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Design and control of robotic shape-morphing pneumatic-hybrid structures for architectural and design applications

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Abstract

Shape morphing systems are extensively explored by designers and engineers to create adaptive structures capable of responding to changing conditions. Recent advances in computational tools, smart materials, and robotics have highlighted new opportunities in the field, originally influenced by cybernetics. However, achieving substantial changes in shapes and multiple states of equilibrium at human and building scales, while utilizing minimal resources, remains a key challenge. The use of elastic lightweight systems, such as pneumatic, bending, and hybrids, offers a promising approach to designing shape-morphing structures in architectural applications. While these systems are valued for their efficiency and aesthetic qualities, there are limited examples of adaptive elastic systems in structural and architectural design, mainly due to the lack of methods that can control continuous nonlinear large deformations. Additionally, while soft robotics strategies focus on controlling elastic deformations, their approaches are limited in terms of design flexibility and scale. This paper proposes a new multi-disciplinary framework for the design and control of shape-morphing pneumatic systems for structural and architectural applications, integrating methods from computational and structural design with soft robotics. Furthermore, it presents successful applications of this approach in developing various shape-morphing pneumatic structures.

Keywords: pneumatic, membrane structures, soft robotics, adaptive structures, shape-morphing

1. Introduction

In a rapidly changing world, the growing relevance of intelligent environments, robotic systems, and adaptive objects marks a progression from the visionary ideas of the 1960s to more recent interactive design projects [1]. Previously constrained by technological limitations, recent advancements in computational design and robotics are now unlocking new possibilities, transforming spaces and objects into intelligent entities that can adapt to changing conditions and enhance human experiences. This includes adaptive envelopes, intelligent building elements [2], and furniture [3], illustrating a paradigm shift in architectural and structural design [4]. The exploration of shape-morphing systems spans multiple disciplines, including architecture, engineering, human-machine interaction, smart materials, and robotics. However, the development of adaptive building systems is particularly challenging, given the requirement to balance shape variability with stability at large scales. Traditional adaptive systems use rigid, multi-part kinematics, while elastic systems allow extensive deformations, offering potential for resource-efficient shape-morphing structures [5]. However, elastic adaptive systems are very limited in architecture, due to challenges in managing complex, non-linear and large elastic deformations.

