Digital Hot Air: Procedural Workflow of Designing Active Spatial Systems in Architecture Studio

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Abstract. Providing inhabitants the protected relationship with the matter of air has been the fundamental drive in almost all aspects of architectural productions, while in some cases clear boundaries are implemented for controlled environment, in other situations they are more porous and ephemeral. This paper presents an attempt of challenging volume and boundary relationships in architecture by designing forms of airflow using state of art 3D visual effect technologies. A computational workflow was established for a fourth-year undergraduate architecture topics studio using 3D VFX software. The workflow integrates smoke simulation, motion operation, collision behavior, and raster data processing, outlined in two simulation exercises. The pedagogical investigation aims to inspire innovative typologies of spatial connectivity and separation by designing fixed forms and amorphous mediums simultaneously. It offers an experimental protocol for using airflow as an architectural material in intuitive design processes. The outcomes of the simulation experiments led to discussions of the visual, tactile, olfactory opportunities of the invisible medium in architectural speculations.

Keywords: Active spatial systems · Airflow form-making · CFD

1 Introduction

Fabricating environment that activates the behavior of amorphous and invisible mediums has been explored theoretically as well as in innovative practices in the past decades, in which case architecture is no longer considered as stable objects passively revealing its environmental conditions [1]. Rather, it is understood as relations defined by adaptive boundaries that track movements of flow-fields within and around [2], and by active systems that modulate the transformation and the evolvement of such flow. Vapor, light, and heat– as a few examples– have become materials for construction, relating human body and the atmosphere in physiological aspects such as thermal comfort or multisensorial perceptions. Such investigations create spatial volumes and boundaries dynamically by altering homogenous mediums, as Phillipe Rahm coined in meteorological architecture approach where climate of the space is considered as a new architectural language "slipping from the solid to the void, from the visible to the invisible, from metric composition to thermal composition" where "limits fade away and solids evaporate" [3]. Furthermore,

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with the public perception of void spaces being heavily impacted by health and safety measures in light of the COVID-19 pandemic, the tendency of designing active mediums and adaptive boundaries urges new sets of rules and constrains to be established, which are related to both space making strategies as well as methods of visualizing and perceiving invisible activities within the void.

In her article "Capturing the Dynamics of Air in Design", Jane Burry emphasizes the critical role of "a panoply of tools and approaches spanning digital and analogue simulations, real time or otherwise intuitively engaging analytical feedback and the opportunity", as they are used to "make design changes and rapidly witness their influence on the complex atmospheric and atmosphere-borne phenomena" [4]. Today, a diverse set of computational tools for energy assessments, ventilation strategies, and sensorial awareness has transformed design methods around invisible mediums. Multiphysics software (CFD) for studying flow behaviors, as an example, provides designers platforms to virtually test out configurations of fixed forms at various scales in relationship to turbulence, temperature, humidity, and velocity of air, where the form and the function of the design are articulated following the climate [5]. Sensor network and advanced display systems such as mixed reality, on the other hand, allow multisensorial aspects of the invisible microclimate in physical spaces to be made perceptible and comprehensible to inhabitants [6]. Nevertheless, the complexity and limitations of integrating CFD in architectural-related computational design frameworks with most of mainstream CFD software packages and plugins [7] demand very clearly defined design problems that are mostly building performance related such as optimizing enclosures and building profiles, or populating spaces based on the distribution of fresh air, wind flow, and thermal comfort. Or, they are limited to the design of pre-imagined effects, such as in *Cloudscapes* by TRANSSOLAR and Tetsuo Kondo Architects. In that case, simulation modeling was conducted to study the wind and solar impacts for constructing a semi-external cloud, where surprises of unintended air behavior were experienced in the built installation rather than being explored as design potentials in the simulation stage [8]. Moreover, even though the development of plugins such as RhinoCFD offer better integration with modeling platforms throughout the design workflow, due to the need of external post-processing step and their data visualization characteristics, these tools usually require designers to have sophisticated knowledge to interpret quantified datasets not only about flow behavior but also on performance driven design techniques.

