions because the particular machine being used has this arrangement. A component is used that isolates every other pair of pins, described in terms of a cull pattern as being either true (t) or false (f). The cull pattern used in this case is t-t-f-f on the first two rows and f-f-t-t on the final two. Essentially the first two rows contain two pins on one side that are isolated and the following two rows then alternate to isolate two on the opposing side. The intent is to only change the length of half the lines which will inevitably alter the original panelization as seen in figure 23 from minimal to maximal relief depth.

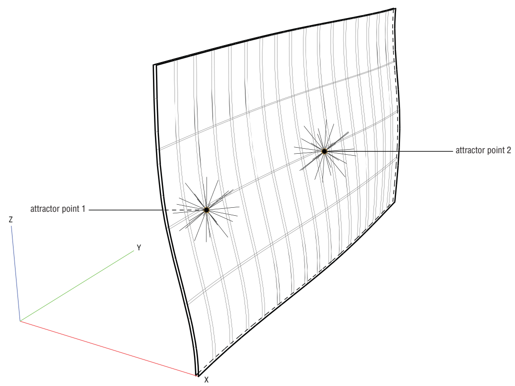

Figure 20: Base Surface

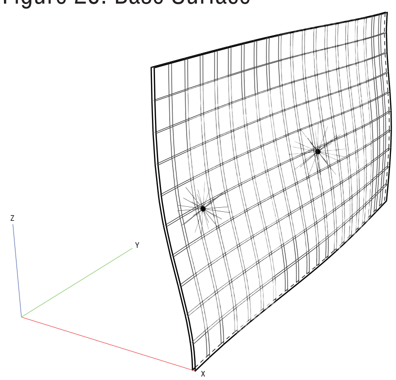

Figure 21: Base Surface Subdivided

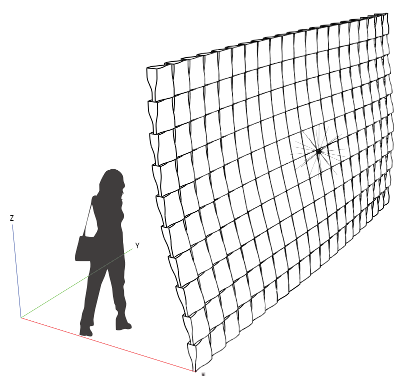

Figure 22: Modularization of Bounding Surface

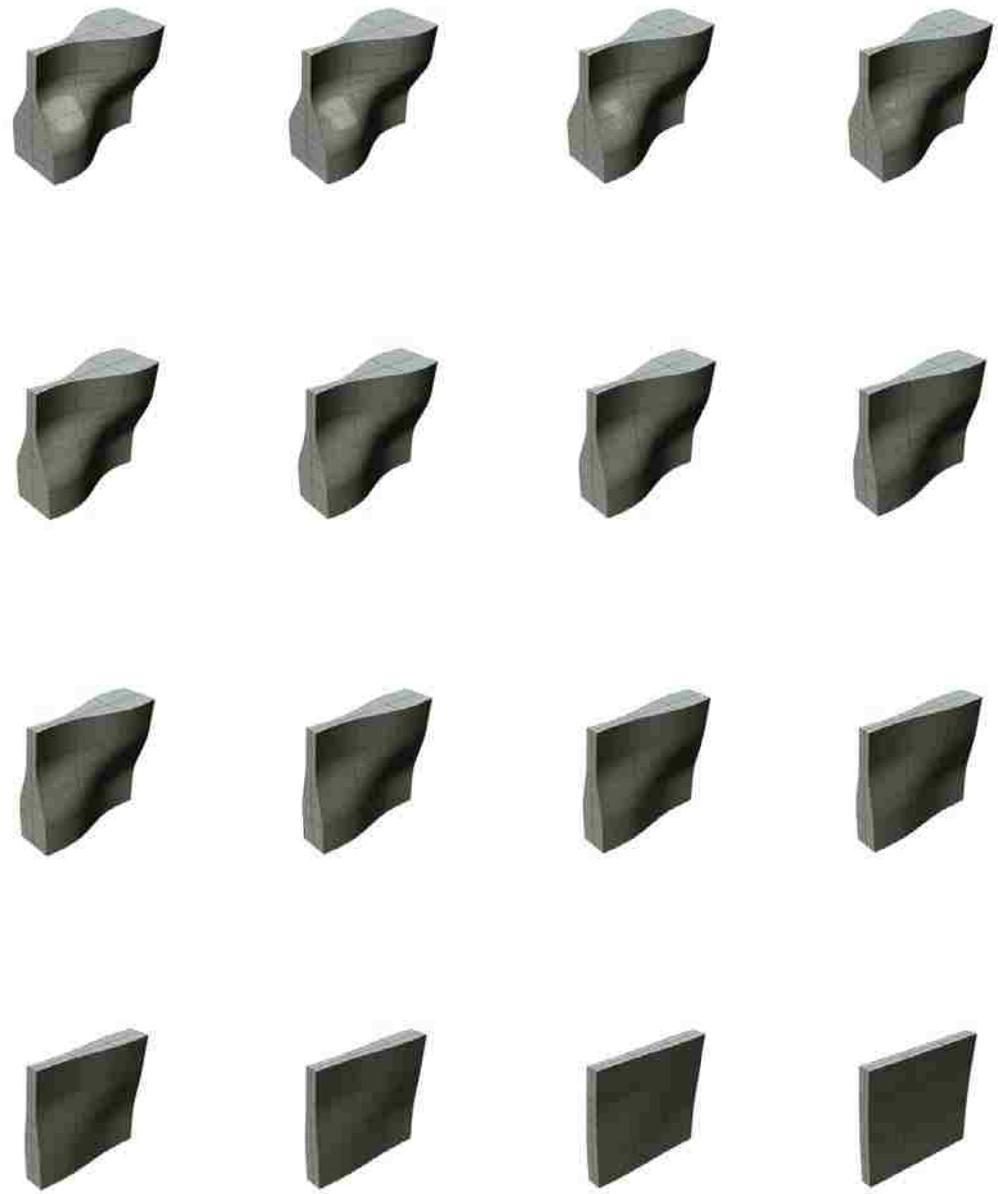
Figure 23: Variations on one type of modular unit

In this case the Grasshopper definition is arranged in such a way that the length of these lines are affected by their proximity to attractor points on either side of the surface. The relief depth of each panel increases as its distance from the attractor point does and vice versa. Interaction between computer and user is still technically in favor of the user but when the cycle comes full circle again this is where physical constraints of actuation and materials are fed back into the system bringing interaction to an equilibrium. This also means that when design intent is exchanged the computer has an equal influence on the direction of the form.

