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DEVELOPMENT OF A PNEUMATIC ACTUATOR BASED ON BIO-PU COATED FABRICS FOR ARCHITECTURAL APPLICATIONS

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1 INTRODUCTION

Sustainability is presently the key driver for numerous innovations in adaptive architecture. Despite the variability of the area's climatic conditions, conventional façades remain predominantly static, resulting in substantial energy consumption to maintain internal comfort [1]. Structures designed to adapt to their environmental conditions can achieve superior energy efficiency compared to static buildings, while simultaneously enhancing or maintaining occupant comfort [2].

There are various means to make a building system/construction/structure adaptive. The characteristics of adaptive systems are based on three main aspects: control systems, stimulants, and actuators.

Adaptive systems can be controlled by humans or by some level of automation, which, in the case of smart materials, can be embedded into the material itself using changes in environmental conditions as the stimulus to actuate the system directly.

Actuators are the part of the systems that provide the movement to the adaptive system. This is usually obvious in a kinetic system; however, some technologies, such as thermotropic glass and hygroscopic wood, have no visible actuators. The most common types of actuator in adaptive architectural systems are electromechanical and soft pneumatic actuators [3,4].

This research focuses on soft pneumatic adaptive systems in architecture. Most soft pneumatic adaptive systems in architecture, as a building component or as a structure, utilise either elastomers, foils, or coated fabrics as their pneumatic chamber envelope. The elastomer can only be used for small actuators, while the foil and coated fabric can be used for medium to large envelopes.

Almost all architectural coated fabrics adopted in pneumatic building envelopes are maade of on oil-based polymers. These polymers make the recycling process of coated fabric difficult. This paper introduces one of the key research activities supported by the SUBBIMATT project, funded by the European Union's Horizon Europe program under the call HORIZON-CL4-2023-RESILIENCE-01-TWO-STAGE. The SUBBIMATT project focuses on developing advanced smart textile materials that incorporate biobased components like debondable adhesives and bio-polyurethane. These materials, sourced from renewable biological sources, aim to reduce fossil fuel reliance and environmental impact, ensuring sustainability and eco-friendliness in smart textiles. The building component presented here will utilise the bio-PU-coated fabric to demonstrate its performance as a pneumatic chamber envelope.

2 SOFT PNEUMATIC ADAPTIVE SYSTEM

There are several terms used in the architectural discipline to classify adaptive building systems or structures actuated by air pressure. The most established options are the terms "pneumatic" and "soft robotics". Part of the scientific literature in this field addresses the topic without providing a clear definition or summary [5,6]. Zarzycki and Decker [4] proposed that the primary features of soft pneumatic adaptive systems include the use of soft, expandable surfaces activated by pressurised air and/or vacuum suction. Nonetheless, the articles mentioned above did not specifically focus on soft pneumatic adaptive systems. The articles reviewed or discussed adaptive systems in architecture, with soft pneumatic systems being one of them. The definitions, as well as the distinctions and similarities among the examples of soft pneumatic adaptive systems, were not provided in detail.