The goal of this paper is to demonstrate a methodology of designing active spatial systems that considers forms of airflow as the agency. It avoids the production of performative architectural outcome in favor of exploratory design by diving into the basics of form-making logics. This leads to experimentations on alternative toolsets which use airflow as a fundamental architectural material to generate innovative forms as well as artistic and perceptual effects grounded in scientific accuracy of the material behavior. The work is outlined through a pedagogical investigation in an architectural design studio in fall 2020. The objective of the research is to establish and test a computational workflow to (1) expand design opportunities that foreground the materiality and form potentials of airflow; (2) be integrated in intuitive design process during conceptual stage that is not necessarily driven by building performance criteria; and (3) provide a core framework for specific design tools to build upon when adapting to various architectural context and agenda.

2 Background

2.1 VFX as Architecture Design Tool

In his article "A Disaggregated Manifesto: Thoughts on the Architectural Medium and Its Realm of Instrumentality", Nader Terhani points out that "computational realm has offered code and rule-based functions" that "produce systemic variations that can proliferate options while absorbing a great deal of complexities", and "unlike ever before, we do have ways of connecting phenomena across scales, to see them side by side and to imagine consequentiality across disciplines" [9]. The advances of visual effects software have offered a new set of protocols in architecture which expanded the designer's ability in understanding and producing aesthetic applications, complex natural systems, performance-driven iterative design processes and so on, where the interplay between natural science and built forms has become closer than ever the gaming of virtual geometry and material attributes. Emerging trends in design with VFX simulation have been greatly benefited from ever-evolving solvers with optimized algorithms. These tools, capable of producing realistic effects, approximate the behavior of objects, mediums, and materials in real world with desirable accuracy and fast computing time [10]. Other than their capacity of visualizing special effects as final architectural representation, diverse design practices favor the immediacy of such tools to pursue innovative forms through the process of simulation. *PULSUS* by INVIVIA, as an example, explores the translation of material properties into form effects as a way to discusses aliveness in responsive installations. Maya simulation of fabric draping onto rigid forms leads to the fabrication of a series of four fabric-like human-form concrete surfaces, enhancing public interactions by establishing intimacy through the play of form and sensorial augmentations using responsive technology [11]. Such investigations avoid reproduction of known systems, rather, they celebrate poesies over accuracy, looking for opportunities to "multiply and make tangible futures that break away from the established momenta of thinking and doing" [12].

With their verified efficiency and precision in CFD simulations [10], the capacity and speed of producing hyperrealistic visualization of effects, as well as the experimental design opportunities, visual effect technologies and their architectural potential are explored in this research through a series of simulation-based design exercises.

2.2 Identifying Key Relationships for Airflow Form-Making

Creating forms with air– a medium with complex physics mechanics– does not follow singular or linear processes. Although building science related approaches have greatly benefited from computational tools, as a material favored by artists and designers due to its mythological and ephemeral qualities, its form characteristics in artistic applications has not been systematically explored with computational processes. The production of physical installations or artifacts usually relies on combining certain machineries to establish physics models. Fog vortex ring or tornado– typologies often found in art installations– are created based on well-known physics principles. Animated and texturized forms in Little Wonder's *10 Kinds of Fog*, as another set of examples, are produced by moving fog through various modulators, filters, or textured surfaces with an experimental process interacting air, water, and machines [13]. Establishing a computational setup for airflow form-making is to translate sophisticated machinery into a set of dynamic systems and relations in a procedural workflow to broaden the typological potentials.

Previous research conducted by the author has showcased effective methods to choreograph airflow through composing heterogeneous contexts such as temperature fluctuations, dynamic external force fields, as well as interactions between rigid and fluid materials. A series of robotic thermal devices was designed to produce a visual catalog of forms of hot air constructed via scripted heat and motion patterns (Fig. 1.a.). Employing physical computing techniques, these instruments consist of (1) points of heat source generating convective flows, (2) motion systems, and (3) surfaces which air currents collide with. The investigation proofed the potential of air for constructing geometric primitives in three-dimensional space. The research outcome– visualized using Schlieren photography– demonstrated the versatility of the material as well as intricate mechanisms and control methods needed [14].