One must consider that the process of producing a physical panel occurs over at least two full cycles. The first cycle is considered a test run where the user selects a module that is suitable for the project from which numerous variations will spring. Assuming the user has identified a module several constraints are then plugged back into the system regarding the membrane's elasticity, the maximum deformation of the membrane before the magnets pull away from the side walls, ball joint failure, and stepper motor failure. These constraints are all defined in terms of their maximum values for which the definition will fail to send this data to the next quadrant if exceeded. In order for actuation to occur the end of the definition breaks the height field of lines down to individuals whose length is converted using a simple calculation. This calculation is based on stepper motor and threaded rod type. The prototype produced utilized a 1.8^{o} stepper motor and a 1/4"-20 threaded rod so the calculation is as follows:

-1 Full Revolution = 360^{o} and 360^{o} / 1.8^{o} = 200 Steps

-1/4" Dia. Rod turned 20 Full Revolutions = 1 Inch

Therefore, 200 Steps x 20 Revolutions = 4000 steps per revolution

Example/ If a height field line length is 1.69 inches, how many steps must it take to travel that distance?

1.69 in x 4000 S/R = 6,760 Steps

The number of steps is then encoded in Grasshopper's plug-in Firefly - a visual programming software based off Arduino - and sent to the microcontroller. The programming is contained within the parametric modeler so the division line between the two

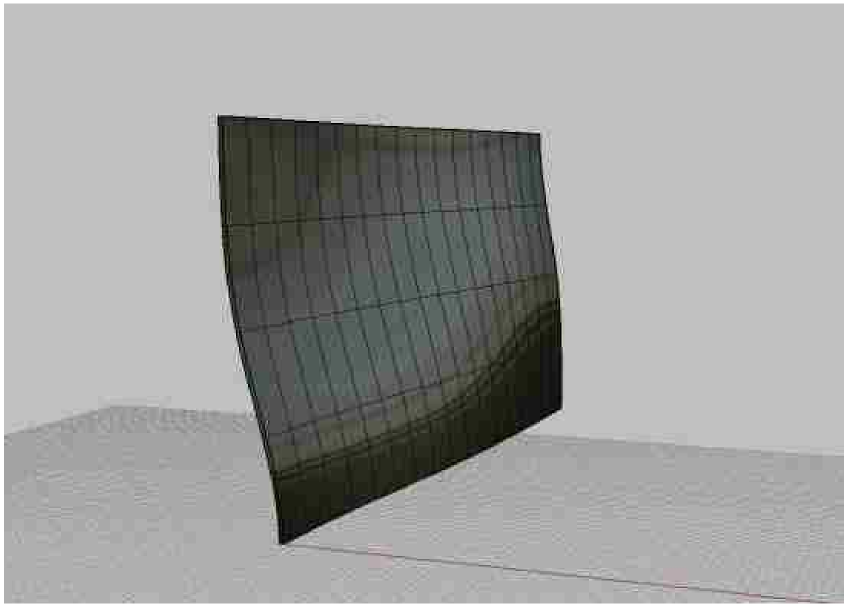

Figure 24: Image relating to CAD quadrant of [m]form process

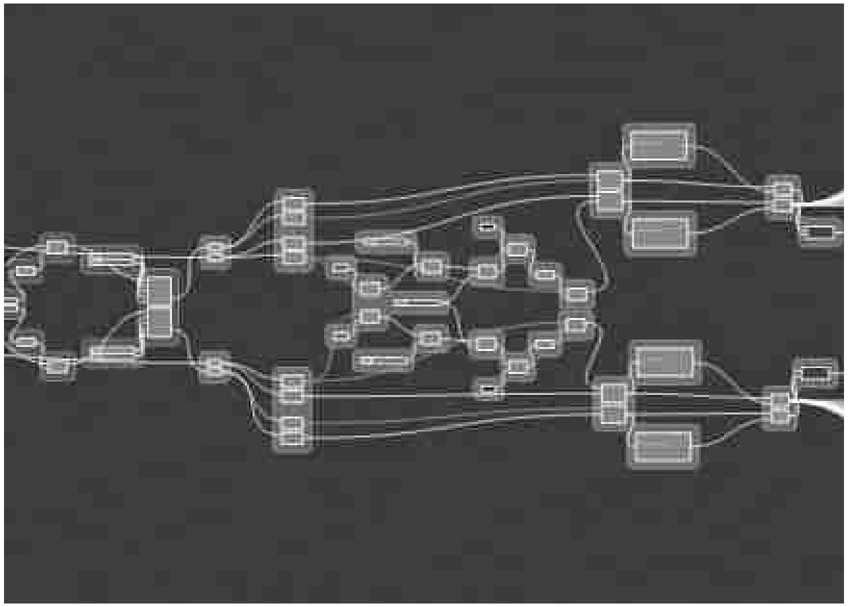

Figure 25: Image relating to parameterization quadrant of [m]form process

Figure 26: Image relating to programming quadrant of [m]form process

Figure 27: Image relating to actuation quadrant of [m]form process

is, for all intents and purposes, nonexistent and thus control is still in equilibrium. This quadrant is the link between the digital and physical realms of [m]form technically inhabiting both. On one side of the equation the programming software is producing constant code updating it as necessary and on the other side the code is being read by the microcontroller board.

Once the data is sent from the microcontroller to the driver board the process has stepped over into the final quadrant. Actuation consists of physically deforming the mold which is the product of moving the threaded rods back and forth in space and requires little or no user input. This quadrant contains the second exchange point that differs from the previous in that information is being transferred from machine to user instead of from user to machine and completes the feedback loop. One can consider this the final step in the first cycle or the first step in the final cycle. It is important to consider [m]form as part of the generative design process given that the shape and module will have a defining impact on the project as a whole. The isolation and location of individual or grouped pins relative to their neighbors have the potential to yield a variety of shapes and can act as a physical form-finding exercise that can be the starting condition for any discussion revolving around design intent. The direct connection between digital and physical form without the repetitious steps in between allows one to quickly learn what the machine's capabilities are rapidly advancing knowledge about both. This enables designers to quickly and effectively adjust parameters based on physical constraints of the machine resulting in an optimized manufacturing process with regards to material efficiency and production time.

