Oppunities for Design and Construction of Pneubotic Structures in Architecture

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Abstract
Actively adaptable and responsive structures in architecture have recently gained momentum thanks to the emergence of affordable programmable controllers, various sensors, new deformable materials, increase in computing power, algorithmic complexity of design and driver software, and other technological improvements. A distinctive type of structures in art and architecture that emerged from this setting is pneubotics – a type of structures formed by combining robotics with pneumatic structures. In this work a simple analysis and basic classification of contemporary pneubotic structures in art and architecture is given to inform the design possibilities that opened with the emergence of this structural polytype. Based on the analysis of the characteristics they exhibit, various possible uses of pneubotics in architectural design are proposed. These range from soft adaptable seismic insulation, adaptable frame structures, self-erecting structures, protective, control and otherwise technical devices, building envelope, etc. Given the early development of soft adaptable and responsive pneumatic structures these proposals should be taken rather as an inspiration for further research and development.

Keywords
Robotic architecture, Pneubotics, Adaptable structures, Responsive structures

Soft environments.
1. INTRODUCTION

Robotics in architecture is a term that can cover a variety of things. It can refer to the integration of automatic components in architecture like escalators, automatic doors and alike; different safety and surveillance systems, kinetic structures, responsive building envelopes, some less common and noticeable structures like active mass tuned dampers in high-rise buildings, and other autonomously controlled subsystems. Further, the term robotic architecture can encompass robotic production of building components, robotic construction, or the robotic structures – structures that can sense, interpret, and react to changing environments and user demands or other parameters influencing the structural response. Therefore, there are three main aspects of robotics in architecture: robotically produced components, robotically assembled structures, and robotic structures – structures that can actively adapt and/or react. The use and development of robotics in architecture, hence, broadens the field of possibilities for adaptability and responsiveness of architectural structures. The benefits of using robotics in buildings – objects often perceived as static and inert – are manifold. Most recently the development is focused on energy efficiency, human-robotic interaction, and mechanical compatibility of built environments with (soft and organic) humans etc. In an era where autonomous driving and self-flying drones are common occurrence, autonomous buildings and structures are also catching up. Robotic architecture is attained when a robotic component is combined or embedded within the building (structural) component. When such robotics is based on pneumatic actuation, pneubotic structures are attained. These structures present a unique structural polytype (Andrić, 2020) that can be pneumatically driven using hard parts such as pistons, or soft parts like soft muscles or another soft inflatable (or in some cases vacuumable) actuators. Although the pneubotics in the field of soft robotics are well covered by scientific writing, the architectural pneubotics fall behind in numbers. Some research on pneubotics has been made in architectural field, most notably by HiperBody group at the Technical University in Delft together with Festo engineering company that develops pneumatic systems and soft robots (Bier et al., 2012). Other research is mostly done in the field of art installations, and design proposals in some student thesis. These include various types of art installations not necessarily applicable to architectural structures from low-tech analogue wind-driven walking sculptures by Theo Jansen (Jansen) made from plastic pipes, tubes, bottles, and textile to interactive inflatable sculptures by Chico McMurtrie that use both soft and hard pneumatic actuators (McMurtrie) and alike. Student research project like Adaptive Pneus by Mehran Gharleghi and Amin Sadeghy conceived as adaptable pneumatic envelope that could stretch and fold its surface to actively respond to changing insolation conditions (Gharleghi and Sadeghy, 2009), or pavilion research design project by Ofir Albag with soft-robotic weather-responsive envelope as a scaled-up version of typical soft robotic bending actuators (Albag et al., 2020), and alike, use pneubotics to attain lightweight responsive structures in architecture. Therefore, a short overview of this type of structures with basic classification is carried out to detect the common types of pneubotics present in art and architecture. This should help assess the prospects for applications of such structures in building structures and the built environment.
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2. MATERIALS AND METHODS

