Soft Mechatronic, Aerodynamic Architecture Studio

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Emerging technologies for the built environment typically mature within the specialized engineering fields that develop fundamental theories and validate their fitness for different applications. In practice this makes practical sense since nascent technologies may pose unforeseen risks to the public and specialized knowledge often takes years to move technologies from first concepts to market-ready products. However, several examples of research and education in the areas of computational fabrication and building simulation counter this narrative by placing designers in parallel with other disciplines working to speculate on future use and to develop application-specific knowledge. This paper presents a studio and 3 case study projects that use these ambitious precedents as a pedagogical and research guide to appropriate new developments in the fields of fluid dynamics and mechanical engineering as primary elements.

***Active air flow separation control*, a relatively new area of inquiry for fluid dynamics, was adopted as the primary emerging technology guiding the design of the studio projects. A tailored pedagogy applied a bio-mimetic approach to the development of soft-mechatronic building facades used to control airflow in and around buildings. Strategic studio organization allowed projects to navigate through a significant learning curve and present useful research in a short time. This was done through the development of bespoke design workflows, the use of open-source libraries such as the Soft-robotics toolkit and through workshops with the interdisciplinary research group. The overall framework and individual tools allowed knowledge from engineering research to transfer to both the physical production of the studio and the extrapolation needed to imagine the speculative designs. The resulting studio output gave researchers a peak into the potential spatial consequences of yet-to-be validated engineering theory and tested the design methods used to develop prototypical models of applications.**

INTRODUCTION

Emerging technologies promise to change the way buildings perform but require long validation periods. While a ‘technology push’ has welcomed numerous new technologies, their applications tend to be explored at a miniscule level for highly specific or simplified applications. (Addington and Schodek 2005) Although architects and designers are not required to delve into a deep understanding of these technologies, standard design approaches may prevent ‘not only the full exploitation of these technologies, but also [deny] a coherent vision of the future to help direct development in the science and engineering disciplines.’ To integrate the existing framework for working with novel technologies between architecture and engineering, restructuring of workflows would have to start from a pedagogical level.

Addington suggests that to accelerate technological advancement, architects should delve into the investigative process of developing new technologies. In line with this, the Soft Mechatronic, Aerodynamic Architecture Studio framework proposed that architects work in parallel with engineering researchers to overlap different discipline-specific methods and tools to imagine the application of a system not yet designed for buildings, thus bringing progress to both engineering and architectural research. Incorporating a mix of parametric software, fabrication, robotics, biomimicry and simulation across disciplines into a single design development strategy provides a fluidity between different domains positioning these technologies as a fundamental component of building design.

To allow such a large number of different techniques to be applied in a short time and to focus on one application for active flow separation control, a strategy was developed along with a context and fundamental problem. The given problem for the studio was the uncomfortable, humid climate of many of the worlds developing megacities in which the airflow is one of the best strategies for improved comfort. (Givoni 1998) This notion parallels the research group’s previous use of physiological studies which have shown that patterns of air velocity can show significant improvement in cooling without increasing aggregate velocity.

Within this context students were challenged to use flow separation to create more comfortable spaces by manipulating the airflow in and around office blocks. To accomplish this students were asked to develop pneumatically actuated, soft-mechatronic facade systems. These systems would be fabricated through scaled models and validated through simulations. To begin the design of the actuators and systems the groups chose biological presidents that exhibited potential in terms of effective fluid dynamic control. These biomechanisms were abstracted and became the basis for the designs.

BACKGROUND RESEARCH PRECEDENT

Flow separation control

Prior to the studio, research developing flow separation control as a method to 'enhance passive cooling effects in warm environments' using calibrated airflows was conducted. (Yogiaman et al. 2018, 2019) As a means of evaluating thermal comfort, studies have shown that factors beyond average wind velocity must be considered; turbulence, flow directions and fluctuation frequencies can change the comfort of space as well. The focus on airflow separation was derived from a prior experiment conducted by Zhou et al. (2006) where test results showed that variation in airflow patterns alone could generate a significant cooling effect. When reverse-engineered, flow patterns can be used to control 'resultant air velocity, magnitude and frequency over long distances in outdoor urban [environments]'. This was further supported by a hypothesis tested by Dash et al. (2017), where a travelling wave was used to control flow separation and suppress the 'downstream wake effects' as fluid flows along a surface. The experiment found that by creating a layer of miniscule vortices along a surface, momentum of the fluid layer originally reduced by drag force and vortex shedding was better able to pass along the surface.