[M]form Prototypes

Over the years reconfigurable forming machines have been created that utilize thermo or vacuum to get more accurate and precise results but reconfigurable cast machines remain largely unexplored territory. As I have found first hand from [m]form prototypes there are reasons why reconfigurable cast machines have eluded researchers thus far. The design and fabrication of [m]form was a very heuristic process. Multiple hypothesis were put to the test concerning an array of topics such as mechatronic actuation, forming membranes, connecting hardware, sealant, and several others. Two [m]form prototypes preceded the current version and each was important in the evolution of the machine now and in the future.

The first machine explored three major issues: the forming membrane, connecting the membrane to the pins, and the pins themselves. Based on previous research it was decided early on to utilize stepper motors to turn the threaded rods and induce movement in and out of a wall. While stepper motors were the early selection for actuation in the design of [m]form the specific type and size was not the critical factor with the first [m]form prototype. What was critical was determining how the rod would move in and out of the wall and how the end of the rod would connect to the rubber membrane. The initial [m]form prototype (figure 28 and 29) used t-nuts counter sunk into a CNC routed plywood wall so that as the stepper motor turned the thread would catch and prompt movement of the rod in and out of the wall. The second item on the agenda was to devise a way to connect the threaded rod end to the rubber membrane. It was obvious that the rod would have to be set inside a bearing that turned independently of the surface so that as the rod turned it would not twist the membrane at pin points and tear.

Half inch ball bearings were selected as possible mechanisms that would allow for the rod to turn independent of the horizontal movement of the membrane. The depth and diameter of the ball bearings were then used to design female cups (figure 28) that received the bearings on the back side of the forming membrane. A major concern early on was the hydrostatic pressure caused by the poured material pushing back. It was initially hypothesized that substructure integrated into the back of the membrane along with

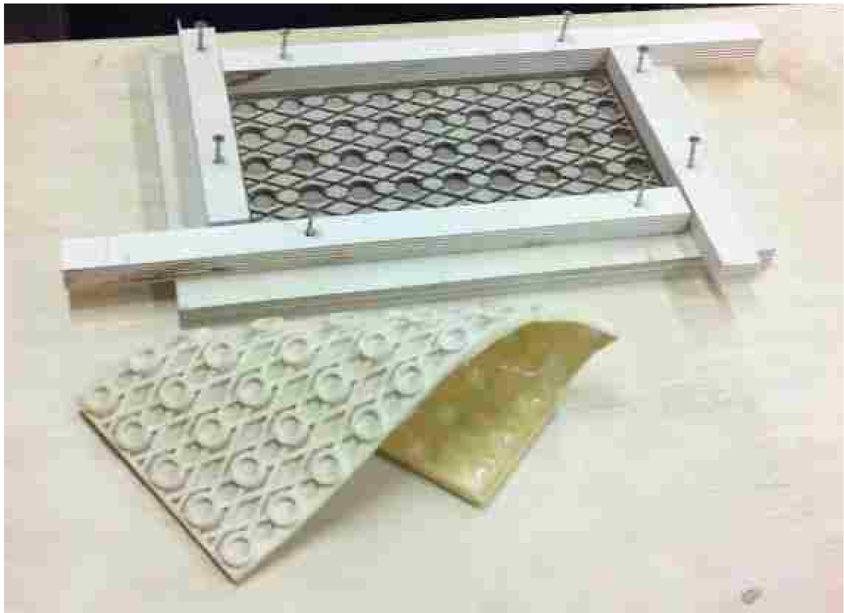

Figure 28: Urethane cast of forming membrane and mold used to produce it

Figure 29: First full [m]form prototype including membrane and forming rods

Figure 30: Two forming walls from second [m]form prototype

Figure 31: 3-D printed ball joints and substructure of silicone membrane

the bearing receptors would provide support in the regions that spanned between pins. With this is mind, a design of the mold for the membrane was CNC routed from Baltic birch ply that was then used to cast urethane rubber as shown in figure 28.

This initial [m]form prototype was a good start but established several glaring problems. First, the t-nuts came loose and lost their durability after being repeatedly hammered into position. Second, casting urethane rubber sets up too quickly, starts to degrade rapidly, and was not nearly as elastic as it needed to be. While the ball bearings were a promising lead to induce the type of movement that was originally hypothesized their flat disc-like form resulted in a faceted membrane. Lastly, it was realized through a brief experiment that the stepper motor produced enough torque to spin itself around the axis of the threaded rod without moving its position thus rails were introduced to contain the stepper and restrain it from rotating while allowing it to move back and forth smoothly.

The second [m]form prototype incorporated lessons learned here and addresses the bigger issues of mechatronic actuation and the connections amongst components. The previous version spaced pins arbitrarily an inch apart from each to test pin-point forming as a concept. With the introduction of a specific stepper motor model this dimension became very specific as the motor's dimensions dictated how densely packed each pin could be relative to its neighbor. The t-nuts were recycled as a method to move the pins in and out but this time utilized epoxy to ensure their placement would be somewhat more permanent. This [m]form prototype also explored various substructure forms and thicknesses of the membrane to help smooth out regions between pins. The substructure was even refined to receive the rod connection in a way that would least affect the resulting cast.

It was evident from the previous [m]form prototype that the connection between membrane and rod needed to not only rotate but swivel to create a smooth shape. After studying various types of ball joints a custom one was 3-D printed from plastic and adhered to the substructure of the membrane with epoxy. The result was promising as it did produce a smooth mold surface and movement

