POP-OP: A Shape Memory-Based Morphing Wall

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Recent tendencies in architecture take a unique point of view, with aesthetically novel and unnatural sensibilities emerging from a close scrutiny and study of apparently natural systems. These tendencies are being driven by mathematical and computational abstractions that transform the way we understand the matter-information relationship. This project was inspired by Op Art, a twentieth century art movement and style in which artists sought to create an impression of movement on an image surface by means of an optical illusion. Passive elements consisting of composite laminates were produced with the goal of creating lightweight, semi-rigid, and nearly transparent pieces. The incorporation of active materials comprised a unique aspect of this project: the investigation of surface movement through controlled and repeatable deformation of the composite structure using shape memory alloy (SMA) wiring technology. The integration of composite materials with SMA wiring and Arduino automation control resulted in an architectural wall that incorporated perceptual and actual motion.

1. INTRODUCTION

In the 1960's art world, some critics faulted Op Art's persistent involvement with optical illusion at a time when "the flatness of the picture plane" was the mantra on either side of the Color Field–Minimalist aisle.

Op Art works are abstract, with many of the better-known pieces made only in black and white. When the viewer looks at them, he or she has the impression of movement, hidden images, and flashing and vibrating patterns.

The basic pursuit of the research project described here was to incorporate both perceptual movement and real movement in architecture, which is an uncharted field. As a line diagram, this project works in Deleuzean terms, basically isolating the figure to break with representation and tie fact and matter. In *The Logic of Sensation*, Deleuze discusses this isolation of a figure to its spatial context and how it helps overcome representation. Deleuze applies the same kind of thinking that he intends the figure to disrupt by juxtaposing figural and abstract representation [1]. An important aspect of this current project—and one that is characteristic of my research—was the combination of two different sensibilities: the parametric geometric field and the moving flowers and motion-scaled panels, all articulated into a particular atmosphere.

In this paper, when we discuss representation, the question of depth becomes critical; it is important to bring the notion of the Gestalt, conceived as a figure against a background. We think of Gestalt as precisely the interplay between the figure and the ground, and Pop-Op treats both as the same by juxtaposing planes of representation and literally producing both depth and figure. Any variation in the figure itself will cause reciprocal topological variations in the underlying field.

1.1. 2½ Dimension

According to Henry Somers-Hall:

> "Husserl's error is to fail to realize that the ground itself is a part of the figure. The ground and figure are different in kind, but also, as is shown by the possibility of infinite regress, infinite reversibility prevents their reduction to a homogenous plane" [2].

This understanding of a figure emerging from the ground is what we will refer to as 2½ dimension. First, it must be understood that the number 2½ is not to be taken literally. It has nothing to do with actual half dimensions or with fractals. Rather, this number negotiates the concept that in reality, we tend to mix figure and ground:

> "We do not actually see all three dimensions surrounding us. Rather, we construct the three dimensions in our mind and project them onto the objects surrounding us. More specifically, what we see is a projection of our surroundings onto a 2-dimensional plane, our retina" [2].

The key to perceiving three dimensions is that we have two retinae. Depth is not a space in the conventional sense of a series of dimensions through which the movements of objects can be measured, but a place where relationships between objects as differential processes are formed. According to Akins:

> "Merleau-Ponty is attempting to move beyond the world of perception to the conditions for the experience of what he is searching for is the origin of the Gestalt in that relation between a perceiving body and a sensible . . . and not perspectival world" [3].

1.2. Intersection of Science and Art

In order to achieve these artistic goals, we utilized technologies and methods that are usually associated with the technically-inclined. The power of science and technology to inspire art and of art to inform the sciences is a topic that has been explored since before the time of Leonardo da Vinci. Science, engineering, and new technologies have a lasting ability to inspire and enable new forms of artistic expression, be they musical [4], graphical [5, 6], or architectural [7,8,9]. The inverse causal relationship is also quite clear. Concepts conventionally considered "artistic" are often transformed into themes for new, sometimes well-funded, science and engineering research. Consider the topic of origami, recently championed in the United States by the National Science Foundation (NSF) and Air Force Office of Scientific Research (AFSOR) as a potential framework for rigorously developing new forms of morphing and otherwise reconfigurable structures [10]. Other classical examples include the drive for more effective visualization of scientific data [11] and the sometimes controversial efforts to add the arts into the conventional science, technology, engineering, and math (STEM) educational framework [12], sometimes referred to as STEAM [13].