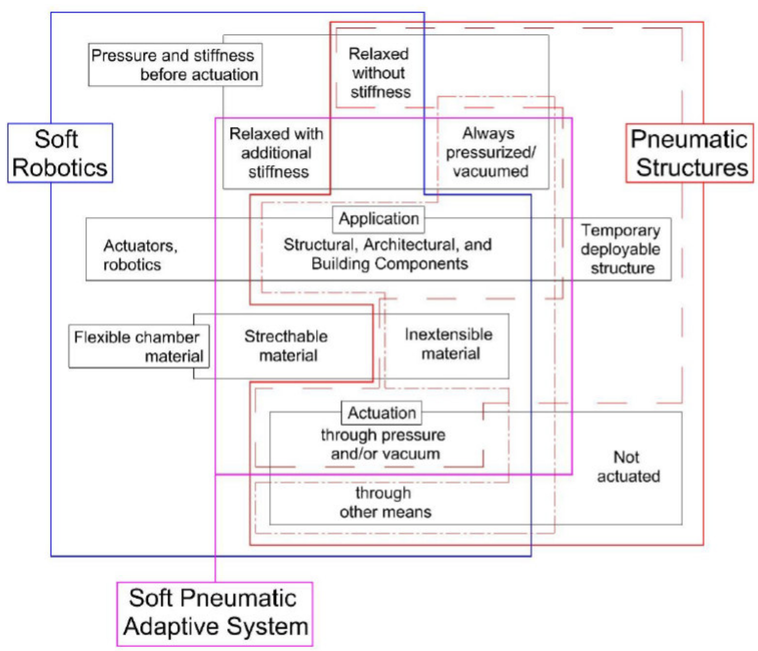

Figure 1: Soft pneumatic adaptive system among soft robotics and pneumatic structures.

Figure 1 shows where Soft Pneumatic Adaptive System (SPAS) in architecture sits between pneumatic structures and soft robotics. Soft robotics, a cutting-edge branch of robotics, harnesses the deformation of stretchable materials and components. This innovative approach, actuated by shape memory alloy (SMA), fluids, or pneumatic, enables smoother movements, a pliable touch, and flexibility against load [7].

Pneumatic structures use air volume locked inside a tension-resistant, flexible envelope to transfer their load [8]. Despite the name, pneumatic structures only encompass soft pneumatic without any examples of "hard" pneumatic structures. Pneumatic structures have the advantage of being lightweight, decreasing the structure's dead load. ETFE cushion structures, such as those used in the domes of Eden Project [9], could reduce significant dead load to the structures compared to using glass.

2.1 Switching Mechanism of SPAS

Figure 1 suggests that, unlike temporary deployable pneumatic structures, SPAS always requires a certain level of stiffness, even when not in motion. This is necessary because, at the very least, SPAS needs to maintain its own shape throughout its operation. Many SPASs that are inspired by soft robotics can retain their own shape through the remaining stiffness of the elastic material [5,10–12]. However, this comes with additional resistance to the actuation load [13].

One mechanism that can achieve this is by always pressurising its chambers and switching the inflation configuration to change its mode or state. It does not rely on material deformation to achieve transformation, thus the material of the pneumatic envelope is an inextensible foil or coated fabric. Compared to the former, the latter could achieve higher pressure and tighter curvature.

Being a composite material, oil-based coated fabrics are challenging to recycle. Separating the fabric from its coating is necessary before further recycling can be done. Breaking down the oil-based coating into harmless components is difficult [14]. Meanwhile, the moving pneumatic envelope would require maintenance and replacement due to wear and leakage. Thus, having a bio-based, recyclable coating will increase the sustainability of the coated fabric.

Two technologies that use this mechanism are switchable foil cushions [15] and Pneufin [13]. While the former is already available in the industry, the latter is still at the laboratory prototype stage. This article provides a critical review of Pneufin and proposes additional tests for its mechanical assessment.

3 REVIEWS ON PNEUFIN

Aditra [16] has already tested the correlation between pneumatic actuation and illuminance, as well as structural performance. The flexibility of the actuation control affects the ability to control the illuminance/irradiance. The more flexible the control, the higher the permutation to achieve the most optimum shading mode (Figure 2 left).

The simulated optimisation primarily focused on building energy and illuminance. However, theoretically, there is a potential for permeability control (Figure 2, middle and right). However, considering air movement in the actuation control increases the need for a deeper understanding of the aerodynamic effect of Pneufin.

The thesis already showed that the structural requirements dictate the pneumatic pressure and actuation, but not the vice-versa. The higher the wind load, the higher the chambers need to be pressurised/vacuumed. Then, when a certain threshold is exceeded, the Pneufin wings need to be closed and locked.

However, the structural performance was still based on load equilibrium. In other words, the previous research assumed that the internal air has no elasticity when pressurised or depressurised by the wind load. A further assessment on displacement, both when the wind load is under or above the designed wind load, is, therefore, needed.