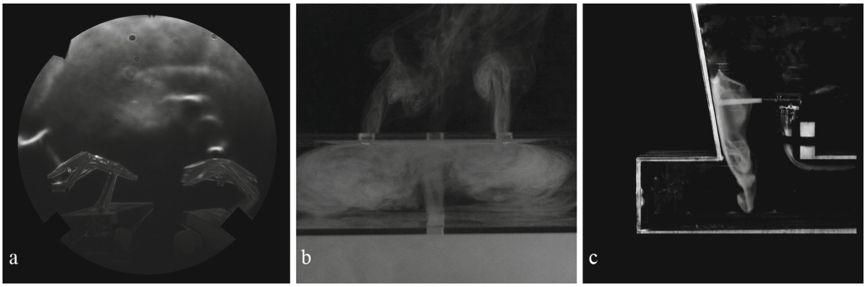

Fig. 1. a: Forms of hot air sculpted by scripted heat and motion patterns using robotic thermal devices, visualized using Schlieren photography. b and c: Physical fog instruments designed and assembled by students in author's fall 2019 studio demonstrating effects of fog colliding with various types of surfaces. Work by Emily Dobbs and Eliot Ball (b), and Andrew Shook (c).

This investigation also builds upon a set of analogue experiments in the author's fall 2019 undergraduate topics studio titled "Respirators", which examined the moving air as a spatial agency to populate territories and habitats shared among human, nature, and machine. Conceptual instruments were constructed by students to study forms of dynamic voids enclosed by visible particles of air (Fig. 1.b and 1.c.). The class developed procedures of reassembling respirators abstractly with kits of parts to create integrated systems that produced spatial effects. Currents of fog colliding at various angles onto articulated surfaces that were layered, perforated, or texturized, resulted in visual and tactile volumes and boundaries modulated by rigid forms while being constantly altered by external forces.

These analogue machines revealed the qualitative interplay among the medium, the form, and the environment through hands-on experiments and directly observed effects, which informed logics of the computational setup. Identified key systems and their relationships are:

- Hot air dynamics: the source and the behavior of hot air controlled by parameters such as source geometry, particle size, density, temperature, gravity, and environmental forces.
- Rigid body systems: rigid objects with kinematics, motion, and transformation potential.
- Collision relationships: dynamic interactions between air currents and rigid objects.

3 Computational Setup

3.1 Architectural Context

Employing VFX software as tools for architectural speculation, this paper documents the investigation in a 4th year undergraduate architecture studio in fall 2020 titled "Filters Applied: Medium Hybrids and Architectural Voids", taught remotely due to the COVID-19 pandemic. The studio intended to respond to urgencies of global public health crises by envisioning possible futures of meat processing facilities– hot spots during the pandemic due to the transmission of invisible particles within the public void and across species along production and packaging lines. In this regard, we seek new concepts of spatial planning and design to establish adaptable and active systems that modulate the behavior of amorphous and invisible mediums to produce architectural, technological, and social effects.

This context led to considerations of designing the distribution of airborne particulate matter, motion paths of their sources, kinematics of objects and machineries.

3.2 Workflow

Prior to the design of the final architectural intervention with specific site and program requirements, the studio set up two exercises of constructing experimental simulation models with particulate air, rigid objects, and void spaces in SideFX Houdini [15], both of which adopted the previously identified key relationships. The first exercise focuses on forms created with airflow at an object level, exploring sources of hot air and its collision relationship with surfaces in motion; and the second exercise looks at image compositing methods, through which 2D raster data are translated three-dimensionally into collective spatial relations. This simulation workflow centers around Houdini Pyro solver which tackles smoke and flame effects based on attributes of points describing the physical properties such as density, temperature, velocity, and so on. With the procedural node-based architecture of the software, the workflow establishes a set of translations among geometry, physics, kinematics system, and raster data (Fig. 2), leading towards various spatial logics interrogating the notion of shared atmosphere.

Exercise 1: Surface/Air. The Surface/Air exercise explores: (1) the creation, the movement, and the transformation of hot air in geometry nodes (SOPs); (2) the form and materiality of solid surfaces functioning as collision objects using solver combinations