In this work, however, we will focus on the potential role of technology, and in particular that of active materials and morphing structures, in expanding the space of artistic expression. For the purposes of context, it is useful to consider other current trends. Technology continues to enable new advances in the graphical arts, for example. There are very few images that we see on a daily basis that have not been somehow modified by tools such as Photoshop, which fundamentally alter the way artists approach "image" as they design and organize graphical information. The impact of technology on the graphic arts is further manifest in the area of animation, where advances in computer science in particular have produced new and ever-more capable software tools. Progressive digital design technologies are pivotal in advancing the field of architecture as well. The design goals associated with multiple architectural complexities are often difficult to quantify and even more difficult to condense into a single formal design criterion. Thus, sets of inter-relational criteria are derived and new design methods are required. In the modern framework of architectural design, the process of concept development may be subsumed completely into the family of technologies, often computational, which are employed [7]. Hardware technologies such as more explicit incorporation of sensors and actuators into architectural forms are also being considered [14].

The Pop-Op explores the intersection of art and science throughout the design and fabrication process. The use of software tools for design (Section 2.1) and computer-controlled fabrication methods (Section 2.2) heavily rely on technological innovation. Through collaboration with engineers on the design of the actuation methods and control system, the Pop-Op embodies the growing importance of interdisciplinary efforts in modern architectural works.

2. DIGITAL DESIGN TO FABRICATION

Instead of form being imprinted upon matter, matter in the context of this project is understood as an active agent in its own formation. It promotes dissolution of linear hierarchies, enabling the heterogeneous and nonlinear nature of complex agencies to hybridize and be incorporated into the complex fabric of architecture.

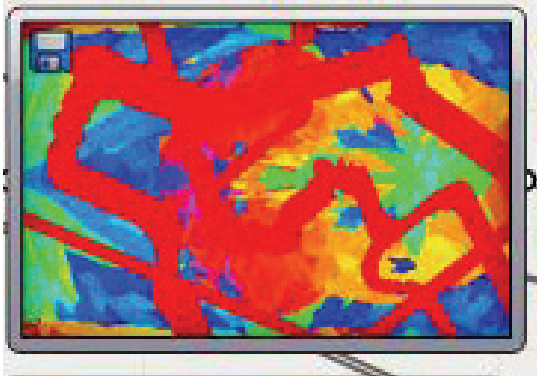
The overall process of structural synthesis employed in this research endeavor was founded in the latest theories of digital design. The project sought to investigate surface movement through controlled and repeatable material deformation. This study of "morphing" was done in collaboration with faculty and students from the Department of Aerospace Engineering. A so-called active material known as shape memory alloy (SMA) was incorporated into a fabricated structure, creating what we called an SMA morphing wall. SMAs are a unique class of metal alloys that can recover apparent permanent strains when they are heated above a certain temperature. They have two stable phases: the high-temperature phase, called *austenite*, and the low-temperature phase, called *martensite*. Upon cooling, in the absence of applied load, the material transforms from austenite into twinned (self-accommodated) martensite. As a result of this phase transformation, no observable macroscopic shape change occurs. Upon heating the material in the martensitic phase, a reverse phase transformation takes place, and, as a result the material transforms to austenite [15].