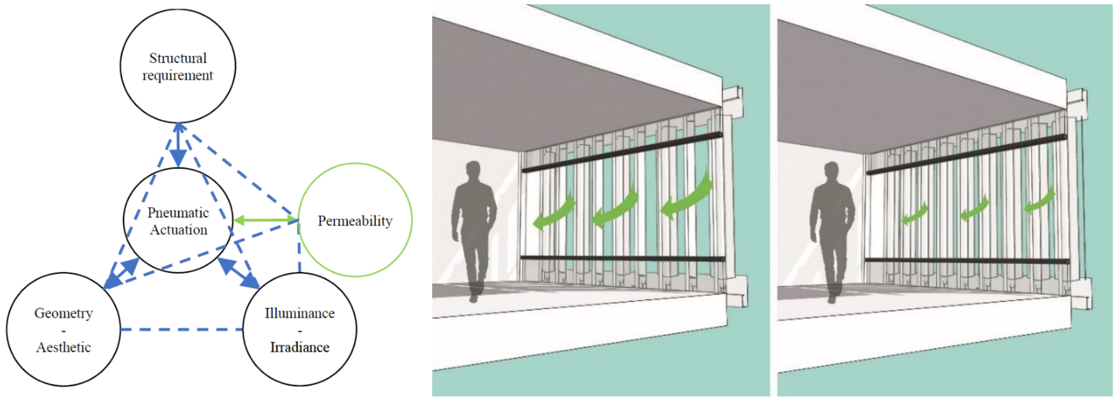

Figure 2: Correlation between Pneufin actuation with various performance parameters (left); and theoretical use of Pneufin to control air permeability (middle and right).

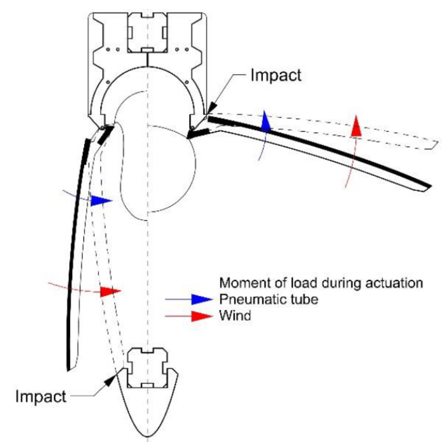

Figure 3: Impact during actuation.

Lastly, the aesthetic prototypes by Aditra [16] have shown that transition can be done in seconds. However, the wing is not in equilibrium during that transition, which means that they are prone to external load (Figure 3). The movement of the wings during transition between modes under external load has not (yet) been assessed.

4 PROPOSAL FOR EXPERIMENT

4.1 Experimental setup

Research about facade and wind can be divided into two: (1) How wind behaves when it interacts with the facade, and (2) the maximum wind speed the facade can withstand. Wind movement around buildings is a complex problem. Thus, the former usually utilises a wind tunnel since it cannot have obstructions to the wind flow that are not accounted for [17]. It sometimes requires scaling the object to reduce the tunnel size.

The latter, however, usually uses a pressure test, in which a blower provides a positive or negative pressure to a chamber with a facade on one side. This method simplifies wind load into air pressure, which is sufficient to investigate the research question. This method is usually used for testing curtain walls [18].

The proposed test of Pneufin is designed to answer questions about structural performance rather than airflow. Testing Pneufin with a wind tunnel test would require a huge experimental setup to reduce the obstruction to the Pneufin itself. On the other hand, Pneufin is used as an external shading which, unlike curtain walls, cannot enclose a chamber. Therefore, a more efficient setup to only provide wind load on the wings is needed.