Figure 32: Second [m]form prototype forming membrane and rods

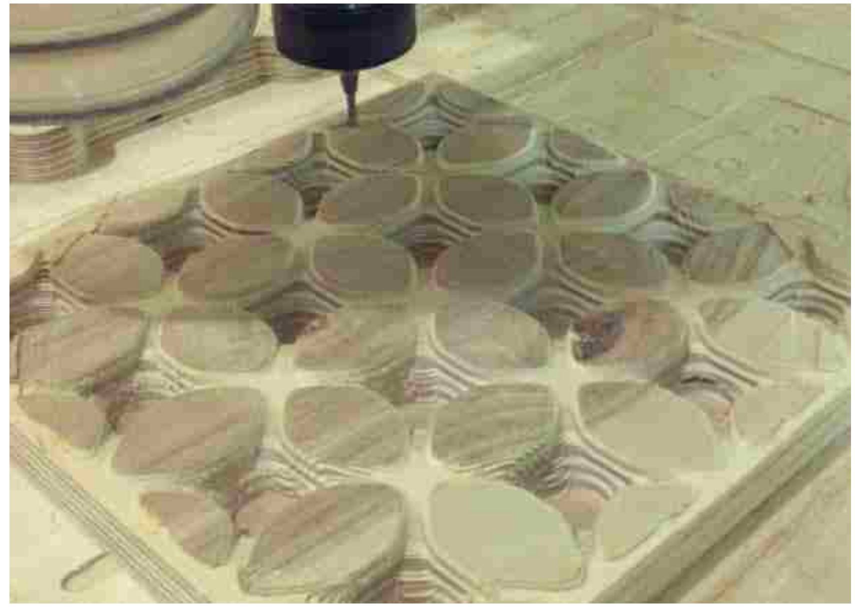

Figure 33: CNC routed plywood mold for second [m]form prototype membrane

Figure 34: Forming rod unit with rails, stepper motor, & connectors

Figure 35: Second full [m]form prototype

horizontally but two problems arose: the printed plastic was not durable enough and would not permanently stick to the silicone surface. As one pin turns past its neighbor the ball joint will swivel away toward the lowest neighboring pin. At a certain point the neck of the ball cannot swivel any further and then fails, or the force of the membrane pulling away from the ball joint causes the epoxy to loose its grip and detach.

The next most important connection was also identified as the one that would connect stepper motor to rod. At this juncture in the project, the stepper being used had a slight divot in the end of its stepper arm. This arm's negative was then designed as a female cavity that the arm would slide into turning the threaded rod that was adhered to another female cavity on the same connector. This connector was very effective but would melt as a result of the heat generated from the stepper motor. This fact also pointed out that the ABS plastic used for the rails that contained the motors would not suffice as the heat generated from one, much less sixteen stepper motors, would surely melt them as well. The most important flaw in the project was realized with this [m]form prototype and it has to do with how deformation of the membrane causes its edges to pull away from the side walls. Effectively, the larger the deformation of the silicone membrane the larger the gap between its edges and side walls become.

This second version was helpful in separating ideas that were promising enough to move forward from those that were not. The t-nuts were one such component that would be replaced primarily because of the difficulty of squaring it inside the plywood hole. This is an important design flaw because over time the misalignment places unwanted torque on the motor causing it to fail prematurely. Based on this experiment the decision was made to resist using epoxy for any connections and swap plastic components for aluminum ones on the succeeding [m]form prototype as neither are suitable for heat. Lastly, it was determined based on a sample cast that the membrane substructure really did not have any affect on the smoothness of the mold and therefore would not be a permanent feature in the next prototype.

The images on the following pages are of the last [m]