Passive elements consisting of composite laminates were produced with the goal of creating lightweight, semi-rigid pieces that would be part of the morphing wall. We specifically used Dynalloy 0.38 mm (0.015 inch) wire, which is capable of self-deformation and enters the design process as an active fiber. This wire can be used in its raw linear form or reshaped into spirals or other configurations. Actuation of these active fibers via low-voltage electrical current can substantially affect motions in a fabricated structure into which they are incorporated. Motions can be magnified by careful selection of attachment points and fiber paths and the exploitation of nonlinear effects such as surface buckling. Such morphing has advantages in the realm of engineering, especially with regard to aerospace vehicles that seek to emulate the morphing deformations exhibited by birds and insects [16]. In addition to contributions to the research of architectural design, it is expected that this kind of STEAM (Science, Technology, Engineering, Art, and Math) effort will lead to advances in the technical understanding of surface morphing as the drive toward aesthetic qualities informs the often overly rigid engineering design process.

The academic aspects of this research effort also included the consideration of control schemes for the active material elements. To this end, we employed Arduino, an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. It is intended to create interactive objects or environments and was thus ideal for our multidisciplinary project.

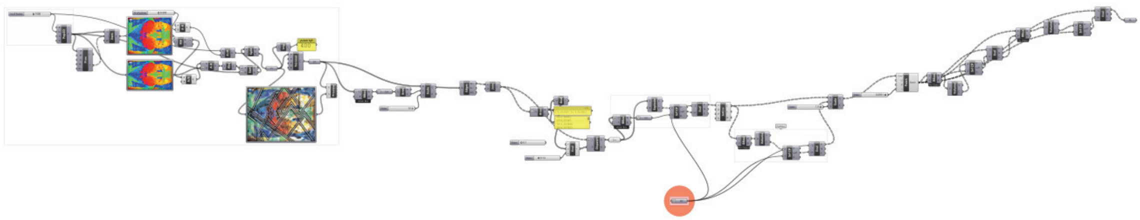
2.1. Image development

The final design for the Pop-Op was crafted through a parametric design process. To begin the digital design of the overall surface, we prepared a sample image in Adobe Illustrator that incorporated the preliminary criteria for a 2?-D drawing including the desired Op Art effects and the desired color palette as shown in Figure 1. The sample image was highly saturated in order to produce a greater variation of hues in the final image. A hand-derived pattern was overlaid in red onto the sample image. The scripting software would later use this pattern as a map for the final image.



◀ Figure 1: Sample image designed in Adobe Illustrator with hand-derived pattern (in red).

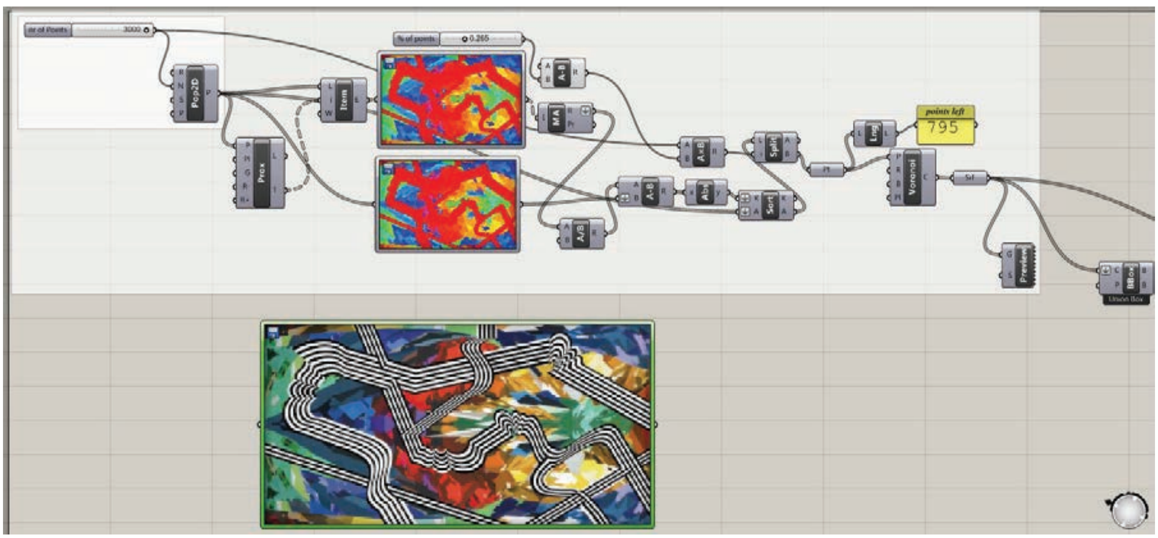
The generative algorithm software Grasshopper was chosen to carry out the parameterization procedure. The process began with the script evaluating the sample image and then interpreting that image through a series of algorithmic steps as illustrated in Figures 1 and 2. The sample image was inputted into the script in its most saturated form to produce