Fluid dynamic control for urban comfort

For an architectural exploration, the relationship of airflow with various surface textures was conducted before additional layers of complexity were added to produce evidence of potential. One such application defined in the Yogiaman et al. 2019 paper was 'retrofitting an active surface mechanism on building facades'. Due to its specificity - flow patterns would vary depending on the environmental context - the context was placed in tropical urban environments. The low diurnal temperature variation and high humidity levels pose a difficult problem for passive environment design (Givoni 1998), but makes increasing thermal comfort all the more necessary. In particular, the precedent research highlighted how the physics of flow separation, a very specific fluid dynamics phenomena, in the context of the tropical climate, could be paired with designing airflow for human occupation. (Yogiaman et al. 2018).

Trans- / Cross-disciplinary design

The intention of incorporating engineering research with an architecture studio made it necessary to modify the way the design studio was conducted. Every new material or technology tends to be 'traditionally defined' by the existing system of understanding in each profession. (Addington and Schodek 2005) Design Build Studios were looked at as a precedent to integrate this multi-disciplinary approach into the architecture design workflow that students were familiar with. This provided a means for 'making a stronger link with material experimentation and construction,' enabling greater exposure to a range of architectural practices for students. (Canizaro 2010; Gray 2010; Hoppa 2002) In a 'Studio One' teaching model put forth by Schleicher et al. (2019), the authors presented a different way of teaching the architecture studio, intending to have it as precedent for the future. Acknowledging that the method of teaching architecture students now could be better integrated with cross-disciplinary understanding, Studio One incorporated 'fundamental research, design exploration, and practical application' into a single design workflow. On a wider scale, this updated the approach to studio and encouraged bolder claims for the future of technological advancement.

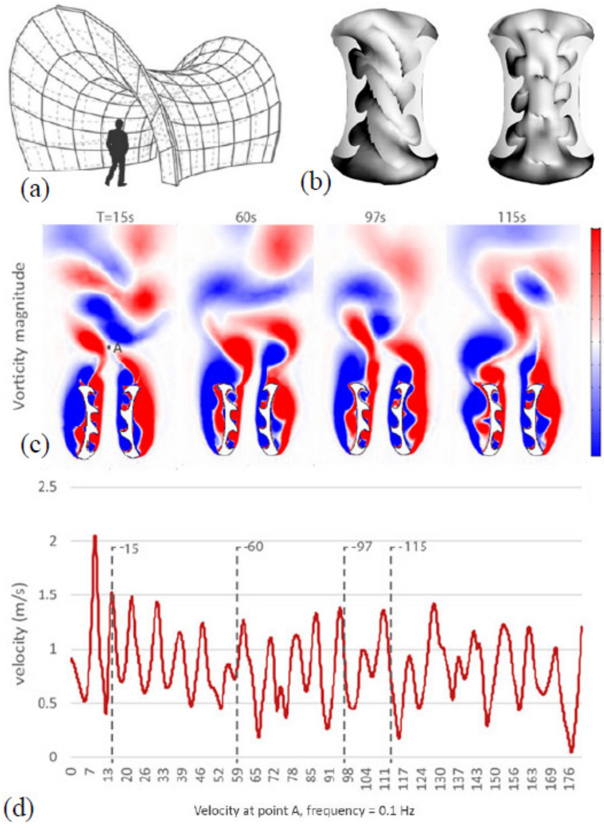

Figure 1. Urban canopy simulations (a) Prototypical urban canopy outer design for the first phase of the research project. (b) Canopy internal designs with static wave-like surface textures designed to alter flow patterns. (c) Simulations of urban canopy designs with asymmetric wave-like internal surface textures show increased vorticity (rotational flow) and flow fluctuations. (d) The velocity over time at point A has similar airflow frequency (0.1hz) in the range shown to provide cooling sensations in experiments conducted by Tanabe and Kimura (1994).