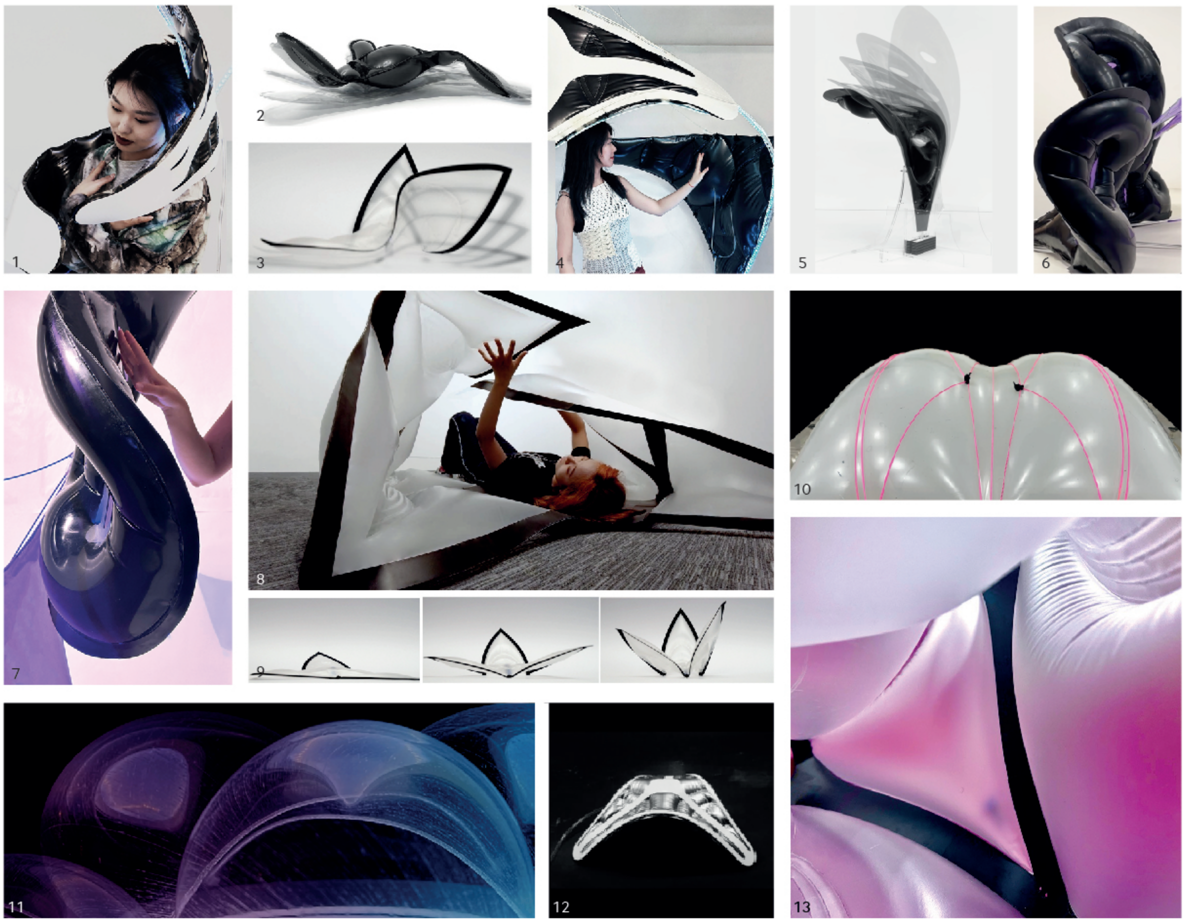

Figure 1: Images of robotic shape-morphing pneumatic-hybrid structures developed with the proposed framework. The figure includes: EMObot (1,2,4); PPS (3,9); ADOOB (5,6,7); WINGS (8,13); PNEU-morph (10,11); PNEUMA (12);

Elastic lightweight structures in architecture [6] include bending-active elements, tensile membranes, pneumatics, and hybrids [7, 8] enabling complex shapes and large spans using minimal materials. Since the 60s, pioneers like Frei Otto and Buckminster Fuller have significantly influenced their evolution from efficient to innovative designs [9], [10]. During the 60s and 70s, new materials and technologies also spurred provocative architectural explorations and radical visions. Concepts of soft adaptive structures emerged from the work of Negroponte, the research on adaptive pneumatics from Miller and Fisher [11], to Otto's PNEUI [12], Webb's Chushicle, and Greene's Living Pod [13]. While the most ambitious interactive visions remained at the prototypical stage, pneumatic systems have since been extensively implemented in building envelopes, temporary pavilions, furniture and objects design. [14].

Advancements in physical computing in the late '90s fostered new possibilities for adaptive systems, although controlling continuous large elastic deformations remained a challenge. In the 2000s, Oosterhuis' Hyperbody Research Group developed the "Muscles projects", introducing new soft interactive structures [15]. More recent methods have focused on using material behaviours as active agents in shape-morphing designs [1], [16], including Axel Killian's projects [17], MIT's transformable meeting space by the Self-assembly Lab [18], and the University of Stuttgart's research on tailored composites for dynamic behaviours [2].

The design of elastic structures relies on force equilibrium and material behaviour, requiring form-finding processes over conventional geometric methods. Unlike purely engineering approaches, which tend to result in simpler shapes, design disciplines necessitate form explorations. Despite advances in computational design enabling simulations of complex elastic systems [19], in architecture these structures often remain static or exhibit limited changes due to challenges in controlling their behaviour over time.

Soft robotics study the design and control of continuous morphological alterations in pneumatic and elastic systems [20]. They offer advantages in safety and motion complexity over traditional rigid robots, using various control strategies (open, closed-loop and autonomous) to achieve desired behaviours [21]. Soft robotics approaches have been mostly developed for small scale and specific applications. The expanding interest in utilizing soft robotics in design applications required collaborative efforts across fields like design, engineering, human-computer interaction, robotics and materials science [22]. These efforts led to the development of a variety of projects encompassing shape-changing enabling technologies[23], [24],[25], flexible metamaterials [26], computational composites [27], wearables [28], furniture[29], assistive devices [30] and large scale soft robotics [31] [32].

Efforts to advance elastic kinetic systems and expand applications in soft robotics have been significant. However, challenges in scalability and shape-morphing capabilities persist due to the absence of an integrated approach for designing and controlling complex systems.