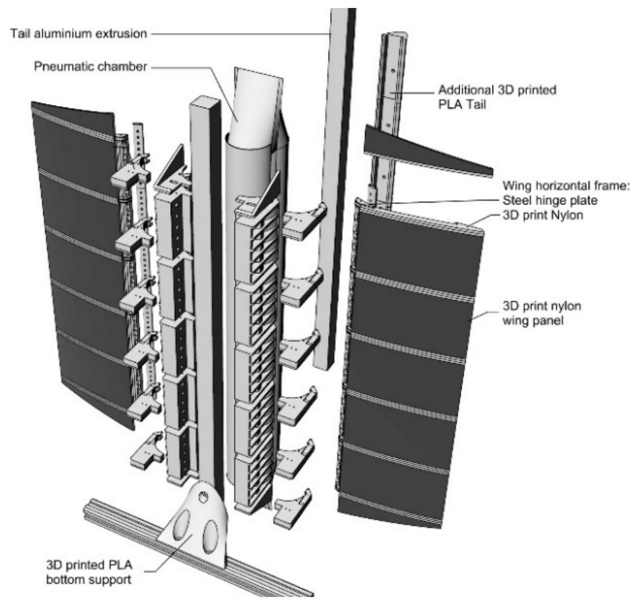

Figure 4: Pneufin prototype.

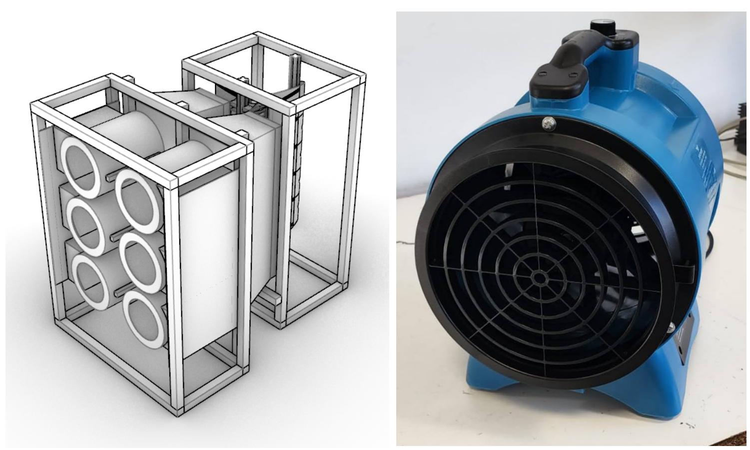

Figure 5: Experiment rig perfective view (left) and blower fan (right).

We propose an additional testing rig to provide wind load to the Pneufin setup similar to the aesthetic prototype tested in Aditra, et. al [13] (Figure 4). The wing frame design mimicked the wings of the final product's expected design. It was constructed with 3D-printed nylon horizontal wing frames and wing panels.

