Multi-dimensional Medium-printing

Prototyping Robotic Thermal Devices for Sculpting Airflow

Catty Dan Zhang\textsuperscript{1}, Allen Sayegh\textsuperscript{2}

\textsuperscript{1}UNC Charlotte \textsuperscript{2}Harvard University

\textsuperscript{1}dzhang14@uncc.edu \textsuperscript{2}asayegh@gsd.harvard.edu

This research investigates the design and prototyping of fabrication machines that utilize multi-dimensional printing techniques to sculpt an invisible medium-airflow, inspired by its unique materiality, philosophical value, sensorial aspects, and increasing considerations of atmosphere and climate in architectural research and design. A series of robotic thermal devices were developed to modulate animated geometry sequences through scripted movements, designated coordinates, and temperature fluctuations. This paper elaborates in depth multi-stage developments and experiments that integrate various systems, fabrication processes, optical experiments and computational analysis. It situates the experimental process of the medium-driven fabrication with possible applications in architectural design as envisioning alternative environmental systems utilizing thermal byproducts under aesthetic and experiential considerations.

Keywords: Airflow, Robotics, Additive Manufacturing, Fabrication, Atmosphere

INTRODUCTION

Yves Klein stated in his lecture at Sorbonne in Paris in 1959 that air- along with gas, fire, sound, electricity, etc- should be considered as architectural material that has main functions “to protect against the rain, the wind and atmospheric conditions in general and to create thermal air conditioning” (Perrin 2004). Airflow in nature, however, is a vibrant, chaotic, and complex medium. It breaks and heals, taking on subtle forces and bringing huge impacts. As a material claimed by Klein in \textit{Air Architecture} seven decades ago, researches on this particular medium related to its architectural applications have been made feasible through diverse approaches including computational fluid dynamics (CFD) and mechanical systems. Nevertheless, these sophisticated tools and machinery, although greatly contributing to energy efficiency and thermal comfort in utilizing flow, limit creative design possibilities for the majority of designers. To breakdown the complexity of the existing systems and to allow airflow to be experimented and understood similarly as other types of materials in fabrication, would offer more intuitive design opportunities and better integration of environmental technologies.

This research looks at precedents in articulating forms of airflow, and explores an alternative approach to embrace its materiality and to expand possible design strategies. This has led to the creation of a series of robotic thermal instruments. Referenc-
ing emerging methodologies in robotics and additive manufacturing, this research undertakes fundamental hypotheses: 1) the construction of a comprehensive taxonomy of geometry with ephemeral and dynamic airflow through an inclusive control system is possible; 2) similar as printing visible forms with many standard materials used in additive manufacturing, there are ways to articulate basic formations of airflow based on geometric primitives, from points to lines or curves, then to surfaces and volumes, so on so forth; and 3) highly sensitive to temperature and pressure, the unique materiality of airflow, and the toolpaths outputted from the designed machines, are two determinants of the sculpted forms.

The outcome of this investigation could not yet be fully predicted though computational models, nor it allows precise reproduction. A basic framework has been set up to control parameters of the machine outputs. However, the background temperature, the subtle flow occasionally happening around, the constraints of space and volume of air in the context, as well as the length of the experiments, are a few factors that will influence the emergence of the final geometry due to the convective behavior. These disruptions are intentionally welcomed in this project as developing a simple, clear, yet flexible system that allows both 1) aesthetics of the imprecision that has large impacts on the result due to the material behavior; and 2) future applications adapting to complexity of thermal activities and site conditions.

**BACKGROUND**

**Expanded Dimensions of Additive Manufacturing**

Originally developed in the 1980s, additive manufacturing- mostly known as 3D printing in the past three decades- has been increasingly adapted and advanced in a great number of disciplines and...
industries. 4D printing and bioprinting, for example, derive from this technology, allowing material evolutions triggered by time, light, water, biological behavior, or other activation energy (Papadopoulou et al. 2017) to be essential processes of achieving desired forms. In doing so, these methods expand dimensions of scripted tool-paths, providing tremendous potential for applications such as autonomous assembly, shape morphing, self-transformation systems, and so on (Li et al. 2017). Another focus has been material behavior in digital fabrication process. Olivier van Herpt’s Solid Vibrations, as one of the examples, employs sound vibration to create surface textures on the 3D printed ceramic artifacts (2015). Other examples include projects that couple unpredictable matter as agency and robotic sensing technology to develop generative fabrication process (Abrons et al. 2014). These investigations transition the fabrication of final products in traditional additive manufacturing into the fabrication of expansive conditions.

Taking airflow as material, the research presented in this paper finds its context within this domain where material transformation in the process of fabrication is articulated in a controllable manner. Here, the evolvement of the material is triggered by temperature and motion as agent.