This paper presents a multidisciplinary framework for designing and controlling robotic shape-morphing pneumatic-hybrid structures for architectural and design applications. It builds on prior research led by the authors on Elastic Robotic Structures (ERS) [33], which involves developing robotically actuated adaptive structures that leverage material proprieties, interact with humans and respond to various inputs. The core of this work is the integration of design approaches and numerical form-finding methods, typically utilized in architecture and structural engineering, with soft robotic techniques. This integration enables design explorations, system development and control of complex shape-morphing behaviours. The process spans from the development of the shape-morphing robotic structure to its operation and characterization, to the control strategy to achieve the desired behaviours. A key aspect of this framework is its adaptability, aiming to provide a tool for designing different systems. We emphasize the framework's capability to facilitate the communication of data between specialized software tools used in various disciplines, addressing a common challenge in interdisciplinary projects. Throughout the paper, we illustrate the application of this framework in developing multiple pneumatic hybrid shape-morphing systems (Figure 1).

2. Multidisciplinary framework for the design and control of pneumatic-hybrid shape morphing structures

This section outlines the ERS framework implementation for designing and controlling shape-morphing pneumatic hybrid systems, structured into three main steps: 1) Shape-morphing design, 2) Development of the elastic robotic structure, and 3) Cyber-physical control and behaviour (Figure 2).

2.1. Shape-morphing design

In pneumatic-hybrid systems, air-filled chambers enclosed in elastic membranes integrate bending or tensile elements to shape and control behaviour. Designers can achieve specific shapes by regulating air pressure and selectively constraining membrane inflation. The design balances the expansion of air-filled chambers with restrictive layers provided by bending or tensile elements to maintain structural integrity and functionality, while allowing strategic changes in shape. The development of shape-morphing pneumatic systems begins with establishing broad design objectives that are translated into sequences of