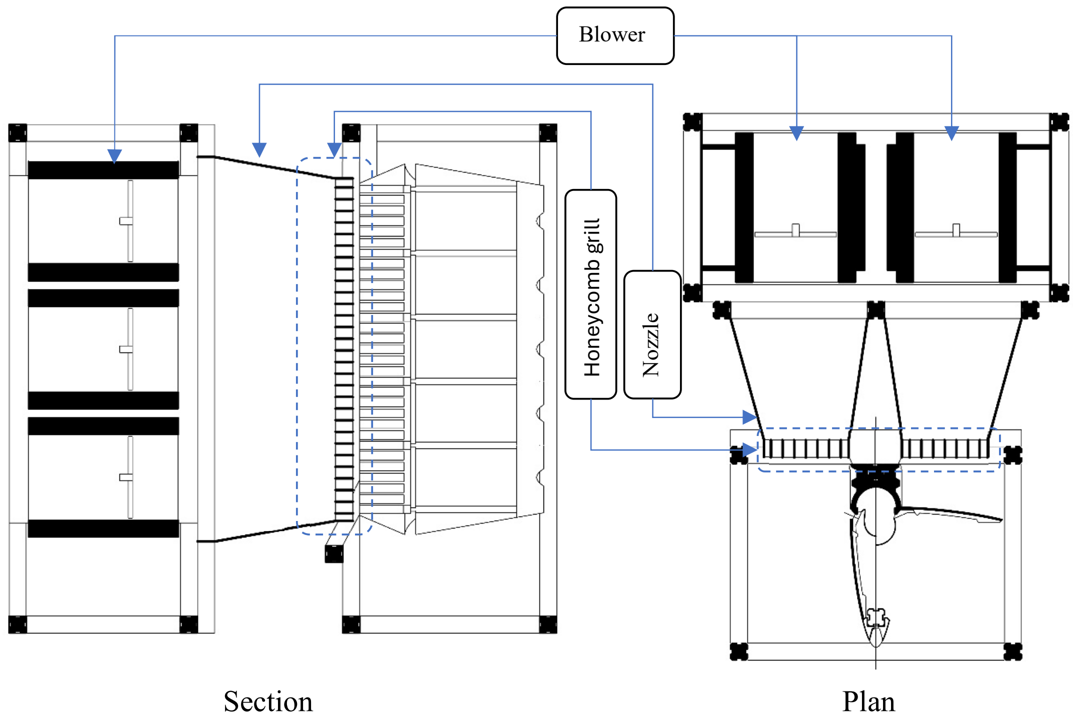

Figure 6: Experiment rig section and plan.

Figure 5 and Figure 6 show the proposed experiment setup. It consists of two pieces of equipment based on aluminium extruded profiles. The small one is the same as the rig used in the previous research. The second one is dedicated to generating the required airflow, and it hosts six blower fans and a set of nozzles to direct the air to the wings (Figure 5 left). The blowers are XPOWER Axial Air Movers X-12, with a diameter of 38 cm and a maximum flow rate of 3000 m^3/h. At the end of the nozzle, a honeycomb grill is attached to reduce the turbulence. To measure the wing movements without obstructing the wind flow, a digital image correlation system will be used.

4.2 Experimental Tests

Two types of experiments are proposed: (1) Wing movement during each mode under wind load and (2) wing movement during actuations under wind load. Every test will be done with both membranes: non-bio PU-coated fabric and bio-PU-coated fabric. The fabrication and the condition of the membranes after the test will be recorded and assessed.

Wing deformation during each mode.

Internal pneumatic pressure provides volumetric stiffness: the resistance of a pneumatic chamber against the change in its volume. The higher the pressure, the more difficult it is to change the volume of a pneumatic chamber. In adiabatic processes, changes in volume will result in a linear change in pressure. Pneufin will most likely be in an adiabatic state as it is a low-energy system [19]. Even though the pneumatic tube of Pneufin is flexible, the hinge and wings are still susceptible to wear and impact. Some pneumatic structures have been observed to act as a negative damping under wind load [20].

The experiment will be conducted at different wind load levels. The blower can be set into three settings: Low, Middle, and High. Based on manual measurements using an anemometer 10 cm from the blower, the Low and High setting gives wind speeds of 2.9 m/s and 7.9 m/s, respectively.

Predicted required pneumatic pressure (P_{pl}, P_{pm}, P_{ph}) for each blower speed is the pneumatic pressure required to produce equilibrium torque against the wind load from the blower. This will be determined through an analytical method or computational fluid dynamics.

The experiment could test the wing movement under the predicted required pneumatic pressure, in combination with two increments in the lower pressure, and one with additional 2 kPa (Table 1). The ¼ and ½ of P_p pressure should be tested to assess a failure condition. The fourth permutation (P_p+2 kPa) is the service pressure needed to simulate a real-world application which should accommodate a safety factor. Other than that, Pneufin will be pressurised above the P_p pressure to allow some time for leakage before being inflated again.

Table 1: Wing deformation test permutations

Blower speed	Approx. wind speed (m/s)	Pneumatic pressure (kPa)			
Low	2.9	¼ P_{pl}	½ P_{pl}	P_{pl}	P_{pl} + 2
Middle	5.4	¼ P_{pm}	½ P_{pm}	P_{pm}	P_{pm} + 2
High	7.9	¼ P_{ph}	½ P_{ph}	P_{ph}	P_{ph} + 2

The blower should only be switched on once the pneumatic pressure has already reached the required range. Once the blower is turned on, the movement/oscillation of the wings is recorded for a maximum of 10 seconds. Once the movement/oscillation is finished being recorded, the blower and the pump can be turned off.

Wing movement during actuation under wind load.