Soft robotics

Soft robots differ from familiar hard machines as they inherently exhibit highly compliant properties. In terms of mobility, the role of a soft robot would require it to be flexible, compressible and robust to high strains. (Trivedi and Rahn et al. 2008) The high degrees of deformation achieved in a programmable manner make it an appropriate actuation mechanism for testing the control of flow separation and realising soft mechatronics in architecture. Moreover, soft robots are characteristically suited to emulate biological systems, making them more desirable as an enabler of biomimicry in the studio workflow. To immerse students in the creation of their own soft robots, the studio used the soft robotic toolkit as reference for fabrication.

The components identified from the soft robotics toolkit were: (1) a moving actuator which controls a mechanism; (2) sensors to trigger responses to changes in ambient conditions; (3) a set of controls to operate actuation; (4) use of relevant software and fabrication methods to mold soft mechatronic units. (Holland and Park et al. 2014)

STUDIO DESIGN PROCESS - METHODOLOGY

To integrate the use of new technologies without current examples, the studio used a sequence of iterative design processes that built up knowledge and tools throughout the term. Overall, the goal was to develop fluid dynamic moving facades that leveraged observed phenomena to enhance the comfort of buildings in warm, humid climates such as Singapore. To initiate this study, students were first challenged to study and derive fundamental functional principles from organisms that control flow in some way. These biological precedents would stick with the projects through the semester. They were encouraged to look beyond biomimicry as an aesthetic model, but rather a big picture of implementing the natural mechanism on an architectural scale.

The studio stretched across 14 weeks with 2 reviews, once at the mid-term and a final week presentation. Throughout the course, the research team worked closely to provide students with the necessary know-how, conducting tutorials on physical prototyping with soft robotics and software crash-courses.

Iterative workflow for design refinement

The studio workflow flips the typical scalar development of an architecture studio. Each stage in the workflow is treated like an exercise; the exercises are repeated to fine-tune and iterate, or progressively developed in a back-and-forth methodology. Alternatively, they could be simultaneously developed alongside the other, forming an information chain that targets the way students use fluid dynamic design to inform their design-build processes. This approach to pedagogy involved physical prototype fabrication, digital simulation and comfort analysis, and open-ended speculation to the application of novel building technologies.

The studio aimed to empower students with three strategies linking tools and simulation to movement and mechatronics: (i) Biomimicry, (ii) Fabrication and Simulation, and (iii) Speculation/Representation. Special emphasis was placed on the collaborative use of these methods, and how they could be used to inform one another throughout the design process. Since no single strategy was expected to take importance over the other, the limit to time meant students were free to strategize their own primary modes of investigation, accommodating differing strengths and interests.

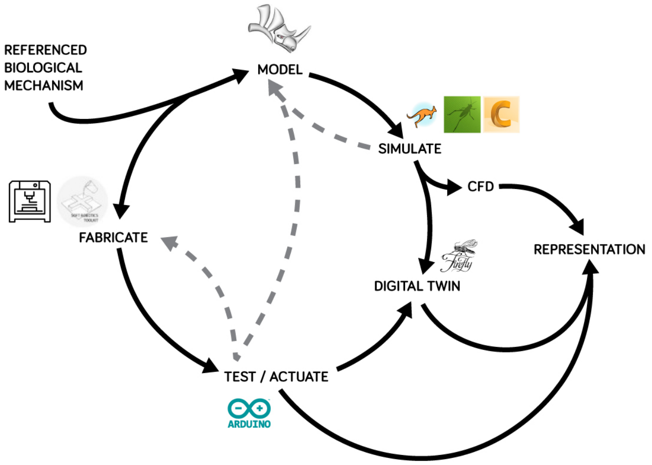

Figure 2. Studio Workflow Diagram.

The "back-and-forth" methodology

(i) Biomimicry

As a starting point, natural organisms were studied as a model to observe how bioclimatic adaptations can be incorporated into the built environment. Given that biological systems serve as a 'valid source of inspiration of the solution of given technical problems,' students were encouraged to consider, on a larger discourse, how they could 'bridge the gap between the biological role model and its technical implementation' to tropical urban architecture at a faster pace. (Magna and Gabler et al. 2013) The biological references were particularly useful in calibrating the design of physical soft robotic units as students could study exactly which part of the natural mechanisms could improve their prototypes. Investigation into the function of these biological precedents also informed potential applications of their creations.