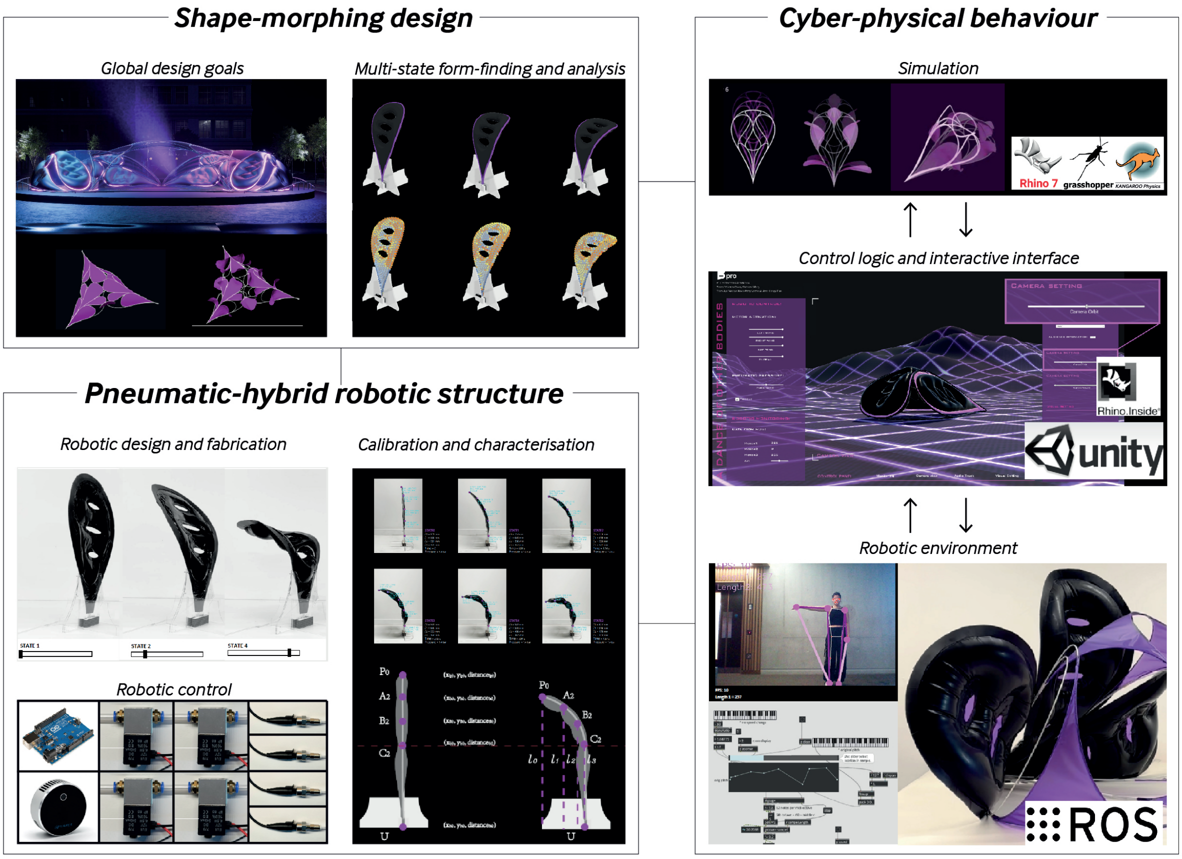

Figure 2: Multidisciplinary Framework for the Design and Control of Pneumatic-Hybrid Shape Morphing Structures. This figure shows the three main steps in the development of pneumatic-hybrid shape morphing structures. As case studies, the images depict the project 'A Dance of Other Bodies'.

geometric configurations. These systems aim to dynamically transform spaces or objects, influencing factors such as function, environmental conditions, structural performance, and enabling interactive experiences. The selection of appropriate pneumatic actuation parameters and principles is a critical next step to effectively achieve these transformations.

Controlling the shape of pneumatic hybrid systems is achieved by altering the membrane itself or adding additional constraining layers, as shown in Figure 3. Key aspects to consider in designing these systems are the following:

Pneumatic chamber design. It encompasses two key factors: the chamber's geometrical shape and the membrane's material properties.

Constraining strategy. Methods for managing expansion include custom membrane patterning and the incorporation of additional bending or tensile elements. Custom patterning is achieved by adding seams to the membrane through sewing or heat-sealing. This creates discontinuities in the membrane's internal airflow, forming micro-chambers. By strategically designing these micro-chambers' size, shape, and distribution, designers can precisely control the membrane's inflation. Adding an extra layer on top of the membrane is another strategy to direct the membrane's expansion in a desired manner. The characteristics of these added elements, such as their number, material, and pattern, significantly affect the membrane's inflation behaviour. A network of these elements can be employed to fine-tune the expansion process, ensuring the membrane inflates according to the specific design requirements. Based on the overall design goals the above strategies are selected. In an adaptive system, design goals correspond