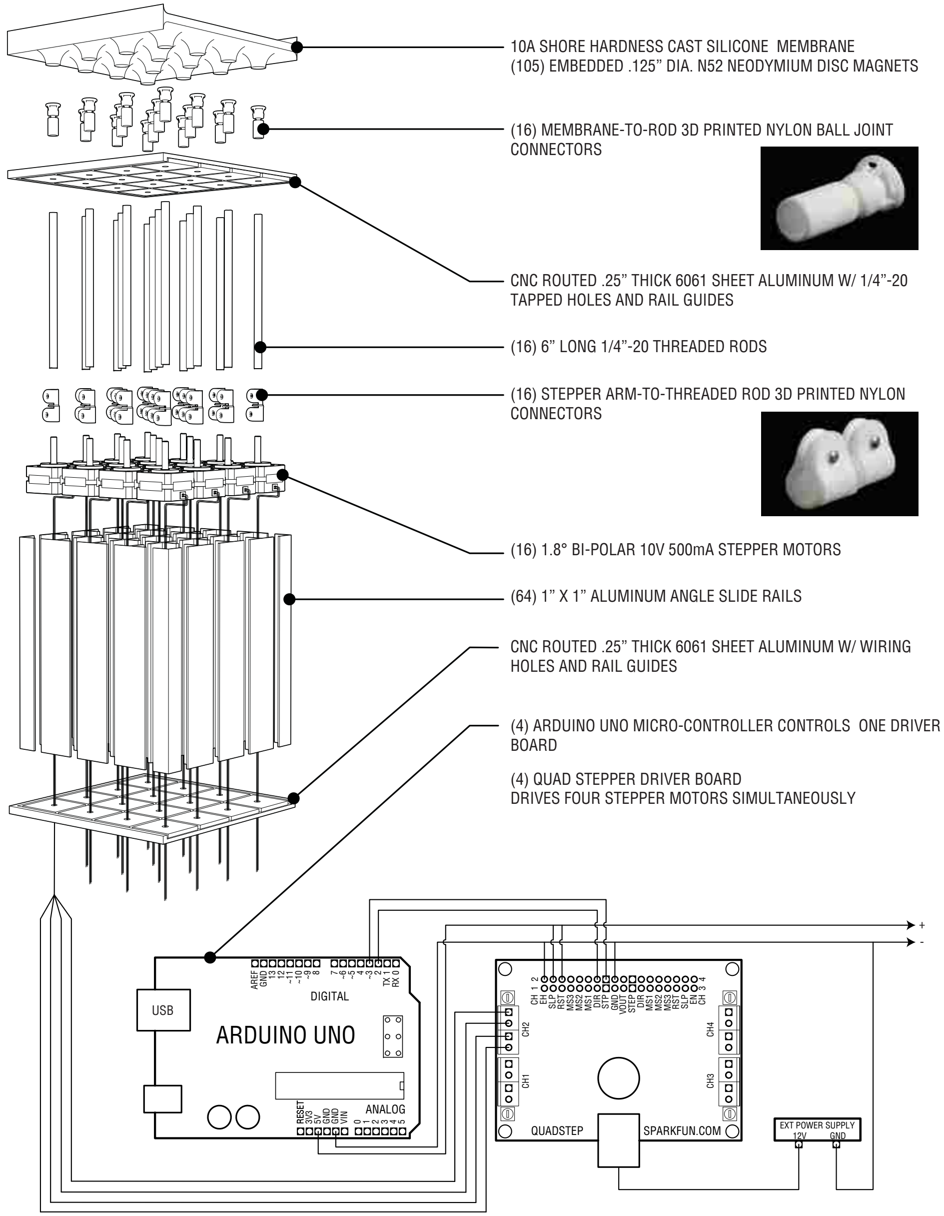

Figure 36: [M]form components and Wiring Diagram

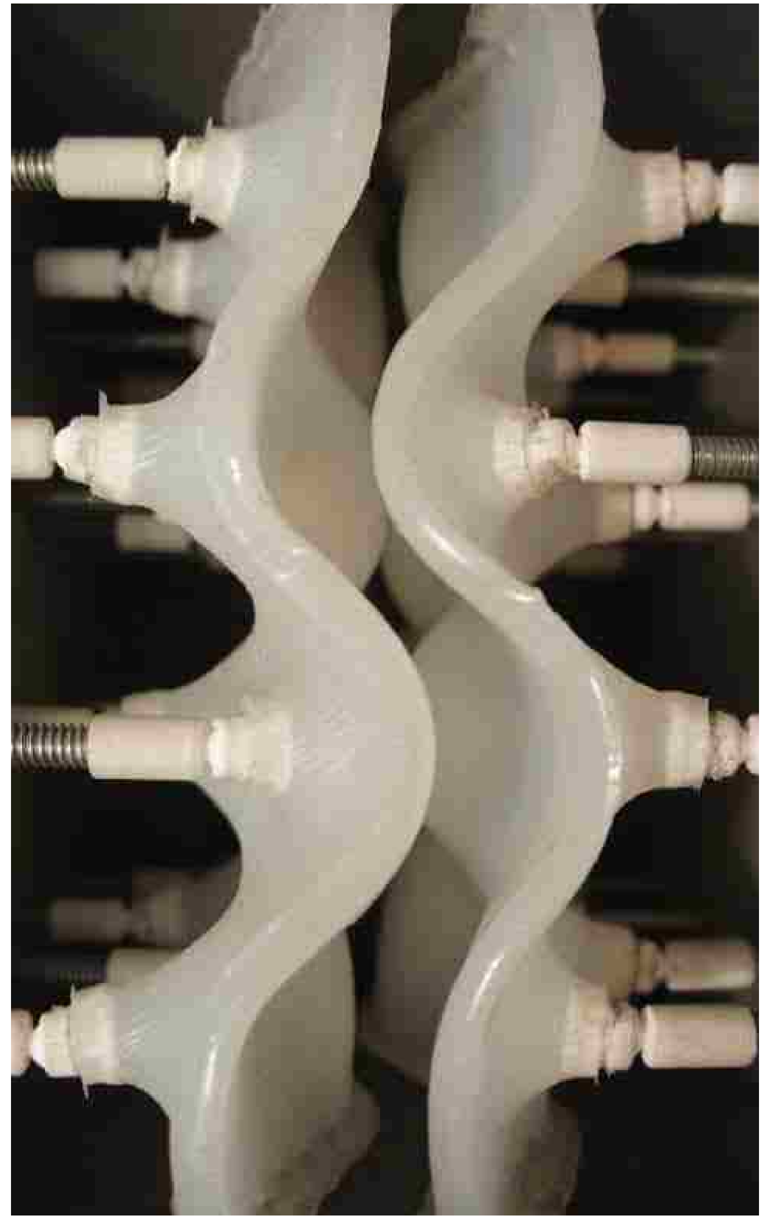

Figure 37: Cast space between two forming membranes

prototype that was produced. It corrects many of the problems that were previously identified and was the first prototype that was fully actuated. The intent from the beginning of the project was to keep [m]form a completely additive process meaning that in the formation of the cast nothing would have to be cut off or wasted. The main concern proceeding into the design of the final [m]form prototype was how to ensure the membrane edges did not pull away from the sides when it was deformed. It was agreed early on that the edges of the membrane would have to be tapered and thickened so that when the membrane deformed in either the positive or negative directions one side of the taper would come into contact with the side and bottom walls but what would keep this in place was more elusive.

Through constant exchange of ideas with colleagues two routes emerged: 1) cast male discs into the edge of the membrane that could be pulled through female holes in the side walls or 2) embed magnets into the membrane that would stick to steel side walls. The latter was decided as the better option for several reasons. If the side walls were porous it would mean that a system would have to be devised that covered up the female holes inside the cast space essentially creating another problem in and of itself. Second the side wall needed to be a material that would separate easily without a release agent from the cast part. Baltic birch plywood was the leading option for this porous wall but the maintenance on such a material was concluded to be more of a nuisance than it was worth. Over many small experiments it was determined that magnets would be suitable for preventing cast material from slipping in between the side wall and mold membrane. These experiments were helpful in identifying the minimum distance the magnets could be embedded in the silicone membrane without ripping out from the attraction to the steel wall and their position relative to each other without attracting one another.

The mold for the creation of the silicone forming membrane is quite complex including multiple materials and components into one poured object. It is made entirely out of machinable wax primarily for its machinable and release agent properties. It consists of three side components and two face components. Each side component features rabbet cuts that act as alignment grooves

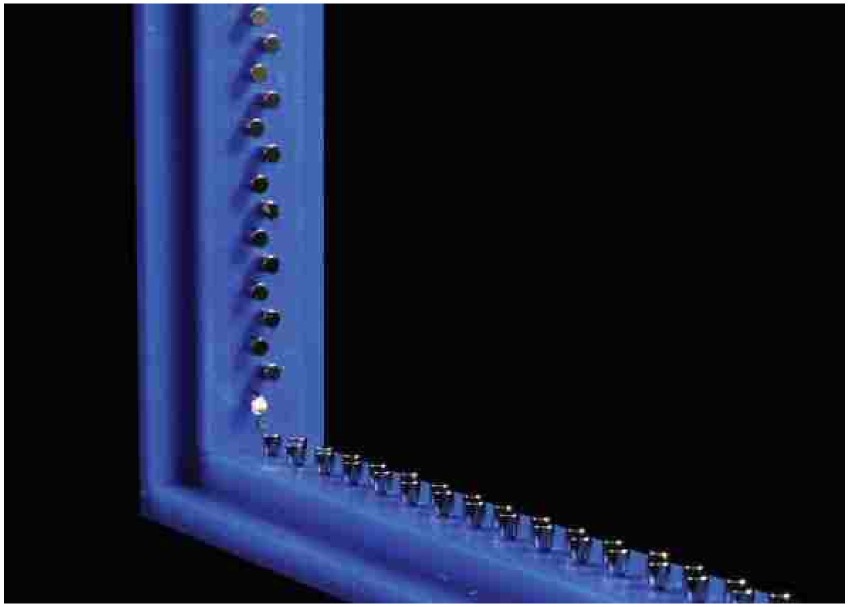
Figure 38: Final silicone membrane mold displaying neodymium magnets