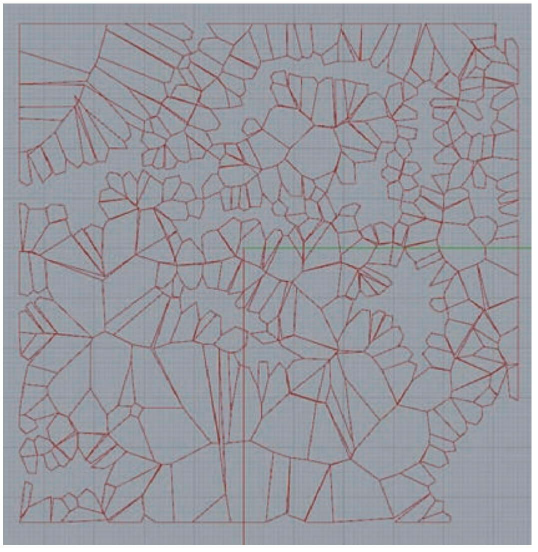
▲ Figure 2: Full image of grasshopper script.

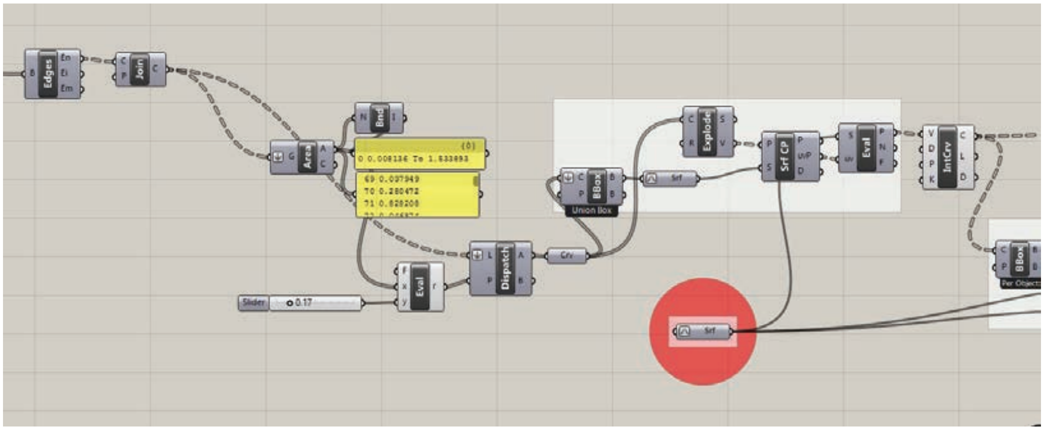
the largest variation of hues. The script outputted a series of stained-glass patterns represented in Figure 4.

▼ Figure 3: Close-up of script showing original and final images.



► Figure 4: Once the image was analyzed, the script produced the stained-glass pattern via a series of curves.