**Material Properties and Form Generation**

Almost nowhere absent, air is unlike majority of materials due to its principal features including the tendency to “mix, compound and diffuse” along with the ubiquity (Connor 2010). It behaves in a fluid manner, which means particles naturally flow from areas of higher pressure to those where the pressure is lower. In the atmosphere, air has a 0.0257 W / (mK) thermal conductivity at 20°C, with a density of 1.205 kg / m³; and a 0.0299 W / (mK) thermal conductivity at 80°C, with a density of 1.000 kg / m³. Just like the concept of convection in fluid mechanics, when the density changes, pressure difference will occur, and flow will emerge.

Various typologies of airflow have been explored in existing research and design projects. They often follow principles of natural physics and use sophisticated machine assemblies to provide pressure difference by applying forces with an array of parameters. AIRED: Interactive Tactile Experiences in Free Air by Disney Research (Sodhi et al. 2013), a device that simulates haptic sensations on one’s skin, employs a sequenced pressure mechanism with a flexible nozzle injecting small air vortexes. Similarly, specific arrangements of multiple pressure sources allow simple control system to animate this amorphous material into complex yet scripted behavior, such as Tornado by Ned Kahn and Air Fountain by Daniel Wurtzel.

**METHODS**

**Key Components of the Thermal Devices**

This project tackles three major challenges: to create, to control, and to detect airflow. With this in mind, making changes in temperature was selected as a stimulus for altering density of air instead of applying external forces as inputs. This is due to two main reasons: 1) it creates an upward linear current in static conditions, using minimal necessary control while creating a great variety of outcomes; and 2) it could possibly be harvested from the built environment both through natural phenomena, and through byproducts of man-made systems such as electronics or building systems, which offers potential for future applications.

As illustrated in Figure 2, the straight line of upflow current generated by a point of heat source in space, transforms into curves and dash lines in motion, sculpted by forces from its surrounding environment; as other surfaces or elements intervene, these curves would be pushed into surfaces and volumes. Based on this basic understanding, four robotic thermal devices have been developed implementing methods from 2D to 4D printing with airflow. Each iteration is electrically calibrated for the sculpted invisible forms being sensed by Schlieren Imaging apparatus as performing initial documentation and evaluation of the outcome. Each instrument consists of three main parts—heat generator made
from nichrome wire roughly 10-15 ohm each; a motion system with a single or a combination of actuators providing certain degrees of freedom; and “fan blades” bringing in external forces. They are compactly designed and assembled to fit within the viewing area of a parabolic mirror 12.5” in diameter, allowing a great amount of visuals of airflow with recurring patterns being captured and analyzed.

The machines are capable to control a set of variables including the amount of electrical current, resistance of the nichrome coils, as well as the duration and interval of running the electricity through them. Temperature fluctuations are results of these manipulations coupling with scripted movements within the designated coordinates of the devices.

**Iterations**

Each stage of developments explores from simple to comprehensive ways of arranging as well as controlling the temperature and the motion system. Major iterations discussed in this paper include: the basic two- 2D printing with single axis motion system and heat sources; the comprehensive one- 4D printing with three axis motion system and heat sources; and the latest iteration- multi-frequency motion system with dual-temperature control.

**Single Axis Motion System with Heat Elements.**

During the first stage establishing a framework for testing, two prototypes were developed, and were evaluated according to both the legibility and the variety of invisible forms captured in the Schlieren images. They provide single degree of freedom (1 DOF) through NEMA17 stepper motors rotating along the central vertical axis. Here, the intention is to use the simplest type of motion for getting clear behaviors of various animated heat patterns.
The first prototype encompasses three heat coils, mechanically assembled on a set of orthogonally intersected acrylic frame (Figure 3a). This frame connects onto a 3D printed rotating plate that has flexible options for holding it in a variety of angles, as well as distances from the central axis (Figure 3b). All the electronic control is done off board which limits the range of motion due to the wire connections.

The second iteration uses on board customized PCB boards to eliminate the restrictions of motion comparing with the earlier one. Another investigation is an input factor made from 25 Dallas One-wire temperature sensors. The scripted movements respond to the sensed temperature pattern, mapping the 2D heat map from the environment onto 3D forms by outputting different range of rotation from the device.

The number of heat coils is increased to five. These coils are mechanically assembled with screws on a 3D printed surface sitting on a rotating plate that houses all circuit boards to control the heat (Figure 3c). A CNC milled base is designed to hold the gradient heat sensor pad, as well as electronics that control the motor. Heat and motion in this prototype are controlled separately. They both are driven by microcontroller ATMEGA328P, with an H-bridge breakout board for the stepper motor, and a MOSFET breakout board with five N-MOSFETs for programming all the heat coils (Figure 3d).