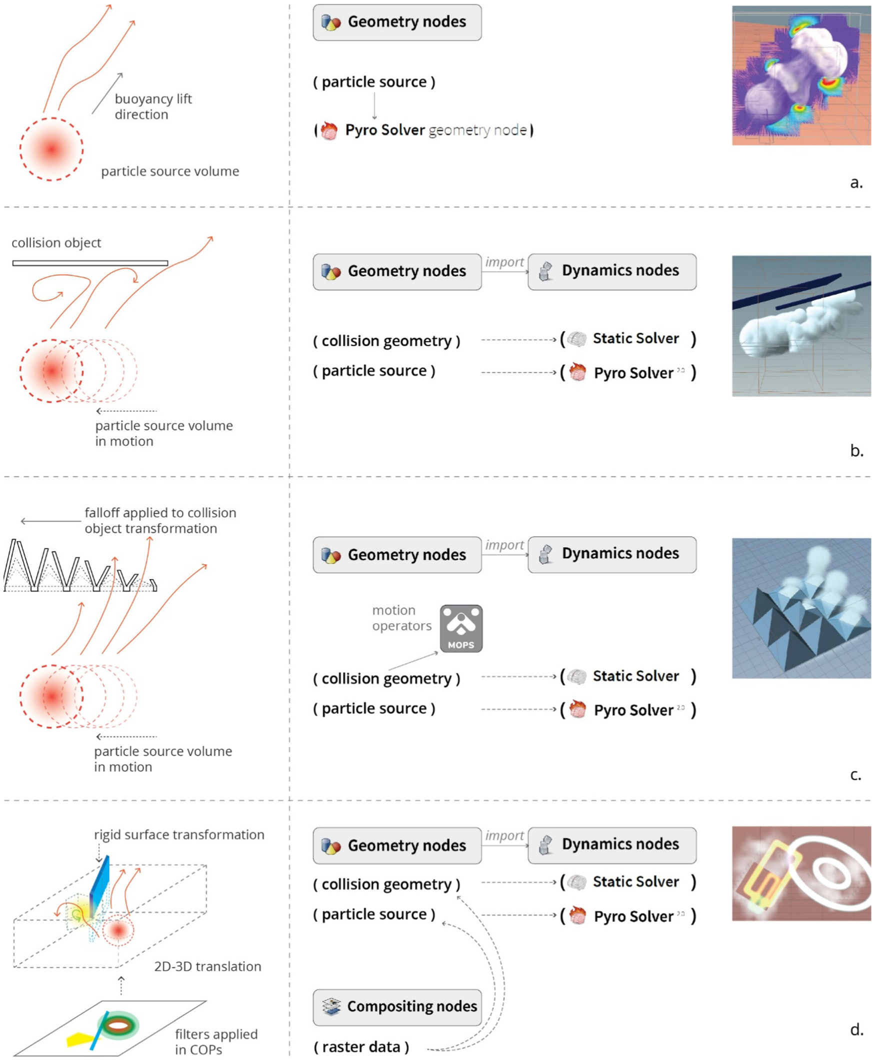

Fig. 2. Procedural workflow established in four simulation steps exploring translations among geometries, physics, kinematics systems, and raster data.

in dynamic node (DOP) networks; and (3) the coupling of the source motion and the surface transformation using motion operators (MOPs)– a free, open source suite of Houdini Digital Assets (HDAs) built initially in 2018 to simplify and automate common motion graphics processes [16]. By playing with the curvature, porosity, motion trajectory, and geometric transformation of collision objects, forms are to emerge interactively as currents of hot air being split, diffused, and redirected (Fig. 3).

Exercise 2: Image/Air. The Image/Air exercise practices spatial and environmental planning process through image-to-form and/or image-to-air translations with Houdini

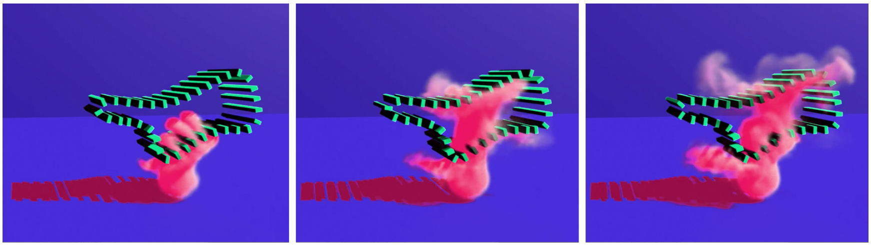

Fig. 3. Smoke emitted from a spherical source colliding onto an irregular belt moving counterclockwise controlled using MOPs modifier nodes. Work by Nick Sturm and Dante Gil Rivas.

compositing networks which contain compositing nodes (COPs) for manipulating 2D pixel data. By setting up "lines through ellipses" scenarios based on abstractions of movements, circulation, proximity, shared public zones and enclosed individual spaces, this exercise intends to rethink the typical plan-based design process through image-making techniques. Animated raster outputs from the interplay between linear and circular 2D shapes are then loaded into dynamic networks for Pyro simulations (Fig. 4). Expanding the discoveries from exercise 1, singular and localized air collision scenarios are to be developed into collective forms, systems, and spaces, where dynamic volumes and barriers emerge autonomously from image manipulations.