Based on the available literature and other published materials and sources on soft, adaptable, and responsive pneumatically actuated structures, basic typological classification is made based on the way individual elements form a structure, along with the type of actuation and its immediate effect. One form of basic typological classification for such structures is presented in (Andrić, Šerman and Galić, 2019), but it is limited to the specific theoretical model based on the idea of a body plan suited for soft modular volumetric actuators. Hence, a general and broader classification that can also include hard and linear actuators is presented here. For every type, only the most illustrative examples are selected and presented. Further, based on these observations, possible application of these structures in architectural design is envisioned and speculated. Real built cases are given the highest priority since they prove functional in at least one instance. Further, some prospectus design proposals are also addressed since they have the theoretical potential to be acknowledged as feasible solutions in some applications. To keep the focus fixed on the topic of architectural pneubotics, and not to slide into the fields of soft robotics of much smaller scale or numerous art installations that cannot directly relate to architecture, these are omitted, unless in cases with noticeable potential for architectural application. Included are cases of structures that pneumatically change shape or move in ways that can be computer controlled. Cases like autonomous analogue wind-powered walking sculptures Strand Beest(en) by Theo Jansen (Jansen) or pneumatic sculptures by Chico MacMurtrie (MacMurtrie) are also excluded since they more closely resemble machines and sculptures than building structures. Although some research in the field of vacuum stabilized structures has been carried out (Huijben, Van Herwijnen and Nijsse, 2011), they are regarded more like pliable matter that could be vacuum-frozen into desired shape and not yet as vacuum actuated robotics. Vacuum pneubotics, at this point, exist in the field of small soft robotics, as actuated by other means (through tension cables for instance) with vacuum being used only to temporarily harden the shape. Some automatic and pre-programmed structures are evaluated under the assumption that they could easily be turned into full-blown logically autonomous robotic level – it has a physical device (a body) that can be combined with sensors and a control system (brain) into a true pneubotic structure.

3. RESULTS

Analyzed cases of adaptive pneumatic structures in art and architecture show some common characteristics that can help classify them into several main types. Namely those are: individual or singular elements that can act as independent elements or in tandem, linear series of elements, surface arrays, and spatial arrays. Additionally compound types can be formed by combining these main types (Table 1). Analyzed cases are shown as sketches in a joint illustration (Fig.1).

Individual or group of individual elements that change space or influence other building components are the simplest structural type of pneubotics. The project proposal called Brexit Pavilion by 3GATTI office for the 2000 Venice Biennale is a singular air inflatable volume.
placed inside a building that can expand and almost completely fill the room and hence reduce the available free space and air volume. It is envisioned as a double inflatable element – one inside the other – with the external element being inflated to a constant air volume, and the internal one that can inflate and deflate completely causing the air structure to increase its volume while only requiring the portion of air to be blown in reducing the time to reach its maximum volume and increasing the speed of filling in the exhibition space (3GATTI, a). A similar concept of controlling the amount of available space by inflating or deflating individual elements spaced out through a designated space is an art installation Bubbles which uses spherical air bubbles to occupy space dependent on the number of people present within the installation (Bubbles). Snowballing Doorway is Alex Schweder’s art installation comprising of a double air cushion that can block or allow passage dependent on the state of inflation of two parts of the double cushion (Schweder, a). Air Danshin company from Japan is developing the system of active pneumatic seismic insulation. A series of flexible tubes are placed between the building and foundation and can inflate in case an earthquake is detected. The rate of inflation is dictated by the type and the intensity of a detected earthquake (Air Danshin).

A series of elements is the next type of pneumotics that consists of a series of identical elements that act as one singular object. It can be further divided into three types: linear series, surface array, and spatial array. Airecture pavilion is a series of frames consisting of inflated columns and beams with soft muscles attached to its ends. Soft muscles create different states of forces in the frame causing the redistribution of stiffness to counteract the changing wind action on the structure (Kronenburg, 2003). The awning of the Adaptive Pneumatics, a design project by Reparametrize Studio, is a linear series of air inflated cushions that can bend depending on the inflation rate of the individual elements (Adaptive Pneumatic). InteractiveWall installation consists of cantilever wall segments that can react independently one from another, but with the tendency of each segment to synchronize on constant readjusting its position to align itself with the position of its nearest neighbors (Biloria, 2012). In this way wall opens and closes depending on the position of individual segments changing its overall appearance from loose to compact.