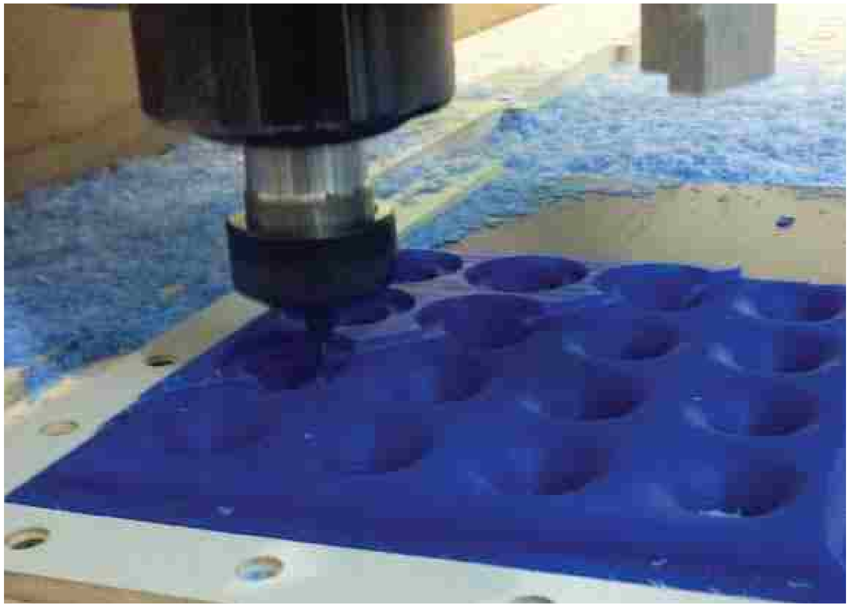
Figure 39: CNC routed machineable wax mold for final silicone membrane


Figure 40: CNC routing fabrication of sheet aluminum wall for final prototype


Figure 41: Aluminum wall showing rail guides and 1/4”-20 threaded rods

for the face components to sit on and 1/16" diameter drilled holes spaced at 3/16" apart from one another. Welding wire is inserted into of these holes and stick out 1/64" above the surface of the wax in order to offset the magnets from the surface edge of the silicone membrane.

The distance between each drilled hole ensures that the neodymium magnets are 3/32" away from one another which is the minimal distance needed to keep them atop the wire and not attracted to each other. In total the mold consists of 105 neodymium magnets and 5/16" long steel wires. The two face components of the mold form the front and back of the mold membrane. The first has a porous undulating form that dips at sixteen points to accommodate the space needed to insert 3-D printed nylon ball joints. The second face component has the same bounding mass as the first but does not feature the undulating surface or the holes because it is the smooth face of the silicone membrane that cast material is poured against. A mother mold made of laser cut 1/8" thick plywood sheets wraps around the wax mold guaranteeing that no silicone leaks out. There is a final plywood sheet placed against the porous wax face component that has holes centered on the holes of the wax mold that is offset a 1/16". Each nylon ball joint is pressed up against these holes and held in place by putty to ensure that they are perfectly centered and suspended within the silicone cast.

The nylon ball joints were custom designed with permeability in its swivel head. This permeability allowed for silicone to seep in between the positive ensuring that when pins moved past each other the ball joint would not release. These joints are then adhered to the 1/4"-20 threaded rods that are then inserted into the CNC routed 1/4" thick aluminum walls. These walls have grooves that the aluminum rails slide into and square 1/4"-20 tapped holes. These features address the heating and squareness issues recognized in the previous models. The same wall is mirrored at the opposite end of the rails only the same size holes are not tapped as they provide an opening for the stepper motor wires to be threaded through.

A huge flaw in the design of the machine is the rail system itself. On one hand the aluminum acts as a heat sink when the

Figure 42: Various mold configurations that [m]form is capable of assuming

Figure 43: Backside of forming membrane showing 3-D printed nylon ball joints and 1/4”-20 threaded rods extending out of aluminum wall

motors get hot but ensuring that they are perfectly aligned for insertion into the second wall was nearly impossible. A last minute design of a plywood template facilitated the process of friction fitting the rails in place but the best solution would be for the rails to be one solid extruded aluminum piece with cavities for the motors to move back and forth. Also the tolerance for the fitting of the motors was 1/32" overall which means that the motors are just minutely off axis with the tapped holes placing added stress on the 3-D printed nylon connectors that attach threaded rod with stepper motor arm. To rectify this problem future designs will incorporate a secondary system within the rail that facilitates movement and centers the motor with the tapped holes. The wires that extend out of the second wall are then connected to a prototyping board that the microcontroller and driver boards are all attached to.

As stated previously the majority of time spent designing the machine was focused on the formation of the mold membrane. The largest unresolved portion of the machine extends from the rail system back toward the electronics. Movement of the motors within the rails is particularly strained and not as smooth as it should be as a result of the motors not being centered in the rail and the electronics not being mobile enough to slide with the stepper motors. Future designs will need a type of cable tracking system on the back end of the machine that will allow the movement of wiring without being tangled up with neighbors. Also, the nylon prints succeeded in fixing many of the material properties associated with the previous plastic connector pieces; however in order to move into a full fledged version of the machine these will all have to be replaced with metal parts. By doing so the identification of failure can be limited to the elasticity of the forming membrane or the torque of the stepper motor. In the end these will become the values that constrain the parametric system.