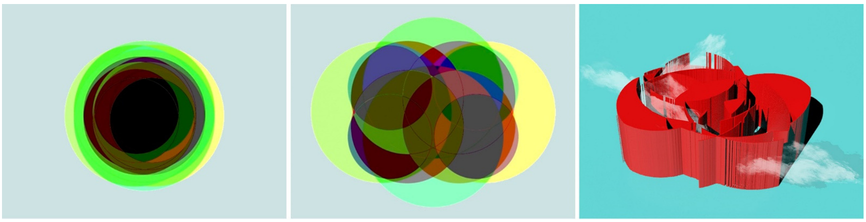

Fig. 4. Animated 2D shapes generated by COPs being translated into form and air. Work by Kyle Brodfuehrer and Michael Allen.

4 Outcomes and Reflection

4.1 Typologies of Spatial Connectivity and Separation

The exercises resulted in diverse design outcomes revealing the roles of rigid objects and amorphous mediums played in the search for typologies of spatial connectivity and separation. By categorizing medium hybrids as volumes and boundaries, effective results could be interpreted as conditions illustrated in Fig. 5. Successful simulation models captured multiple of these conditions sequentially with curated sets of motion and collision events throughout time, presenting the capacity of generating both subtle and drastic variations by altering a simple set of parameters.

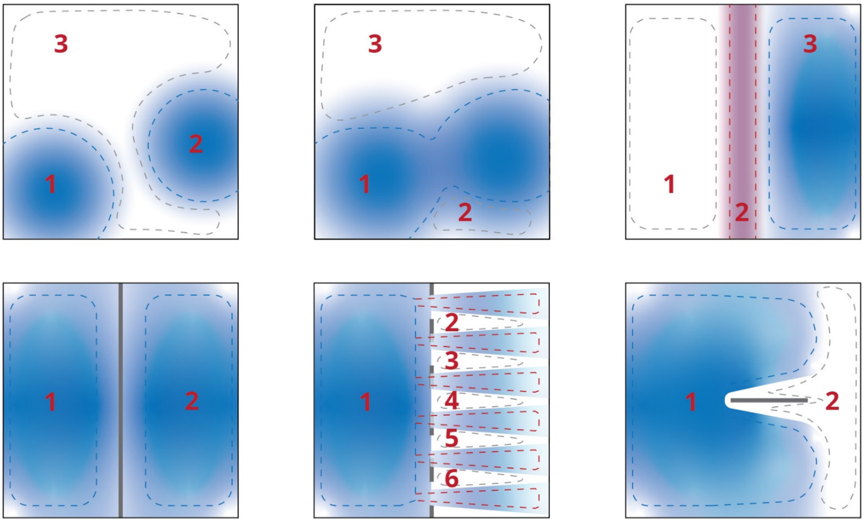

Fig. 5. Subdividing voids with connected/separated air volumes, and rigid/soft boundaries.

Figure 6 and Fig. 7 showcase examples from exercise 1, where form sequences derive from rigid surfaces splitting, venting, and colliding with hot air in a particular order. In the first example (Fig. 6), the initial state of the collision object consists of two flat surfaces intersecting at 90°. By applying a series of operations including pivot rotation and tapered extrusion, the vertical portion of the surface moves downwards while the horizontal piece turning into a 4 × 4 grid of 3D modules each with an opening at its center. This transformation follows a gradual pattern starting from the far end and moving towards the origin of the smoke. The directionality of flow, the timing and duration of the surface movements, are among parameters being tested. The horizontal surface subdivides the volume of smoke into thinner plumes when panels open up, resulting in turbulences and vortices due to the disturbance generated in the velocity field. These plumes colliding onto the vertical surface afterwards, become puffs merging back into a whole. The second example (Fig. 7) practices a similar set of relationships in a different configuration. Smoke emitted from a spherical source being sculpted and redirected by a series of moving arcs positioned between the source and a horizontal perforated surface, results in streams of smoke emerging above with fluctuating intensity. These soft thresholds or thick barriers define ephemeral “rooms” above the perforated panel with dynamic borders.