Between linear and surface arrays a structure made by Miguel de Prada Pole, a prototype of a varying morphology beam (Cobo Arévalo, 2014) is a suspended beam with individually inflatable cells that can change the beam geometry – from concave to convex and vice versa.

Surface array of elements are another common type where unit elements are multiplied in two directions to create surfaces with adaptable morphology. Aegis Hyposurface (Goulthorpe, Burry and Dunlop, 2001) is such research structure constructed as a surface array of piston actuators that support soft interconnected surface elements with metallic facets. The software interprets the sensor data and runs the pistons. Thus, a vertical interactive media surface is formed that can rapidly animate the array of facets producing the visceral effect of considerable out-of-plane surface deformation. The pneumatic system was chosen against the electric actuator for the robust reliability, speed, and relatively low cost (Goulthorpe, Burry and Dunlop, 2001). Pneumatic Envelope by Rick Sole is a structure prototype consisting of interconnected air cushions with expandable sun-blocking foil that
lets more sunlight as an individual cushion is inflated allowing for the local or global control of insolation in the building. Inflation of individual cushions influences the geometry of surrounding cushions due to their shared edges, making them pull and stretch one another (Sole). Soft Skin is a research project by Arch2O made from soft silicone rubber and elastic fabric that can adaptively inflate the groups of cells as a reaction to changing wind and light (Arch2O). Bubble Building, a design project for façade retrofitting on an existing office building in Shanghai by 3GATTI Studio utilizes the adaptive inflation of soft textile skin addition to the existing facade to improve building ventilation, air conditioning and filtering with additional sunlight amplification for the offices during working hours deflating while the building is vacant (3GATTI, b).

Spatial array of elements offers a true three-dimensional pneubotic construction. Muscle Tower I and Muscle Tower II research structures consist of fixed length metal rods with hinged connections and linear air muscles acting as tension diagonals of variable length. Inflation of individual muscle shortens the tension element drastically deforming the structure thus achieving the effect of leaning and bending the tower in all spatial dimensions (Oosterhuis and Biloria, 2008). Dynamat art installation is a suspended spatial array – a double layer of interconnected inflatable cubes – with a soft body that can change its form depending on which layer of the cushions is inflated, and which is deflated – or rather vacuumed (Pneumatic Structure Archives). Although in this case there was no true computational component present but a rather primitive form of pre-programmed automatic inflation sequence, this structure exhibited a form of variable topological transformation – It could take on a concave, straight or convex form. Wall to Wall Floor to Ceiling is an art installation comprising of 12 volume elements, 6 attached to the ceiling and 6 attached to the floor. Through different inflation, individual volumes push one another reconfiguring available spaces into constant flux (Schweder, b).

Compound type is achieved through a combination of any types. ONL Muscle, for instance, is a research pavilion conceived as a soft air bubble wrapped in a network of soft muscles that can contract and thus deform the bubble by squeezing or relaxing its various parts causing it to bounce, sway, shake or tremble (Kievid and Oosterhuis, 2012). Another hybrid structure that consists of flexible strips wrapped into a closed three-dimensional loop of a floor, walls and ceiling actuated by air muscles is The Muscle Re-configured research installation. In its dynamic series of interdependent elements that can attain specific configurations through changing curvature of its surfaces (Biloria, 2012).