**Three Axis Motion System with Heat Elements.**

Both of the previous two prototypes rotate along horizontal planes, which result in limited visual effects due to the deficiency of depth detection of the Schlieren Optics system. Therefore, to increase the capacity of moving along the vertical plane, a three-actuator device that has three degrees of freedom (3 DOF) in a kinematic chain was developed (Figure 3f). Each degree of freedom is provided by a servo motor. It intends to accommodate the maximum capacity of motion trajectories for sculpting a wide range of possible forms, and at the same time, to maintain the smallest amount of space the device itself occupies. Housed within a 3D-printed mechanism, each of the motors provides a 180 degree range of motion relative to the rotation of the other two (Figure 4).

This prototype also has a simplified arrangement of heat elements. Two heat coils located on each side of a perforated double-curved surface, mechanically connected to an acrylic press fit structure frame using copper rivets. One is close to the convex peak area of the surface, while the other is protruding out further on the other side. The major purpose of doing so is to

---

**Figure 4**
Control diagram of the multi-frequency motion system with heat and cold components.
analyze a clear set of flow pattern generated from the two individual heat sources in relationship to one another as well as to the surface during various moving conditions.

Heat and motion are controlled with the same microcontroller. A vinyl-cut circuit mounted on a piece of acrylic, serves as a breakout board to control the heat coils with two N-MOSFETs (Figure 3e).

**Multi-frequency Motion System with Dual-temperature Control.** The three axis device proves its capability of sculpting a diverse set of forms based on geometric primitives with desired quality. However, one could find a much wider vocabulary of flow in the abstract visual patterns- lines consist of clusters of points varying in density, or surfaces composed with jiggling curves which dissipate swiftly. Fundamental features of the chaotic behavior of flow mechanics, such as elliptic vortices, buoyant jet, wake turbulence, etc, are results of heterogeneous medium flowing with different velocities. To further explore the material evolvements during the fabrication process inspired by this natural phenomenon of flow, a multi-frequency motion system was developed which utilized both heat and cold elements.

Two movable modules (Figure 6) with one heat coil on each situate towards the bottom of a structural frame which provides continuous rotary motion and holds cold components above. The cold elements create down-flow air currents. The overall dimension of the frame is constrained by the diameter of the mirror in the Schlieren Optics setup, the size of the mirror stand, as well as space needed to accommodate a full rotation of each module.

Motion system in this prototype is assembled with three different types of motors: stepper motors located on the structural frame and connect to the movable modules, servo motors on these modules sweeping along the vertical plane, and tiny DC motors with high RMP attached to four-bar linkages. The four-bar is designed so that the continuous rotation could be transferred into a small range rotary motion at a high frequency, mimicking the aerodynamic performance of insect wings. An “umbrella” shape double-curved surface made out of thin polyester film is attached to each module, with one edge located right above the center of the heat coil.

The components on the structural frame, including the stepper motors and the cold elements, are controlled separately from those on movable modules, such as heat coils, servo motors, and DC motors. However, employing accelerometer and gyroscope as input, the vertical and horizontal movements, as well as the high frequency vibrations could all be choreographed simultaneously during each move. The on-board micro-controller controlling each movable module transmits gyroscope inputs, and outputs signals accordingly to the servo motor, DC motor, and the heat coil. Meanwhile, the electrical
cooler pads, heat sinks, and 5V computer fans assembled as cold sources, are all controlled by MOSFET circuits and are wired up onto a separate microcontroller housed at the bottom of the structural frame, which also drives the stepper motors (Figure 5).

RESULTS

Experiments were conducted on each prototype after it was constructed (Figure 7). The visual data captured by Schlieren Optics allow direct comprehension and qualitative evaluation of the sculpted invisible forms, leading towards ongoing revisions and refinements of the design.

After the visual data was documented, each segment of movement was analyzed computationally using the frame differencing technique of OpenCV, to break down the geometric sequences into individual frames so as to draw comparisons along the same motion trajectory with different moving velocities, directions, and sequences. (Figure 1). Dramatic difference in results due to small adjustments of variables clearly show in this post-analysis of collected data, suggesting the strong impact of material evolution during the medium-driven fabrication process.

Test 1
The experiment on the first single axis prototype was conducted intuitively through an observation process. To get a legible reading of the forms produced by heat while maintaining the subtlety of the smallest variations, the voltage applied to the heat coils was set to 7V, lasting for 1 second with an interval of 6 seconds—these settings served as a reference for later experiments conducted with different prototypes.

Recurring patterns clearly appear in Schlieren images—lines generated during the static modes; curves and surfaces during the moving action. Straight lines bend downwards during the 6-second interval when the heat was turned off (Figure 8).

Test 2
When testing the second single axis prototype, the range of rotation of the stepper motor was programmed in relationship to the input from the gradient-heat-sensor pad. Curves either arose parallel, or wove into 3D meshes depending on different movements (Figure 9).