Another major trajectory focuses on position relationships of particle sources. Figure 8 showcases an investigation based on composing images with circular and rectangular shapes in motion using a series of Houdini compositing nodes to create dynamic inversion, blur, and gradient color effects. The color attributes of the resultant images are imported into geometry nodes, parametrically controlling the spatial distributions of smoke sources and collision objects using pixel sorting techniques. Figure 9 presents multiple particle emitters within contained geometries. Rectangular and round corner conditions, proportions of horizontal and vertical linear obstacles, and proximities

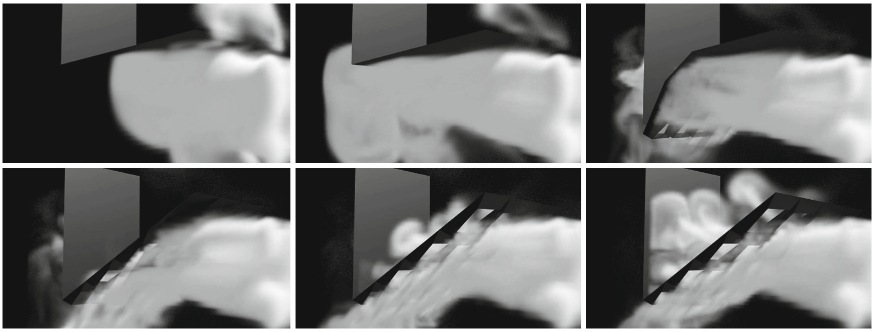

Fig. 6. Sequential volumes created by smoke colliding onto kinetic surfaces. Work by Michael Allen and Kyle Brodfuehrer.

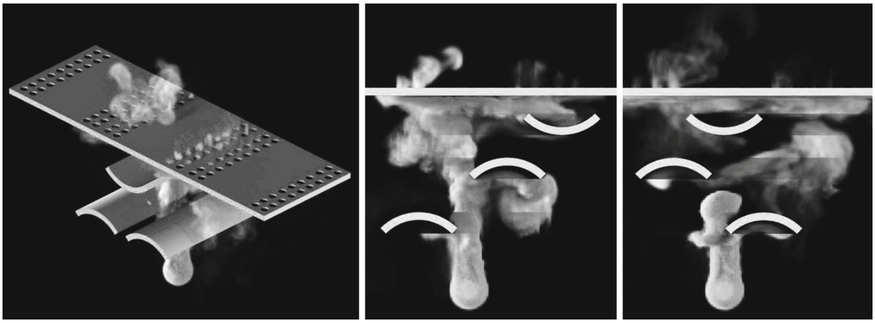

Fig. 7. Dynamic smoke barriers formed above perforated panel. Work by Hunter Thurlo and Lea Mitchem.

between the sources of the emittance are a few parameters for generating a taxonomy of animated distribution patterns. As the direction of flow being altered dramatically while colliding onto the enclosure of each rigid volume from within, redirected currents of air interact with existing particle volumes, resulting in diverse volumetric subdivisions within the homogeneous medium.

4.2 Speculative Applications

Based on computational experiments conducted in both exercises, students then translated simulation logics into architectural strategies when designing their final projects. These design proposals adopt previously defined air/surface/image relationships in various program scenarios, building components, and spatial organizations. Roof system filtering exhausted odors, façade penetration allowing thermal byproducts from meat processing to serve as visual barriers, and circulation planning considering proximity for controlled social interactions, are a few examples of final projects tested in part in Houdini as proof of concepts (Fig. 10). The discussion of these design proposals is beyond the scope of this paper, however, the investigation at architectural scale demonstrates promising opportunities of direct and indirect translations between forms of air