Table 1. Analyzed cases with observed characteristics and effects

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Actuation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Brexit pavilion</td>
<td>Singular element</td>
<td>Soft volumetric</td>
<td>Increase/decrease in available space</td>
</tr>
<tr>
<td>- Snowballing Doorway</td>
<td>One double element</td>
<td>Soft volumetric</td>
<td>Passage control</td>
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<tr>
<td>- Bubbles</td>
<td>Group of individual elements</td>
<td>Soft volumetric</td>
<td>Increase/decrease in available space</td>
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<tr>
<td>- Air Danshin</td>
<td>Group of individual elements</td>
<td>Soft volumetric</td>
<td>Seismic insulation</td>
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<tr>
<td>- Adaptive Pneumatic</td>
<td>Linear series of elements</td>
<td>Soft volumetric</td>
<td>Lifting through bending of elements</td>
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<tr>
<td>- Airtecture pavilion</td>
<td>Linear series of elements</td>
<td>Soft linear</td>
<td>Load path management</td>
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<tr>
<td>Project</td>
<td>Description</td>
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<tr>
<td>InteractiveWall</td>
<td>Linear series of elements, Hard linear, Aligning or spreading of segments</td>
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<tr>
<td>A prototype of varying morphology beam</td>
<td>Linear series of elements, Soft volumetric, Change in the curvature of the beam</td>
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<tr>
<td>Hyposurface</td>
<td>Surface array of attached elements, Hard linear, Dynamic topology of the beam</td>
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<tr>
<td>Soft Skin</td>
<td>Surface array, Soft volumetric, Stiffness distribution across the surface</td>
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<tr>
<td>Pneumatic envelope</td>
<td>Surface array of attached elements, Soft volumetric, Dynamic light permeability</td>
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<tr>
<td>Bubble Building</td>
<td>Surface array of independent elements, Soft volumetric, Increased air volume + light amplification</td>
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<tr>
<td>Muscle Re-configured</td>
<td>Spatially bent surface array of elements, Soft linear, Dynamic topology of walls, floor, and ceiling</td>
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<tr>
<td>Wall to wall floor to ceiling</td>
<td>Spatial array of elements, Soft volumetric, Opening and closing of passage</td>
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<tr>
<td>Muscle Tower 2</td>
<td>Spatial array of elements, Soft linear, Bending and twisting</td>
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<tr>
<td>Dynamat</td>
<td>Spatial array of elements, Soft volumetric, Changing surface curvature</td>
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<tr>
<td>ONL Muscle</td>
<td>Hybrid – pneumatic cushion in a network of actuators, Soft linear, Overall shape change + shaking, bouncing</td>
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![Images of project examples](a.png, b.png, c.png, d.png, e.png, f.png, g.png, h.png, i.png, j.png, k.png, l.png, m.png, n.png, o.png)
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4. DISCUSSION AND CONCLUSION

Pneubotic structures in architecture are type of structures that emerged recently and is still in early stages of development. That is the reason for their slow adoption in architectural design, and most of them are present as experimental pavilion structures, or research design projects. Nevertheless, they are a valuable source of ideas for consideration of future architectural solutions. Another reason for their slow penetration into an architectural design is the fact that they can be found, both, in the field of hard robotics as well as in the field of soft robotics, and while the hard robots are easy to control, soft robots are much harder to control due to fact that their parts are soft with everchanging geometry, thus complicating the actuation of soft pneubotic structures. Although in some instances, they can be hard and closer in logic to classical robots or kinetic structures, in most instances they are soft simultaneously changing their shape and achieving actuation through the same inflation of flexible elastic parts.

The analyzed cases of pneubotic structure types opened prospects for some possible use scenarios and design opportunities (Fig. 2). These include the control of available useful space in a building, like in the cases when a reduced volume is sufficient for the operation while there are few users in the building, and increased when the maximum volume is needed – with the maximum user capacity. Another possible application of such structures is temporary or flexible partitioning of large spaces into several small ones. Also, exclusion or protection of parts of the building can be achieved through adaptive inflation of individual strategically placed pneubotic volumes. Further on, facades could be equipped with such devices to control the entrance and evacuation of a larger number of people like in stadium structures where tight control is wanted before the event and quick emptying of the facility afterward. The seismic insulation prototype opens, apart from that obvious advantage, some other possible uses of pneubotic substructures. For instance, active tilt control is possible when structures are temporarily erected without foundations and on soft grounds like earth or sand prone to different settling. It is also possible to imagine the use of different kinds of inflatable supports and stabilizers to prevent tilting or the collapse of structures.