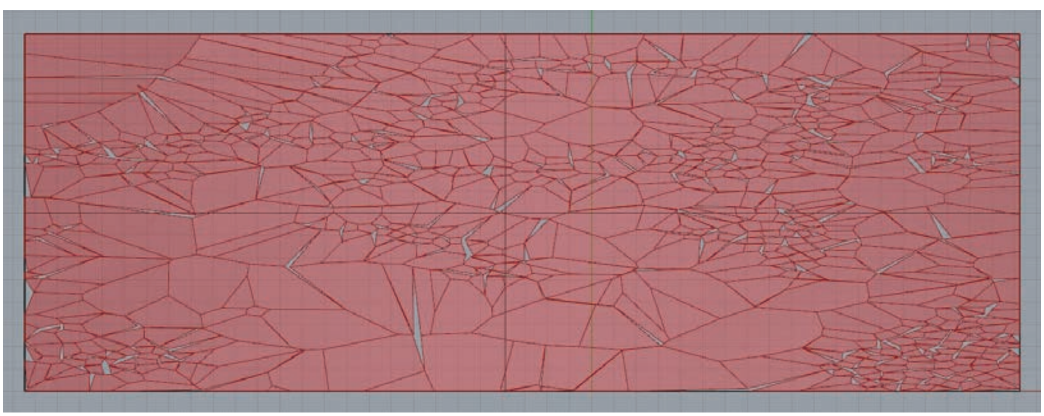




◀ Figure 5: Script showing slider.

Once these curves were derived, we projected them onto a surface. This surface is shown in Figure 6. For this design, the surface matched the dimensions of the Pop-Op installation site.

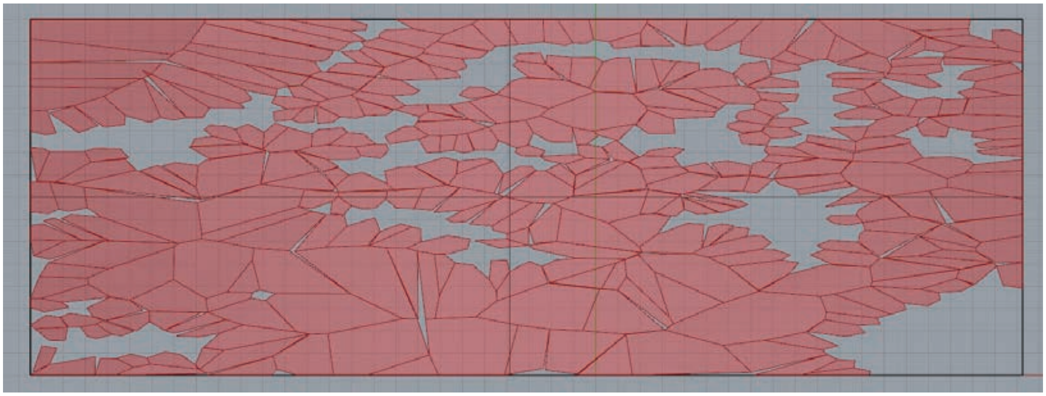
The stained-glass patterns shown in Figure 4 were evaluated. Different versions of the original pattern were generated through the fenestration filter as presented in Figure 5. The filter works by selectively removing elements from the overall pattern. The user inputs the "size" of elements that should be removed via a "numerical slider". Elements with dimensions below the inputted threshold are erased from the pattern. Setting the value to 0 indicates that no pieces will be removed, as highlighted in Figure 5. Choosing a larger value removes a greater number of pieces from the pattern, causing a more intense amount of fenestration as illustrated in Figures 6, 7, and 8.



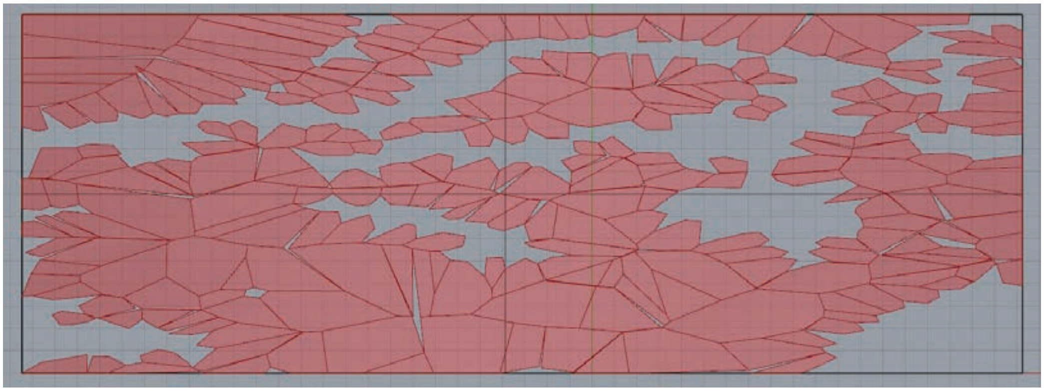
◀ Figure 6: Pattern breakdown.