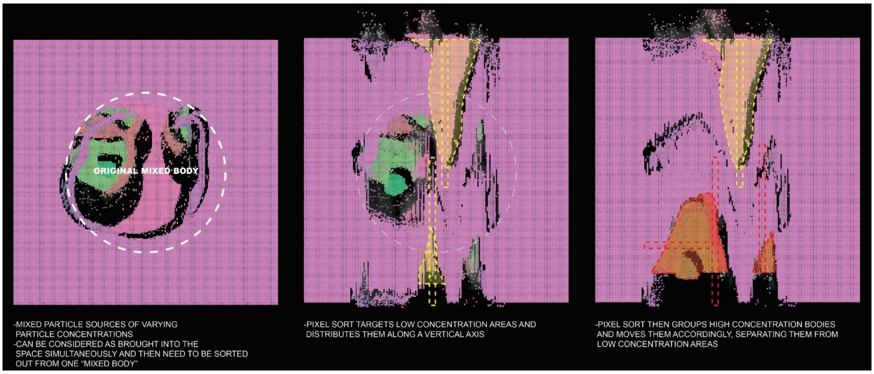

Fig. 8. Applying pixel sorting operation on composed images which were then turned into smoke source and collision objects in Pyro simulation. Work by Michael Allen and Kyle Brodfuehrer.

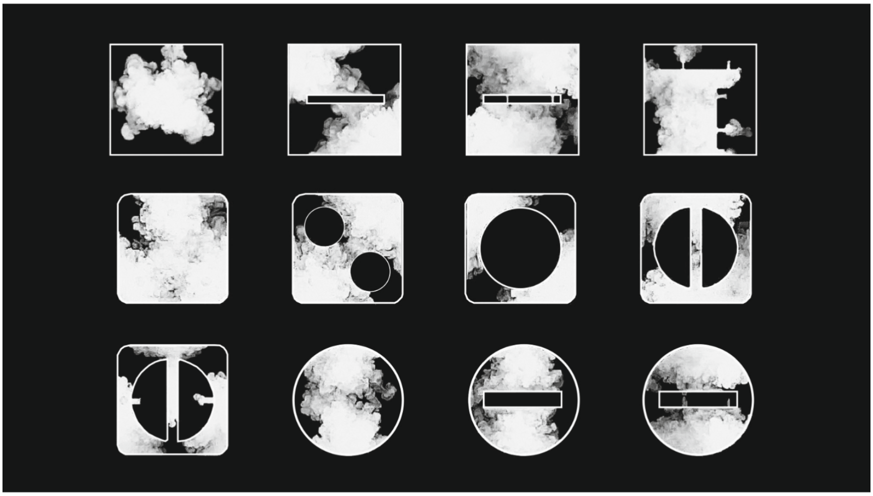

Fig. 9. Smoke distribution studies in partial circulation spaces with various types of corner conditions. Work by Amelia Gates and Carson Edwards.

and architectural spaces. Following a procedural workflow and with the immediacy of effects generated, the work produced in this studio breaks away from conventions and preconceptions of the solid and the void, the interior and the skeleton, the fixed and the ephemeral, projecting a new set of relations between architecture and atmosphere.

Fig. 10. Speculative design applications tested in Houdini: (left) roof filtration system, work by Hunter Thurlo and Lea Mitchem; (middle) steam penetrating through façade dynamically based on sorted items in the building, work by Michael Allen and Kyle Brodfuehrer; and (right) aggregated circulation spaces considering human emittance within, work by Amelia Gates and Carson Edwards.

5 Conclusion and Future Work

Borrowing VFX tools, this paper presented a computational workflow of designing digital hot air to rethink mediums, visible forms, and integrated systems through intuitive and artistic process. This methodology translates principles of physics in airflow form-making into key relationships in the computational setup, demonstrating effective visual outcomes that are beneficial in exploratory design processes. While the research mainly focuses on using air simulations as experimental design tools to expand new forms of architectural knowledge, the outcomes also suggest the potential of future scientific developments with more articulated parameters to examine specific conditions and to generate pragmatic applications. However, without built-in functions of comprehensive quantitative data analysis in VFX software, additional steps would need to be carefully tested for such purpose in future work. Due to limited access to machines with higher computing powers during a semester of remote teaching and learning, those simulations were preliminary. Nevertheless, the procedural workflow established in the process allows easy refinements and adaptions when tackling larger scale and higher complexity situations in the future.

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