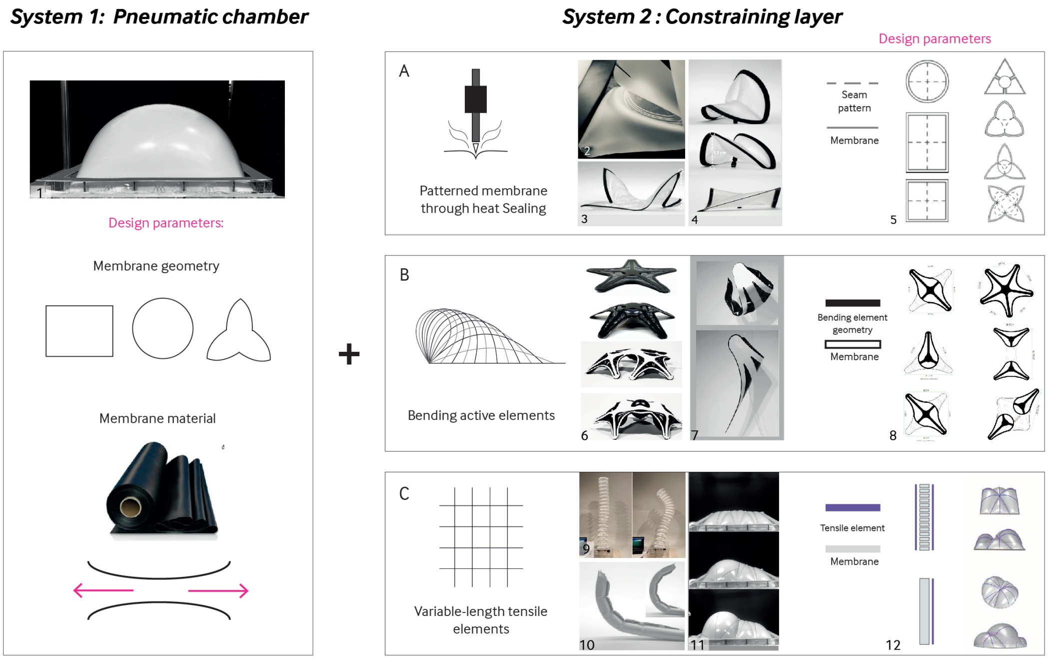

Figure 3: Figure showing the three main strategies to achieve shape-morphing pneumatic systems and design parameters. This includes the integration of the following constraining strategies on pneumatic chamber: patterned membrane through heat-sealing, integration of bending plates and variable-length cables. The figure includes images of the following case studies: 1: PNEUmorph; A2: WINGS; A3,4,5: PPS; B6,7,8: EMObot; C9: Aerobot; C10: Tpop; C11,12: PNEUmorph.

to a sequence of shapes/states. Generally, these transformations enable the system to change from a flat to multiple volumetric configurations, such as folding, bending, and expanding in new shapes. This can be achieved for different applications ranging from adaptive envelopes, furniture, actuators, mobile robots and wearable that can respond to human inputs.

Substructure. The design of the boundary conditions of the pneumatic hybrid system can significantly affect the overall behaviour. This determines whether the membrane is fixed in place, to a flexible or actuated structure, or is allowed to move freely.

Actuation principle. The system can be actuated solely pneumatically or in combination with another method. The elastic constraining layer (either bending or tensile) can either passively constrain and shape the pneumatic chamber or actively interact with it. The overall shape and behavior emerge from the interaction and combination of these actuated systems, determining the final form. For example, variable-length cables or robotic bending active elements could be used.

Like other elastic systems, pneumatic structures undergo a form-finding process where the final shape is determined by the behaviour of the actuated materials. After establishing design goals and selecting a pneumatic-constraining strategy, multi-state design explorations are conducted using the Kangaroo physics engine in Rhino Grasshopper. This involves custom parametric definitions to study how various geometrical and material parameters and actuation sequences influence the system's shape. These explorations are compiled into a design catalogue, organizing systems by different actuation values and evaluated against design goals. Due to challenges in simulating non-linear elastic behaviour, Kangaroo values are calibrated against physical models. The simulated geometries are further analyzed in K2 engineering for structural analysis and verified by exporting form-found meshes for Finite Element Method

(FEM) analysis in solvers like Abaqus or Ansys.

2.2. Pneumatic and hybrid robotic structure

In parallel to the simulation studies, selected configurations are translated into a physical robotic system. This phase comprises three main steps: fabrication of the physical system and setup, the development of the actuation system and control strategy. The fabrication process entails the selection of the pneumatic chamber material and of the constraining layer. Different materials have been tested for the pneumatic membranes over time. For the membrane, we explored nylon, TPU, PVC clear latex, natural latex and custom-made silicon membranes. Depending on the desired elastic behaviours, appropriate materials and techniques are selected. Bending elements comprised glass and carbon fibre rods and custom laser-cut plates and geometries made of Polypropylene or Styrene. Tensile elements were made of nylon and polyethylene. Most of the elements were laser cut to shape and embedded and connected through sewing, gluing and custom 3D printed connections. The setup design includes the actuators' mechanical development and the substructure's fabrication. Pneumatic actuation takes place through a custom feedback system that entails the use of pressure regulators, valves and pressure sensors. For the actuation of hyper-elastic materials, the required pressures can be extremely low (below 0.005 bar); therefore, commercially available pressure regulators cannot be used, as their range is well above the needs. In that case, we used valves connected to pressure sensors that could open and close based on the desired input pressure. In addition to the pneumatic actuation, certain systems have an active constraining layer or substructure. This means that the bending or tensile elements can be actuated mostly through cables of variable lengths. In this case, the cables are controlled through custom motorised spooling mechanisms capable of sensing. All the sensors-actuation systems operate in the ROS (Robotic operating system) environment that enables an effecting exchange and process of data between different devices. Once the system is operational, it can be characterised. Pressure and other actuation values can be stored and evaluated in relation to geometrical deformations. This phase integrates the use of an RGBD camera to rebuild the mesh of the system. This process is integrated into the ROS ecosystem, such that each significant geometrical state corresponds to parameters. These information are crucial for the behavioural design.