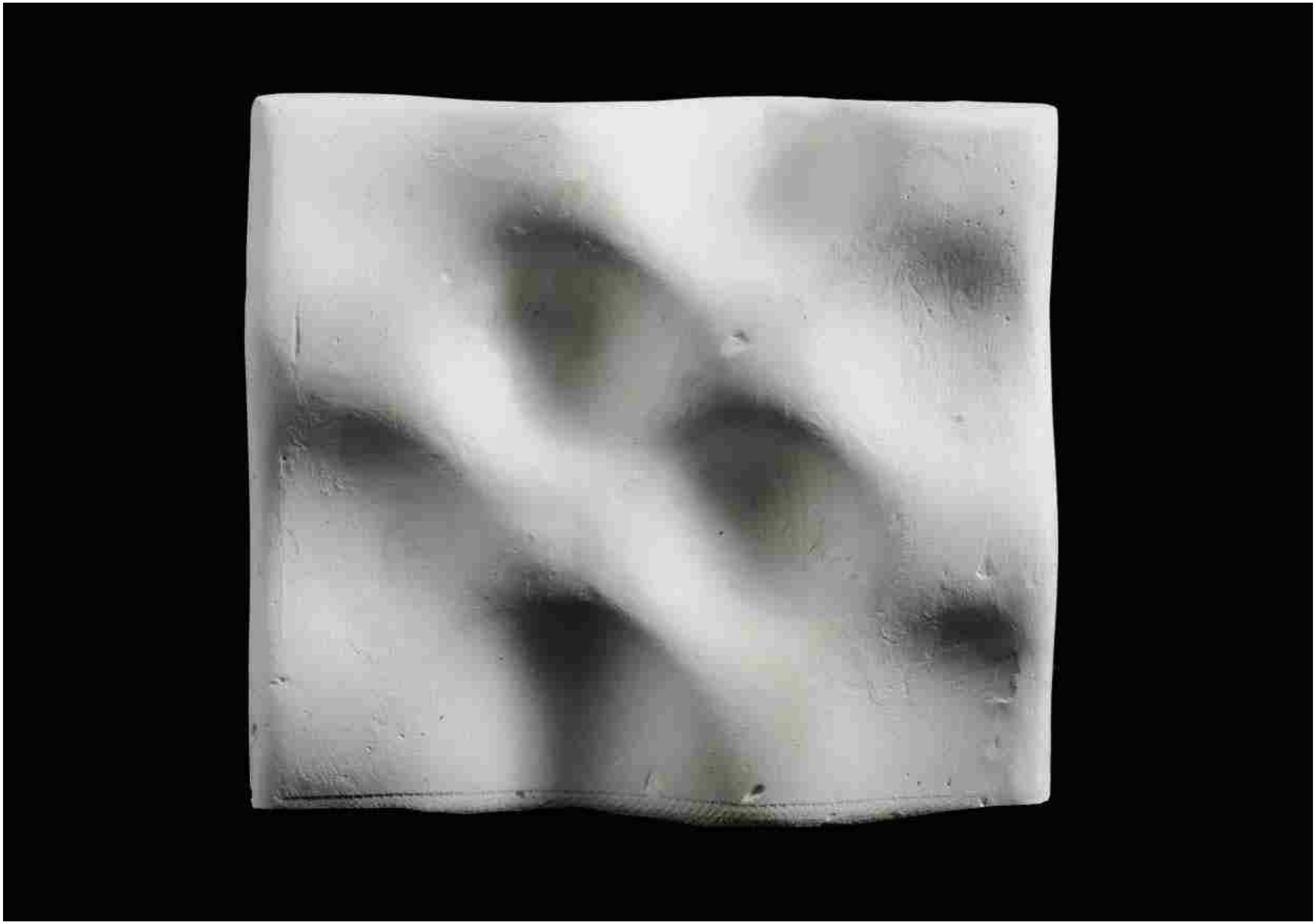

Figure 44: Cast plaster panel produced using final [m]form prototype

Conclusion

Physical computing is opening up a new world of possibilities for design and manufacturing and will be a key component in the realization of variable form in architecture. [M]form is still in its infancy but has many different routes that it can go from here. As stated previously the second exchange point that falls in the last quadrant of the symbiotic process needs to be addressed. The question is how the material properties and capabilities of the machine are fed back into the dynamic system. Are sensors integrated into the machine that can identify the breaking point of these constraints that automatically notify the dynamic system that these maximum values have been triggered or is it a manual process that is observed by user and plugged back in? Certainly there are arguments for both that revolve around budget and resources but more importantly there is an acknowledgement that this feedback is critical to facilitating a truly symbiotic relationship between man and machine.

After the completion of the machine it was noted that the overall system is too rigid and ties back to the problem of design. If in the future [m]form is sold as a tool for manufacturing are designers limited to dividing their bounding masses/ surfaces only around a given UV arrangement of pins? It raises the question of reconfigurability beyond the mold membrane and actual reconfigurability of the pins themselves which implies the pins will need to be modularized to snap together. This will enable designers to purchase individual pin modules that can then be arranged in any profile they'd like (10 x 20, 6 x 15, 70 x 120, etc.) with the only constraint being how spaced out they are from one another.

This also raises the question of flexibility in the UV directions fostered by swiveling connectors between modules allowing for two levels of reconfigurability. The first being how the pins modules could be configured where two lengths of the modular system act as rails to sweep the other two side sections. If say the pin modules were flexible enough to assume a gently curving mass the pin movement back and forth within the module could allow for complex curvature incorporating highly concave or convex scenarios. An underlying theme of this thesis is acquiring variation from seemingly regular forms as a result of material properties such as elasticity. There is the potential to swap the smooth face component of the mold that produced the silicone membrane with various repetitive patterns that are routed into its flat smooth face. By doing so the elasticity of the membrane will surely create variable patterns from regularly repetitive patterns at taut and loose junctures of the membrane.