Figure 1. Conceptual Sketches of Selected Cases of Interactive Pneubotics in Art and Architecture: a) Brexit pavilion, b) Snowballing doorway, c) Bubbles, d) Air Danshin e) Adaptive Pneumatic, f) Airecture pavilion, g) InteractiveWall, h) A prototype of varying morphology beam, i) Hyposurface, j) Soft Skin, k) Pneumatic envelope, l) Bubble Building, m) Muscle Re-configured, n) Wall to wall floor to ceiling, o) Muscle Tower 2, p) Dynamat, q) ONL Muscle
Figure 2. Some proposed uses of pneubotics in architecture and construction: a) partitioning, b) space reduction or exclusion, c) access control, d) envelope opening and additional exits, e) self-leveling substructure, f) stabilizing devices, g) telescopic roofs, h) self-erecting structures, i) adaptable geometry structures, j) responsive awnings, k) protective walls and barriers, l) morphodynamic roofs, m) morphodynamic terrains, n) adaptable formwork, o) manipulation devices

A series of elements is an inspirational type of pneubotics that can take on multiple forms for specific purposes. For instance, roofs that can telescopically shrink and expand provide the possibility to transform space from closed to open as needed. Or facades and dynamic awnings that can partly lift to let more sun in or lower to prevent hyper insolation. In case of vertical placement, they can form walls that can be compact or spaced to block the wind, or to secure privacy in space etc. They can be envisioned as adaptable embankments in case of floods, or noise barriers that can “thin out” during the periods of quiet to allow air circulation. When a structure is made from a series of pneubotic frames, those can be used to optimize building’s stiffness for different wind conditions or allow for self-erecting construction. If frames were to be made from a series of unit elements, those could be adaptively inflated to allow the change of the frame and/or beam and/or column geometry raising or slightly bending parts of the structures to actively adapt to the asymmetrical loads, accommodate other unexpected temporary actions on the structure or other spatial demands.
Surface array pneubotics allow for the construction of morphodynamical surfaces that can bend in and out of the plane, stretch their edges or lift corners making building envelopes and roofs that can change geometry according to needs like roofs that can maintain a low profile for minimum air volume to save on conditioning power, and raise it if activities like various sports demand greater room height. Also, facades that can increase room volume by extending outwards to increase usable space and contract during the night to save on heating are possible using adaptive pneumatic façades. Suspended ceilings that can change thickness or floors that can change inclination facilitating the mobility of disabled users can easily be imagined using pneubotics as well as some semi-permeable building envelopes that could regulate how users, air or other elements can be let through.

Another important aspect enabled by the introduction of pneubotics in architecture is their capacity to retrofit existing buildings with the added functionality in energy conservation and sustainability of existing building stock.

In the case of robotic building component production, pneubotic structures could be used as formwork or mold with variable geometry to cast different concrete, polymer, or other composite elements. Where robotic construction is needed, pneubotic structures could present a soft and pliant construction site machinery for erecting, stabilizing, lifting, leveling, tilting, jacking etc. Cases like Muscle Tower 2 indicate that some special types of construction lifts and cranes like robotic manipulation hands could become reality with the use of hybrid pneubotic structures.

These proposed scenarios for pneubotics in architecture based on the observed cases and their characteristics exist as virtually multiple realities that may or may not be realized in the future. Whether such speculations on the field of possibilities for architectural pneubotics, that the emergence of pneumatically adaptive and responsive structures has opened, will manifest as possible and viable is now hard to predict. The truth is that this newly opened field is yet to be further ventured and explored.

REFERENCES