The scripted pattern generation was beneficial for multiple reasons. It helped streamline the design process, aided in rapidly generating the amount

► Figure 7: Second iteration, creating more apertures within the pattern.



► Figure 8: Final pattern.



of material we would need for the entire project, and motivated the installation process.

2.2. Fabrication

The Pop-Op design called for the fabrication of three distinct composite component groups: 28 "panels", 9 "flowers", and a large background element. The complete fabricated sculpture is shown in Figure 9. As shown in Figure 11, the panels are small, roughly rectangular pieces that are actuated with SMA springs. When no actuation is occurring, the panels are flush with the wall surface. During actuation, the SMA springs pull them away from the viewer. The aptly-named flower components are cut into floral patterns as demonstrated in Figure 10. The flowers are actuated by SMA wire running along their surface. When actuated, these flowers bend toward the viewer. The immobile background panel covers the bulk of the Pop-Op surface and complements the morphing panel and flower elements. The material selection and fabrication processes had to take into account the morphing nature of the flowers and panels in addition to the typical design and structural constraints.

The fabrication research began with the exploration of specific materials including C-glass reinforced with a two-part epoxy matrix (resin), fiberglass, and polyester. We applied the soaked glass onto a flat non-stick surface. The goal was ultimately to produce light, rigid or semi-rigid, and, most importantly, nearly transparent pieces.

To obtain the transparent results, we continued using epoxy resin and C-glass layers. Three layers were used for the flowers and four layers for the panels. The amount of epoxy was lowered for both of these morphing structures. These changes did in fact produce the desired transparency, semi-rigidness, and light-weightiness. In between these layers of C-glass, we used a layer of paper with the printed pattern so that the underlying color pattern was persevered and protected in both brightness and scale. The print had an origin point in one of the corners that acted as a reference point for the Mastercam tool path input; thus, we were able to accurately and automatically cut various features such as the flowers and panels using the CNC mill.

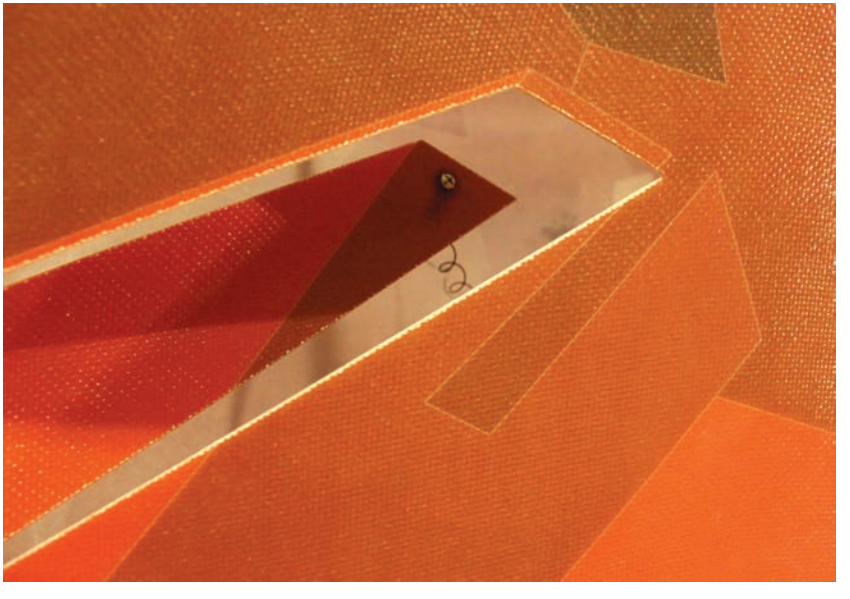
The epoxy resin featured an available working time ranging from 0.5 – 4 hours, depending on the type of hardener used. This resin also released a reduced amount of toxic material while curing. However, the epoxy resin proved to be extremely sensitive to the weather and was difficult to cure in humid conditions. During the material fabrication process, we had to give special consideration to the unusual morphing application of the composite material. The composite material required enough flexibility to morph in

◀ Figure 9: Final installation.