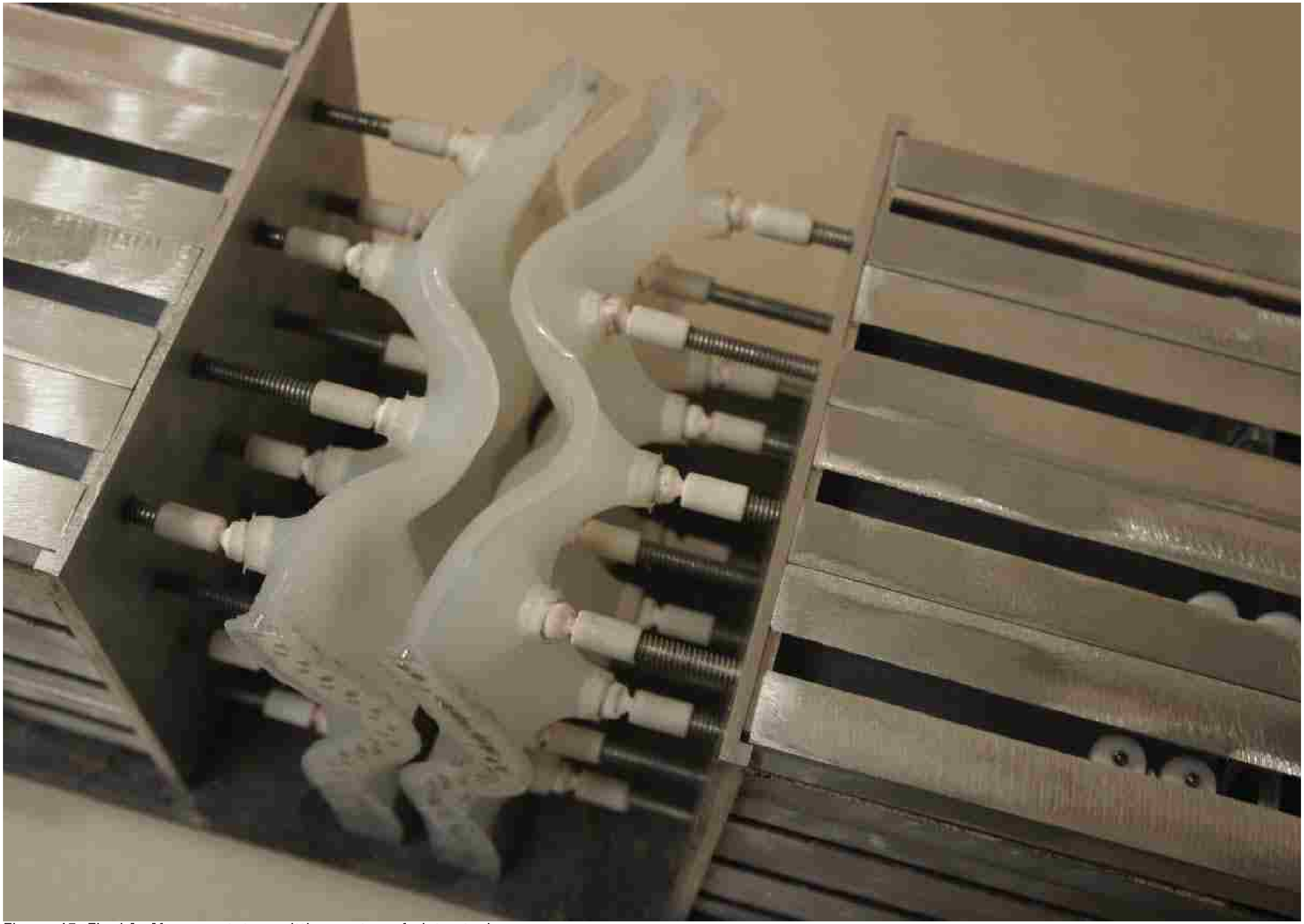

Figure 45: Final [m]form prototype sitting on top of plate steel

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Al-Haddad, Tristan, Vishwadeep Deo, and Ted Ullrich. Georgia Institute of Technology: Parametric Modulations in Masonry Systems. Tommorow Lab: High Performance Concrete Systems. Web. 7 Jan. 2012. <http://tomorrow-lab.com/projects/project_4.php>.

The author, professor of architecture at the Georgia Institute of Technology, formed the basis for this paper while participating at a research seminar that raised issues of modular variation in ultra-high performance concrete and produced two variable systems of construction one of which is described in detail in the paper. Control points are extracted from a digital model, CNC milled in plan, rods are inserted into milled holes, and bendable boards are wrapped around the control points to form the mold surface. While analog in composition and semi-subtractive in nature, the project utilizes cutting edge forming materials that can be implemented into current building processes and cut down on the time and material typically used to produce a similar result.

C.J. Williams and T. Skinner, "Spring-Forming Device," US Patent no. 1465152, issued Aug. 14, 1923.

The first reconfigurable mold based off of pin-point forming was created by the authors for the creation of automobile leaf springs which they acquired a patent for in 1923.

Kahn, Omar. "Reconfigurable Molds as Architecture Machines." ACADIA 08: Silicon + Skin:Biological Processes and Computation : Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA): October 13-19, 2008. University of Minnesota, Minneapolis. [United States]: Association for Computer-Aided Design in Architecture, 2008. 286-91. Print.

The author, graduate student of architecture at the University of Buffalo, focuses on the bidirectional design process that a parametrically linked and digitally reconfigurable mold has to offer. He presents four different types of "one-way" reconfigurable molds (RCM) one of which utilizes a numerically controlled height-field as the primary means of form making. The paper also focuses on the importance rubber membranes play in the forming process as well as the ability the design has on informing the machine itself and vice versa.

Papazian, John M. "Tools of Change." Mechanical Engineering Feb.-Mar. 2002. Web.

The author, a technology development manager at Northrop Grumman's Integrated Systems Sector, revisits an earlier design of a reconfigurable die built in the late 1970's by Dr. Hardt of MIT's mechanical engineering department.

T. Walters, "Press," US Patent no, 2334520, issued Nov. 16, 1943.

The second reconfigurable mold that utilized a pin-point forming method was first expanded into three dimensions by the author for the purpose of forming sheet metal.

Spuybroek, Lars. "Ali Rahim: Uniformity and Variability in Architectural Practice." Research & Design: the Architecture of Variation. New York: Thames & Hudson, 2009. 41-47. Print.

The author, principle of NOX Architects and Ventulett Distinguished Chair in Architectural Design at Georgia Tech, focuses on variation in architecture rooted in biological evolution and assemblies. In the book he interviews Ali Rahim – Principle of Contemporary Architectural Practice and Professor of Architecture at the University of Pennsylvania - on the implications variation has in his practice. The most interesting point being that in order to bring designs out of the digital and into the physical world the practice had to develop a reconfigurable mold to make variation more affordable. Ali Rahim goes on to address the ramifications of working with a reconfigurable mold and that its limitations/

potentials (e.g. panel size, thickness, edge conditions, etc.) must be implemented into the script early in the design process to alleviate the transfer process from digital to physical artifact.

Tibbits, Skylar. “Logic Matter.” Web log post. SJET. 2010. Web. 15 Feb. 2012. <http://www.sjet.us/MIT_LOGICMATTER.html>.

The author, junior TED fellow and principle of the design office The Very Many, is an expert in the area of programmable objects. This field of study conflates assembly, fabrication, and aesthetic in a manner where each contributes toward effect in what can be described as a bottom-up design process.

Walczyk, Daniel F., and David Hardt. “Design and Analysis of Reconfigurable Discrete Dies for Sheet Metal Forming.” Journal of Manufacturing Systems 17.6 (1998): 436-54. Print.

The author, Mechanical Engineering Professor at MIT, coves the history of pin-point forming as a method of manufacturing and the constraints that play a role in what is possible in the formation of sheet metal.

Figure 46: One forming wall from final [m]form prototype