(ii) (a) Fabrication

In order to encourage a physical, iterative design approach to soft mechatronics, students were recommended to start off with physical prototypes to gain familiarity with the technology. Under this section, students would use the soft robotics toolkit and start off with representing their biological references in a series of abstracted 3D digital models, before designing molds to cast their models as physical soft robots.

As the soft robot would need to expand and deflate continually, the robust elastomer matrix in silicone made silicone the ideal material for rapid prototyping in this design studio. The studio also explored silicone of varying stiffness - a crucial material property determined by the design of the prototype. Depending on the design of the group, a single unit would

STRATEGY	CONSIDERATION	TOOLS	BENCHMARKING METRICS
Biomimicry	Natural organisms as biological references	-	Bioclimatic adaptation
Fabrication and Simulation	Physical actuation of soft mechatronic prototypes	Silicone of varying stiffness levels	Fabrication process and actuation of soft robot
	Biomimicry simulation with soft mechatronics	Kangaroo Physics	Digital model showcasing aperture control, expansion amounts
	Computational Fluid Dynamics (CFD)	Autodesk CFD, OpenFOAM	Wind velocity, pressure gradient
Speculation / Representation	Application of soft mechatronics to tropical urban architecture	Rhino3D, Grasshopper	-

require varying levels of stiffness within the same material. Access to fabrication technologies such as 3D-printing and laser cutting to aid rapid prototyping allowed time for fabrication to be further minimised. Although limited in scale and iterability, the data from the fabrication models were used to calibrate the digital simulations (part (ii)), which in turn informed the team when calibrating the larger fabrication models.

To test and actuate their physical prototypes, a pneumatic set-up controlled by Arduino was built. This allowed the amount of air pressure in the prototypes to be controlled by students, depending on the amount of inflation they wished to achieve. It was a necessary step to evaluate if the soft robot was (a) cast in its mold correctly, or (b) not efficient in terms of design. The initial difficulty faced by students was casting the silicone without air bubbles, which affected the effectiveness of the soft robot and gave rise to the soft robots bursting during actuation. This was later eliminated by placing the silicone mixture into a vacuum chamber before casting.

The approach catered to hands-on learning and provided instant cognitive feedback. Architecture students worked with an unconventional material with their own hands, giving them a basis to make extrapolations on how it will perform or behave when on a building. These prototypes formed a basis for speculation on the potential of such units and its cooling effect on buildings.

(ii) (b) Simulation

The studio was equipped with digital methods of simulation, particularly Kangaroo Physics and CFD, as means of digital prototyping. With digital models, the limit of scale and iteration are removed - they can be made and simulated endlessly, post-processed for visualisation and iterated to critically analyse changes on multiple scales of design. While the digital Kangaroo model showed the dynamic response of a soft mechatronic design, CFD data allowed visualisation of how nuanced changes to their designs could influence comfort levels. The visualisation of airflow with CFD became a language of simulation that could be used to infer a design result for an architectural intervention.

Originally, the studio was equipped with Autodesk CFD and trained on how to set up their own steady state or transient CFDs, using the climatic conditions of the tropical context. However, it was later observed that students were interested in learning other platforms for CFD and went ahead to equip themselves with OpenFOAM as well. Instead of a single-metric benchmark from the environmental data, the studio focused on the implications of what could be made, creating possibilities that do not hinge on a particular matrix.

(iii) Speculation/Representation

Following the insight gained in part (i) and (ii) of the workflow, the studio worked to project the imagined potential of these technologies on urban buildings in the tropics. This tied the entire process back to being a proposal of environmentally focused investigation and innovation. This ‘speculative’ aspect to the studio was unrestricted; students were encouraged to take their biological reference as a basis for suggesting possible applications, and then design an architectural representation for it. Expected outputs from this exercise were: (a) a hierarchical representation of the building system and how it would behave, and (b) a visualisation of the effect of the intervention on comfort, inferred from CFD data and airflow patterns. The former entailed an exploded assembly detailing the fabrication of a single soft mechatronic unit, how the actuatable robot could be applied to a large assembly and its relation to a building.