► Figure 10: SMA wires, Dynalloy 0.38 mm (0.015 inch) wire, running along the surface of a flower.

response to the SMA actuation while at the same time producing enough tension to return to its original position when the actuation was completed. Surface performance was interpreted precisely from the number of layers and the type of wire application—along the surface for the flowers and the coils for the panels (see Figures 10 and 11).

► Figure 11: A typical panel design.



◀ Figure 12: SMA coils attached to the back of the panels.

3. ACTUATION: ELECTRONIC CONTROL SYSTEM

The Pop-Op electronic control system provided a reliable and flexible method for controlling the motion of the wall. Once installed, the timing of the actuations could be readily changed by modifying and uploading a computer program.

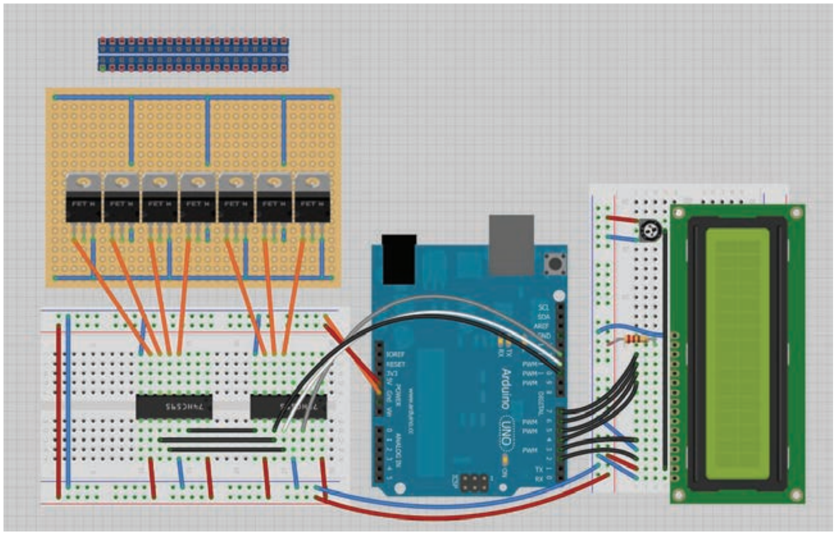
The Pop-Op contained 37 controlled components (28 panels and 9 flowers). To simplify the electronic hardware design, the control system was designed around the principle of control channels. Each panel and flower was grouped into one of 16 channels. The channels were individually controlled by choosing the time each would actuate. All components within a channel actuated at the same time.

3.1. Design

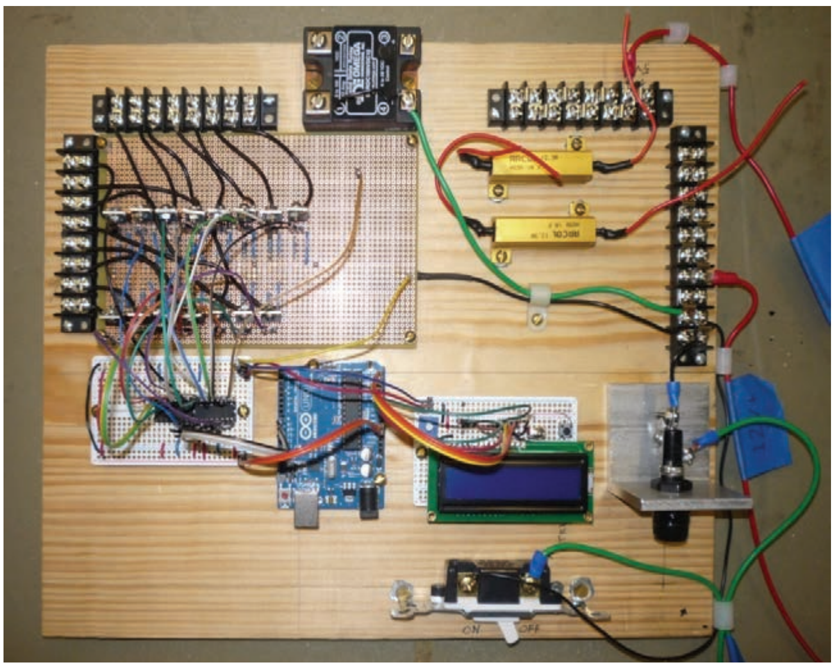
The heart of the electronic control system was the Arduino microcontroller board. The Arduino is an open-source hardware and software prototyping platform. Using a series of input and output pins, the Arduino can be programmed to monitor and control an environment using a C/C++ based programming language.