2.3. Cyber-physical behaviours

The design of a pneumatic hybrid shape-morphing system's behaviour is centered around defining its shape transformation logic in response to specific parameters. This involves delineating how the system should morph in response to specific conditions. The core challenge in this design phase is to establish a decision making logic that allows the system to behave in a desired and controlled manner. Given the complexities in controlling behaviours in soft systems, particularly those involving significant deformations, the control process occurs within a cyber-physical space. This environment facilitates the real-time exchange and processing of both digital and physical data. The environment connects the simulation environment in Kangaroo/K2 engineering and Grasshopper with the ROS space through custom and interactive interface in Unity 3D Engine. In these systems, behaviours are often not predictable in uncontrolled environments due to the high deformation of materials and their response to continuous changes in conditions. Therefore, the integration of digital control mechanisms with physical data is crucial for maintaining desired behaviours. While pneumatic hybrid shape-morphing systems can have the capacity to respond to a variety of conditions, our focus has been on transformations in response to human states. While each system was different, the overall scope of these structures is to exploit the inherent soft nature of the materials used in these systems in order to make them particularly suitable for safe and engaging interactions with humans. This alignment with human states emphasizes the need for intuitive and sensitive responses from the system. We focused on behaviours based on human motion, facial expression and heartbeat data. We created a control logic where RGBD camera and heartbeat sensor data were used to control the air pressure based on design and simulation data.

3. Results

Utilizing the previously described framework, several pneumatic and hybrid systems were developed, each contributing uniquely to the field (Figure 4). In this section we highlight a selection of developed projects:

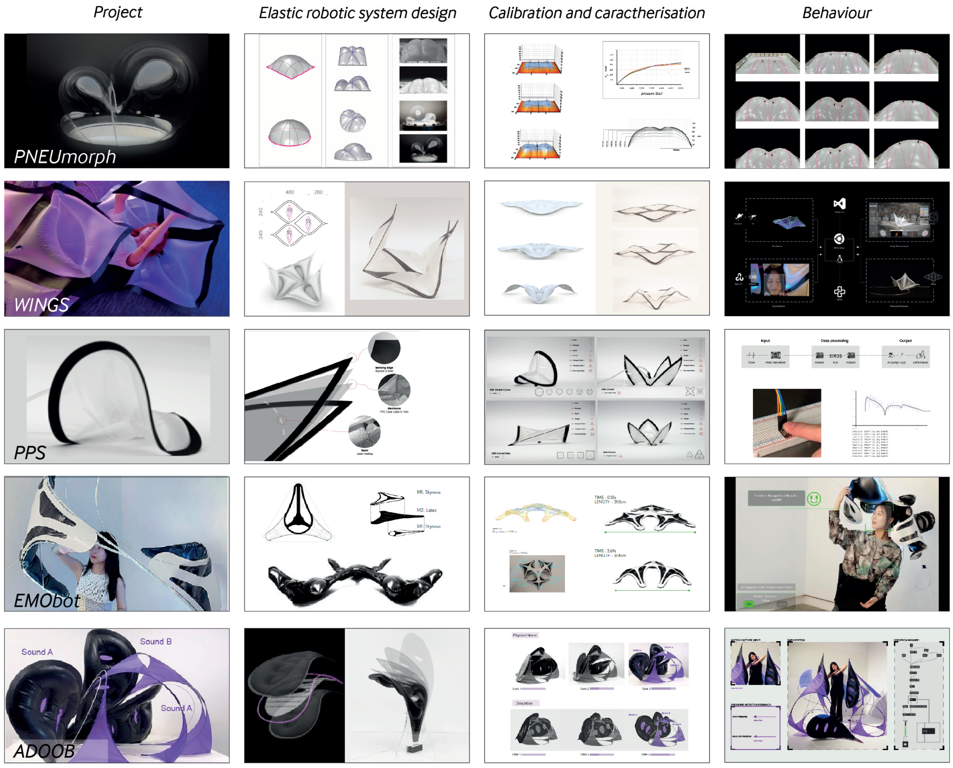

Figure 4: Table showing a selection of developed pneumatic hybrid shape morphing systems and comparing approaches across the main development phases.