Relating the strategies to one another

The inter-linking of these strategies encourages a cross-disciplinary design process, where the workflow is not limited to a step-by-step path. The biological reference informs actuator design but also the potential application to architecture. Actuator design posits novel building configurations and are in turn refined by both its potential application and its biological precedent. The representation of actuators in architectural drawing needs to showcase its dynamic quality, which is informed by the simulated actuators. Each member of the workflow develops within itself and synergises with the others to iterate and refine.

Creating a digital twin

As the prototyping process matured, the studio worked toward linking physical and simulated prototypes to create a 'digital twin'. When the digital model was 'actuated' on Kangaroo, the corresponding physical soft robot would inflate via the pneumatic set-up simultaneously. This was done using Kangaroo Physics and Firefly (a platform that enables instant communication between the Grasshopper/Rhinoceros 3D interface and Arduino).

OUTPUTS AND APPLICATION

The group consisted of nine students: five Master of Architecture candidates and four Undergraduate Architecture students. Groups of three were self-formed and encouraged to explore different scales of application for soft mechatronics in building skins in tropical urban architecture (10-30 storey buildings), representing their speculative applications in architectural drawings. The focus on building skins was justified since facades can be seen as a linking element between the internal and external environment; they 'fulfil a multitude of vital functions and [are] a principal factor in the energy consumption of a building.' (Nady 2017)

As emphasised in the above section on studio methodology, no particular weightage was given to any of the three strategies (Fabrication, Simulation or Speculation). Coincidentally, the three groups chose to focus on different strategies, resulting in interesting variations in their project outcomes.

Group 1 - Building Stoma: Architecture that Breathes (see Figure 3)

- Biological Reference: Stomata in plants as a breathing/ventilation mechanism
- Main Strategy: Fabrication
- Architectural Representation: Pneumatic Facade Screen

During the investigation of plant stomata, the group found that a single stoma controlled the 'breathing' of a plant to an extent that it was able to vary the osmotic pressure within an entire plant. Instead of water, the intention for their soft robot unit was to influence air pressure, increasing ventilation and airflow within and around a building. A large portion of time was spent fabricating physical prototypes of likeness to microscopic imagery of stoma in leaves, with the actuated soft robots compared back to the likeness of their biological precedent for improvement. These were in turn simulated on a series of building forms, with the investigation aimed at finding the ideal form to enhance the passive cooling effect by the soft robots. Eventually, the application was imagined as a pneumatic facade system, where soft mechatronic units are placed at certain positions in a facade and regulated by sensors. The changes to airflow helped the building to 'breathe' and could create pockets of cool air externally, which would move downward into the urban public spaces, generating more urban air circulation.

Group 2 - Windscraper (see Figure 4)

- Biological Reference: Hygroscopic response of pine cones
- Main Strategy: Simulation
- Architectural Representation: Wind control and manipulation

Pine cones unfurl for seed dispersal only in warm and dry conditions; once the humidity increases, the scales on the surface close up again to protect itself from excess moisture. Using this understanding, the group studied the effect of such dynamics with CFD simulations. This informed their speculation into a building modeled after a literal pine cone, and how it would change the affect on the spaces in and around it. The visualisations went beyond the idea of comfort, but also looked at leaving an impact both aesthetically and emotionally.

Group 3 - Learning from Ctenophores: Manipulating Fluidic Movement (see Figure 5)

- Biological Reference: Motion pattern created by cilia on ctenophora
- Main Strategy: Speculative Representation
- Architectural Representation: Redesigning public spaces

Ctenophora move around in water by controlling the flow of fluid around their bodies. This is done through bumps and flaps along their cilia. Through initial simulation building on the design of surface topology variation, a hypothesis on how the undulating profile could affect spaces was developed. The focus on architectural speculation led the group to design a building skin that could envelope spaces or buildings and regulate interior comfort levels.

CONCLUSION

The resulting experimental architecture for all groups showcased modular soft mechatronics that served as a proof-of-concept of the applications of soft mechatronics in the control of architectural comfort. The difference in strategy for investigation and time spent under each area became a form of confidence in the projected applications on such scales/outputs.