The complexity of controlling five heat sources, however, has made the process of parsing the sensed forms very challenging. This is mainly because of the location of heat coils, although at various height and different distance from the central axis, fails to present clear difference as the curves of flow emerging within an extremely short period of time once the heat is turned on. As a result, the location of the coils is less effective than the speed and angles of each move.
Test 3
By syncing the control of heat and motion, the three axis prototype has an increased precision comparing with the previous ones. Meanwhile, the capacity of scripting movements with three servo motors along three axes, allows a much more diverse set of forms generated by this device. The experiments, however, followed a simple matrix of possible movements- from controlling a single motor, to combinations of two or three, and to phased control (Figure 10). Each series of movements shares a designated origin. Various origins, speeds, and ranges of rotation were tested and analyzed (Figure 10, 11). Heat was on for two seconds before each motion sequence got started. Because of the portable battery provides only 3.7V as opposed to the previous power supply of 7V, the duration was set to be twice as long.

Test 4
Working with both heat and cold sources, the fourth prototype offers opportunities for programming diverse combinations of thermal and spatial conditions. Due to the deficiency of the electrical cooler pad used as a cold source, as well as the thermal complexity caused by its necessary accessories such as the heat sink and the computer fan, the visualization of cold air currents was presented with an unclear behavior. Therefore, during the actual test, liquid nitrogen was used as cold components instead. Hanging from above, the down-flow air currents at times collided with the up-flow ones; while at other times affected the curvatures of the warm air from a distance as a result of the changing location of heat coils. It set off chain reactions of transformation, such as the arising of symmetrical vortices, the morphing between lines and vaults, and the stretching from wide plumes into thin curves. Rich dynamic patterns are triggered by mild motion inputs, evolving autonomously into formal narratives that span long duration (Figure 12).

NEXT STEPS
The dual-temperature control system opens up new possibilities for this project. Different from most of other materials explored in additive manufacturing, the characteristics of airflow present unique impacts on this medium-driven printing process as it responds to subtle movements, as well as the temperature changes caused by both convection over time and inputs from the machine. To improve the control over the cold elements, to decrease their sizes, as well as to explore the alignment and misalignment between heat and cold components, would result in more articulated geometric and textural patterns.

On the other hand, the visualization technique used throughout the process- Schlieren Optics- casts restrictions on detecting depth as well as on scaling up applications. A PIV system would be worth exploring as it allows geometries to be sensed three-dimensionally.

CONCLUSION
Philippe Rahm described the space- the “void invisible to the eye”- as “a less dense mass, disconnected, transparent and yet nevertheless filled with material” as claiming the importance of constructing atmosphere. The robotic thermal devices constructed
Figure 10
Trajectories of scripted movements of the two heat sources, and selected frames along those paths from the video documentation of test 3.

Figure 11
Frame differencing technique was used to process video documentation of the test 3 in order to subtract background noises and to extract swift movements of air in the Schlieren images. This is one selected case where the forward stroke along the scripted trajectory consists of two separate moves, and backward one is a result from two motors moving simultaneously.

in this research customize existing additive manufac-
ing with specific material of airflow in this “void”, intersecting the principles of natural physics and the technological advances in scientific studies. Effects are unveiled from both machine operations and the material evolutions within swift moments.

While the devices have potential of being continuously evolved, this investigation also questions environmental aesthetics, exploring the potential of invisible mediums informing the design of the “visible” as envisioning an alternative approach towards environmental architecture. If the architectural form should follow climate as Rahm stated (Stalder 2010), the design of environmental system should follow perceivable forms and effects of thermal activities and aerodynamics. By integrating proper sensing methods such as Schlieren Imaging and PIV into the prototypes developed in this research, potential applications in architectural scale include transforming these fabrication machines into embedded heating and cooling materials and building blocks that provide thermal needs while choreographing visual effects of convection. One of many other possibilities is constructing prostheses of existing building systems that alter the temperature distribution and utilizing thermal byproducts with a similar intention.

ACKNOWLEDGEMENT

This project was developed as part of a master thesis by Catty Dan Zhang, advised by Professor Allen Sayegh, at the Harvard University Graduate School of Design. All the experiments were conducted using equipment and spaces from the Harvard Natural Science Lecture Demonstrations.

REFERENCES

Li, XL, Shang, JZS and Wang, ZW 2017, ‘Intelligent materials: a review of applications in 4D printing’, Assembly Automation, 37:2, pp. 170-185
Noever, PN and Perrin, FP 2004, Yves Klein: Air Architecture, Hatje Cantz Publishers
Sodhi, RS, Poupyrev, IP, Glisson, MG and Israr, AI 2013 ‘AIREAL: Interactive Tactile Experiences in Free Air’, ACM SIGGRAPH 2013, Anaheim, CA, USA