Before construction began, a schematic of the circuit was created in the prototyping software Fritzing, as shown in Figure 13. Figure 14 is a photograph of the uninstalled control board.

► Figure 13: Circuit design schematic.



► Figure 14: Uninstalled control system.



The electric current required to actuate the SMA wires far exceeded the maximum current output of an Arduino pin. For this reason, some type of transistor was needed to act as a switch for a higher-capacity power supply. The transistor used for the Pop-Op electronic control system was a Logic Level N-Channel MOSFET.

Because the Arduino contains only 16 output pins, directly connecting the Arduino to the 16 MOSFET channels would require all of the Arduino output pins. In order to compensate for this shortage, an integrated circuit known as a shift register was used in the design to extend the number of input/output pins. Using just three Arduino output pins, two shift registers were able to control all 16 channels.

Each shift register had eight output pins, and each register pin was connected to the appropriate pin of the MOSFET. When the Arduino sent instructions to the shift registers, the registers sent a voltage signal (5V or 0V) to each MOSFET. A 5V signal switched a channel on, while a 0V signal switched it off.

The components in each channel were wired together in series or parallel in such a way that each component received approximately 25W of electric power. The control board interfaced with the channel wires through a series of screw terminals. The terminals provided common 12V, 5V, and 0V rails. Additionally, 16 channel terminals connected to one of the 16 MOSFETs.

3.2. Power, Safety, and Monitoring

The control system and SMA wires were powered by a 250W computer ATX power supply. The power supply could be manually shut off at any time by opening a switch on the control board. The output of the power supply was tightly regulated and would automatically shut off if the output current became dangerously high. As a final precaution, a replaceable 20A fuse would shut down the entire system in case of a short circuit.

The wall was designed to run autonomously throughout the day and then turn off at night. This was achieved by using an external battery-operated clock that interfaced with the Arduino. The Arduino received time information from the clock and was programmed to turn on or off at specific times of the day.

An onboard LCD monitor displayed the status of the system and which channels were currently actuating. In addition, it displayed the system time to ensure that the external clock was set correctly.

4. CONCLUSIONS

Pop-Op has impacted the field of architecture by addressing the concept of using materials as a means of creating diverse atmospheric sensations in a space, focusing on the effects produced by material textures and surfaces exacerbated by motion of elements in a controlled game of ornament and pulsation. In this way, beauty, ornament, and pattern can find their way back into contemporary design. According to architecture critic Eric Goldemberg:

"Pulsating architecture generates and distributes such matter in excess, which assumes the form of innate ornament and augments the awareness of the beat that articulates space" [17].

Within this ornamental attitude, this project sought to represent the intentional and potentially transformative collision of two concepts: (a) a high reference to the conditions of Op Art, highlighting the shifting terrain between craft and material in relation to design production; and (b) a highly technological and performative base on the actuation of aerospace engineering technology.

Nonlinear systems require many experimentations and trial tests, as well as constant importing and exporting of files from software to software. The future is promising, but it requires a careful understanding of these systems when performance is derived from them. We will continue to explore ways in which architecture can demonstrate, test, and apply insights and theories from mathematics and the sciences—nonlinear, algorithmic, and complex—in the design of material structures across an open-ended range of scales, materials, and design disciplines.

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