By restructuring a standard step-by-step workflow and removing the focus of single-metric environmental data targets, the studio was enabled to present a compelling evidence-based speculation. The enhanced ability to collect and produce data to enrich design outcomes and aims to train designers to take on complex, dynamic problems. Steep learning curves and intensive, hands-on learning further prepare students for future projects where environmental factors and technology play an ever increasing role in all stages of building design.

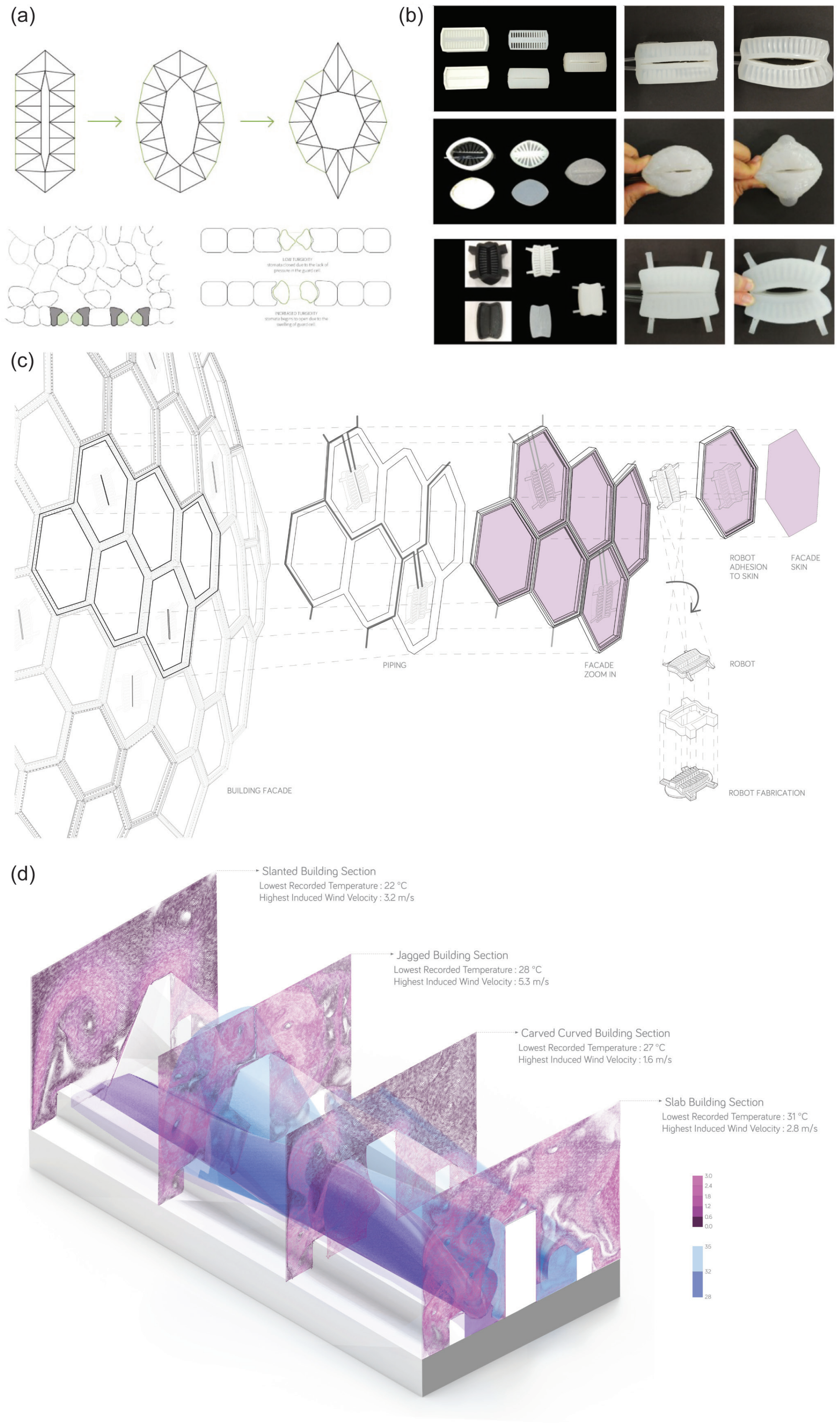

Figure 3. (a) Biological precedent and its simulated model. (b) Fabricated soft-robot prototypes. (c) Exploded axonometric representing application of a single unit in an architectural context. (d) Projected CFD visualisation to show the passive cooling effect around different building forms.