A pivotal ongoing project that contributed to this framework is the development of a pneumatic chamber controlled by variable-length tendons, PNEUmorph. This design is innovative in its activation of both the chamber and its constraining layer, diverging from the more common approach of passive constraining layers in pneumatic shape-morphing systems. The project initially focused on a feedback-based pneumatic actuation system that precisely regulated air pressure within a highly elastic membrane. Small pressure variations resulted in significant deformations, challenging the control and predictability of the system. The latest configuration used natural latex for a large-scale setup (30m x 30m), achieving maximum actuation values of just 0.015 bar. The key advancements of this system were: a) the integration of a geometrical reconstruction system using RGBD cameras within the ROS environment, and b) the application of numerical form-finding strategies with Kangaroo/FEM validation for exploring hybrid pneumatic systems.

The WINGS project created over 50 medium and large-scale systems using custom pneumatic cushions and PVC Latex with curve-folding principles, including a 2m tall hugging column and a 2.5m foldable lounge chair, both operating under 0.8 bars. These systems were built from curved rhombus pneumatic modules with heat-sealed seams, designed to fold and become interactive human-scale elements that responded to facial expressions and digital feedback. The Programmable Pneumatic System (PPS) project extended these concepts by exploring new shapes like circles, squares, and helical triangles with curved seams. PPS developed modules that deformed in response to human heartbeats and visualized breathing patterns, effectively turning the system into a dynamic interface that merged physiological data with responsive design. These projects showcased the systems' ability to serve functional and aesthetic purposes while also acting as interactive mediums that reflect human physiological states, offering the potential for more personalized and responsive environments.

EMObot and PNEUMA advanced previous designs by integrating bending-active plates with pneumatic cushions, enhancing design versatility. They introduced a new catalogue of systems featuring triangular-based cushions with smooth corners and bending plates for curved deformations, moving away from WINGS' sharp folding behaviour. These innovations resulted in medium-scale modules actuated under 0.1 bar to form complex curves, and larger units (1.3m) that could wrap around human figures. These systems expanded design possibilities and utilized bending plates for finer control. EMObot incorporated a cyber-physical network with RGBD cameras and user feedback for behaviour optimization, while PNEUMA introduced sound and heartbeat data integration, enriching sensory experiences and showcasing pneumatic systems' adaptability in interactive environments.

In parallel to other projects, "A Dance of Other Bodies" (ADOOB) developed a leaf-like pneumatic module that bends smoothly due to a bending layer within the cushion and strategic seams/cuts. ADOOB created leaf-like shapes that could aggregate into larger, complex structures. The inflation process also generated sound through a real-time sound generation engine connected to the ERS cyber-physical framework, marking a significant advancement in the functionality and interactivity of pneumatic systems for dynamic design applications.

4. Conclusions

In this work, we have applied our framework to develop various pneumatic-hybrid shape-morphing systems, highlighting their potential for interaction, structural efficiency, lightness, and aesthetic appeal. These systems suggest a future where living and working spaces dynamically adapt to human needs, with applications ranging from adaptable building systems and furniture to responsive wearable technologies. However, challenges in fabrication and control still require multidisciplinary solutions. Overcoming these issues is vital for advancing the field and fully realizing the potential of soft adaptive systems. In summary, the progress in developing these systems is substantial, pointing to a future where technology and human environments merge seamlessly, creating more intuitive and empathetic spaces. Addressing these challenges is crucial for achieving this vision.

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Ray. *Aerobot*, Students: Wenxuan Hu, Rungrawee Jaratwilatwanit, Shuhai Wang. RC2 2021-2024: Design and Technical: Valentina Soana; Technical: Shahram Sabery,Aya Meskawi (RC2 22/23). Projects: *WINGS* 21/22, Students: Yuting Lei, Eduardo Nunez Luce, Xiangyu Zhang, Yue Xu. *TPop* 21/22, Students: Jahui Li, Yuanxin Li, Weicheng Dong. *A dance of other bodies (ADOOB)* 22/23, Students: Aya Meskawi, Vaishnavi More, Kexin Wang, Xiangyi Tian. *EMObot* 22/23, Students: Aofan Song, Zihen Chen, Keke Zhao. *PNEUMA* 23/24, Students: Wen Jun Tan, Yunning Pan, Anqi Cheng. Federico Bosi acknowledges support from the EU H2020-MSCA-ITN-2020-LIGHTEN-956547.

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