As mentioned above, this second test aims to investigate the transition between two modes, determining the performance during the actuation. Thus, the procedure will be different from the static load test mentioned in previous research [13]. The procedure should be similar to the aesthetic prototype actuation test in Aditra's thesis research (Figure 7) [16]. The procedure will be as follows:

- Switch the inflation system on until the pneumatic pressure reaches its service pressure (P_p + 2 kPa).
- Disconnect the Pneufin from the rest of the inflation system by closing the four valves close to the prototype (E in Figure 7).
- Switch the pump off.
- Switch pump valves into the target mode.
- Switch the pump on until the manometer (G in Figure 7) shows the target service pressure.
- Switch the blower on.
- Reconnect the Pneufin to the rest of the inflation system, starting actuation.
- Record the movement of the wings with DIC.

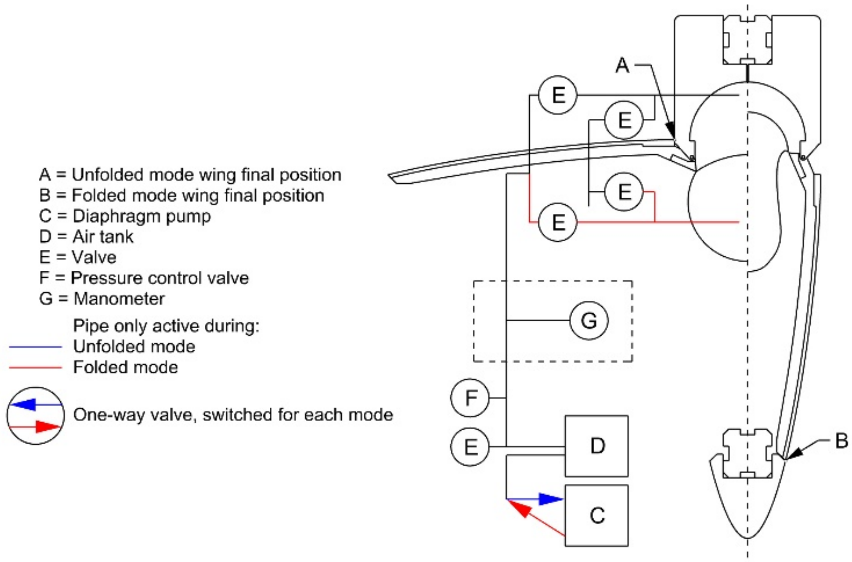

Figure 7: Inflation system setup for the actuation test.

Table 2 summarises the test permutations for the actuation loading test. Both actuation (opening and closing wings) should be tested as both have potential for impact (A and B points in Figure 7). Similar to the first proposed experiment, the blower should be located at the front of the prototype. During opening actuation, it might hinder the actuation and/or cause fluttering. On the other hand, during the closing actuation, this setup might accelerate the actuation and can cause impact. Testing a wind load from the side is also essential. Wind from the side of the Pneufin will introduce an asymmetric load. The asymmetric wing movement might also not change the volume of the pneumatic tube, meaning that volume stiffness cannot be utilised.

Table 2: Wing deformation test permutations

Actuation	Opening		Closing	
Blower Position	Front	Side	Front	Side

5 CONCLUSIONS

This article proposes continuation research of Pneufin, a soft pneumatic adaptive shading actuated through a switching mechanism. Previous research has only considered static load equilibrium. Thus, this article discusses the experiment to assess the aeroelastic behaviour of Pneufin. In addition to testing the performance of each mode, assessing wing movement during actuation and under wind load is also important. To record the dynamic movement of the wing, digital image correlation will be used. Although the proposed experiment focuses on Pneufin, the idea and approach could be applied to other flexible adaptive building systems.

This research will also investigate the potential related to the use of bio-PU coated fabrics as a pneumatic envelope. The aim is to implement sustainable fabrics on adaptive building envelopes that can provide on-demand shading and harvest solar energy at the right time to improve internal comfort and energy savings.

6 ACKNOWLEDGEMENTS

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