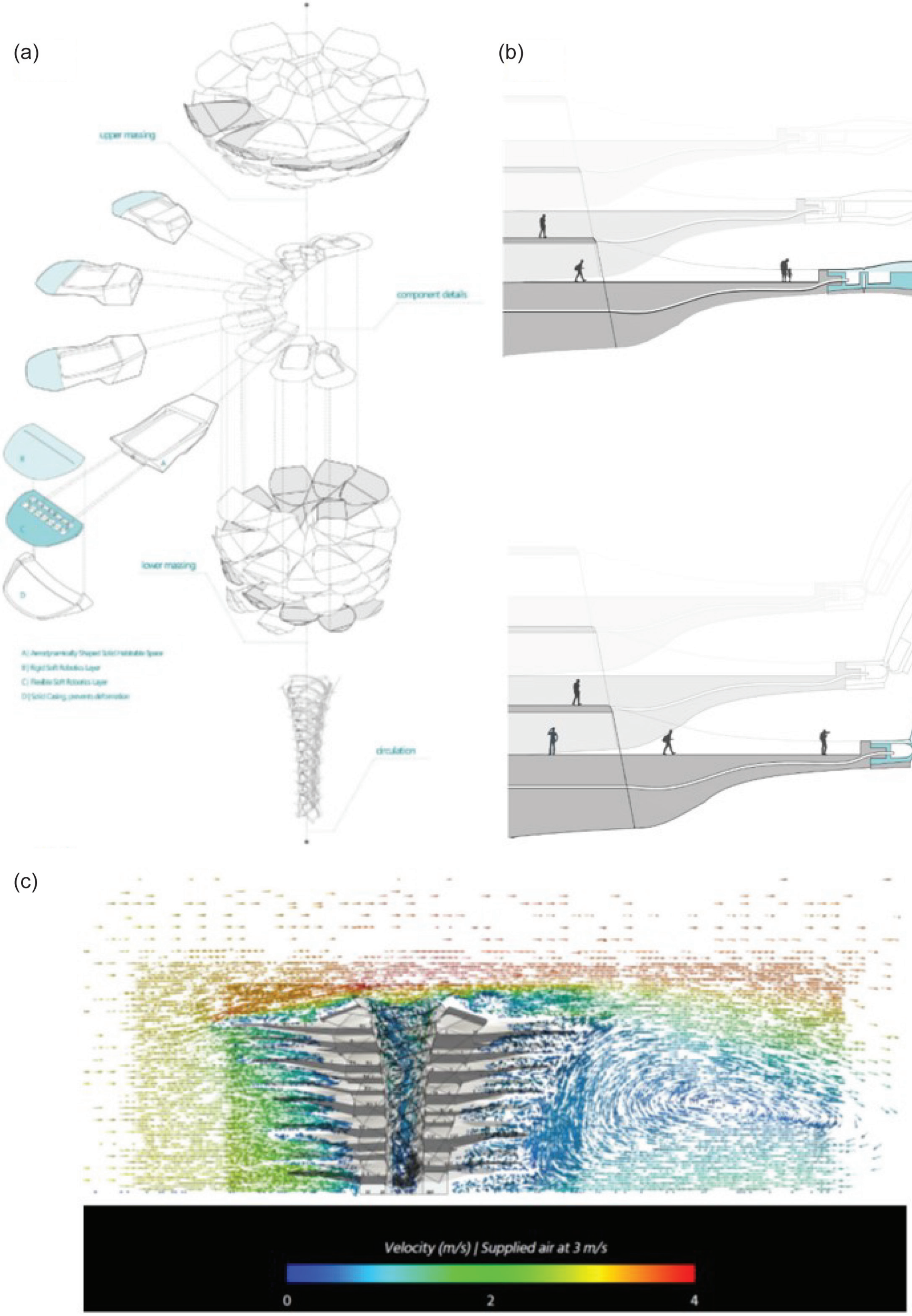

Figure 4. (a) Exploded axonometric of soft robot system applied to buildings. (b) Section drawing of soft robot under actuation. (c) CFD visualisation.

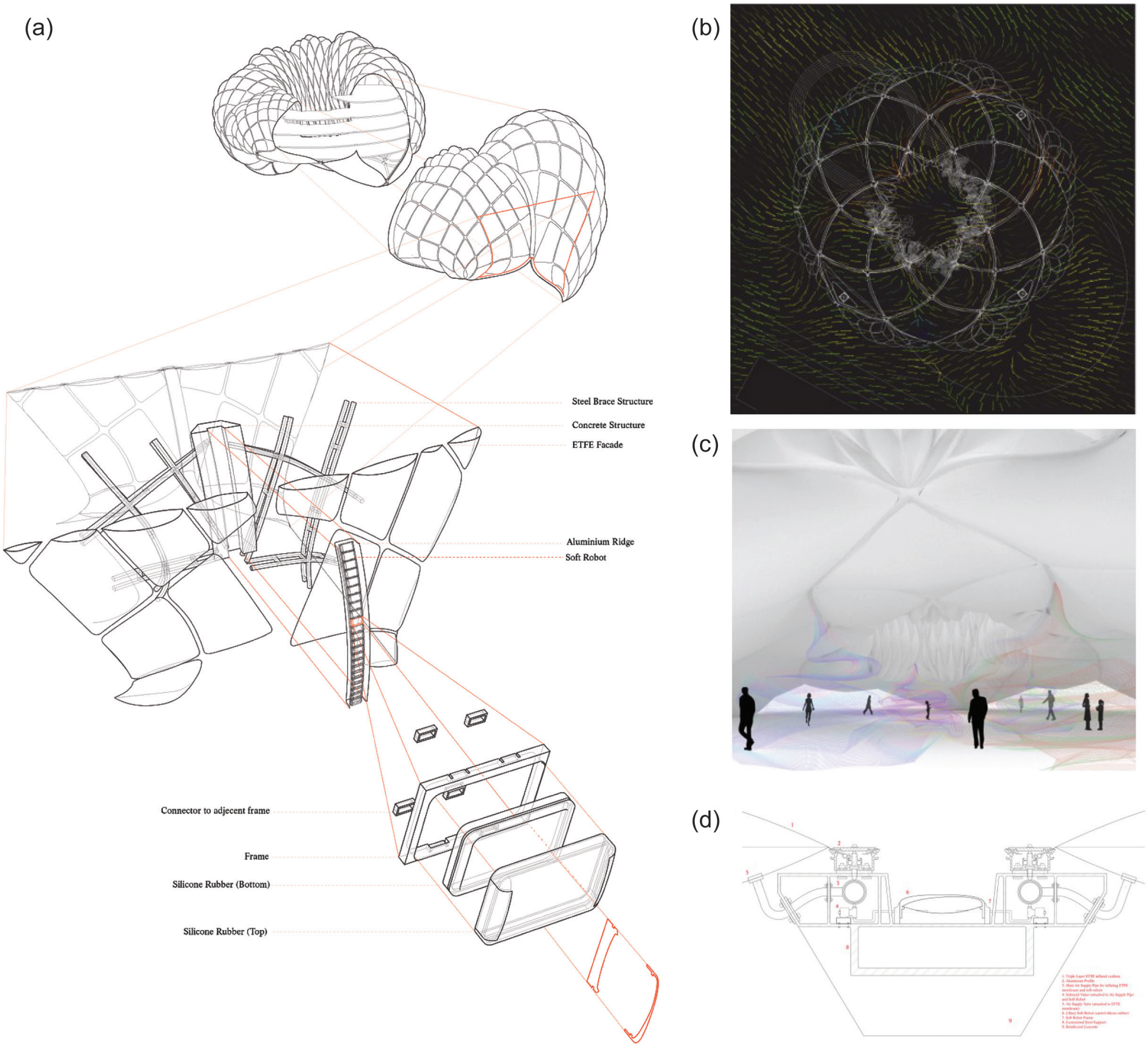

Figure 5. (a) Exploded axonometric of soft robot application. (b) Speculated flow of fluids. (c) Interior view of large scale assembly. (d) Construction drawing.

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