Bio-Inspired Ventilating System for Building Envelopes

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Abstract
A breathing skin for buildings based on principles and methods abstracted from nature is presented. Installing and integrating services in the envelope for building renewal, result in less interference with the interior spaces. And by moving the old services from the interior, an extra space is provided. The developed skin reacts to changing conditions and influences the air pressure on the surface to perform a process of inhaling and exhaling. The system is created by a specific arrangement of a basic component, to utilize the space and the materials in an efficient way. The orientation and the geometry of the components allow deformations. These deformations are important for creating gradient pressure on the surface of the building skin, in order to allow sucking and expelling the air, which results in regulating the interior microclimates. Piezoelectric wires are used to generate the deformations. The rate of air-exchange is affected by the velocity of the component changing shape (deformation velocity). By developing this system we are not dealing with a separate ventilation system, but with an integral part of the building envelope, which functions as a protective layer too. In this way we save material and energy and thus improve the sustainability of buildings.

1. Introduction
The envelope of the building is mostly responsible for building’s energy consumption. In the last decades, systems for buildings that respond to environmental changes have made rapid advances. New building systems and products, software and procedures are being developed. The consciousness for the relation between façade and energy-consumption resulted in making research on integration of climate-technology into façades (Ebbert et al. 2006).

After the world-war-II a huge number of people were left without housing. As a result, a big mass of buildings were constructed, where the quantity was more important than the quality. This existing housing stock needs to be upgraded with today’s and future’s needs of the users (Kendall 1999).

Façade development is increasingly concerned with ongoing changes within the existing building stock. Industrialized production is possible due to the current façade stock which is based on post-and-rail systems or on element systems (Krewinkel 1998; Oesterle et al. 1999).

In building renewal, installation and integration of services in the façade structure is one of our major tasks. In our research we develop envelopes, as adaptive systems to changing environmental conditions and integrate them into structures. Our aim is to combine new façade technologies with research going on new materials, where we improve the performance of the façade.

The envelope of the building is responsible for a major part in controlling the climate and energy consumption. By upgrading the envelope of the building, the performance of the building (the organism)
improved, thus contributing to a more efficient building. For developing services and systems for facades, we use the nature as a source of methods and principles. For millions of years have nature been revolting and creating structures that tend to perfection in terms of energy consumption, environmental adjustment and survival. In “On Growth and Form”, D’Arcy Thompson (1961) suggested that living things adapt their shapes to physical forces applied on them. When a new structure is “born”, a number of elements of the same environment participate for a certain period of time in its creation, either directly or indirectly. This environment can be influenced from other environments. Hence, every new structure (that survives) is born after a long and complicated procedure where many elements have contributed each in its own way and magnitude to build the features, characteristics and mechanism of the structure.

2. Biomimetics
Biomimetics is not about nature imitation, but the observation at their properties and principles, and the transformation and the development of these principles into sophisticated technological solutions. These solutions can result in new means by which buildings can respond, adapt and interact to regulate their interior environment for the satisfactory of their users.
Nature has always inspired technology, and led to effective algorithms, methods, materials, processes, structures, tools, mechanisms, and systems (Bar-Cohen 2006).
Constructing structures with cells is a method used in the majority of plants and animals. This method provides the ability to grow with fault-tolerance and self-repair (healing). Honeycomb has been a model for construction, for its perfect cellular shape (hexagonal) that result in an optimal packing shape. Maximum stability with minimum amount of material is the aim of the bees while creating their structure. For that reason it is an ideal solution in aircraft, where they need light weight structures.

3. Methods and Principles in Nature
The main aim of the research is to develop adaptive systems for buildings based on principles and methods in nature abstracted and transformed into technical solutions. These adaptive systems regulate the interior environment, by responding to changing environmental conditions. In developing these systems we take advantages from ongoing research in the material field. Some advanced materials can be applied to systems in structures and buildings to adapt their properties and hence optimize their performance. In this paper we, specifically, address the piezoelectric material to be integrated in the envelope as will be further discussed later on.
Nature presents an infinite source for research and knowledge that has been used by many researchers from different fields for different aims. Living organisms have unique integration geometries and techniques that allow them to adapt to different environments. They can sense and react to local changes causing a global behavior. Their development through evolution can take decades and centuries to give structural solutions (such as ventilating systems). One of the challenges is the development of effective and efficient envelopes that uses the natural dynamics in the neighborhood of structures instead of counteracting with them.
Investigating and analyzing natural systems can result in models for dynamic and adapting materials. And we are able to analogously apply solutions abstracted from nature in the desired system. Size and proportion is important in such systems and should be considered prior to abstracting principles. In this paper, we present some breathing organisms and circulation systems (air exchange), which can be found in many living creatures for different tasks. The main methods and principles are abstracted and transformed to develop the presented envelope.
The following cases from nature are brought to show different methods for ventilation and integration patterns:

1. **Ascoinoide sponge**: It has an interesting geometric regularity that provides a unique circulation of water through and around its walls. The sponge consists of membranes on the envelope which sucks the food through them, and expels the water out through an atrium in the middle. The outer layer consists of thin cells which are tightly packed together. The inner layer consists of internal chambers, which are surrounded by a membrane that makes beat movements to create an active pumping process of water throughout the sponge walls and to absorb nutrients.

2. **Respiration systems**: many living organisms have a mechanism in their body for exchanging air (inhaling and exhaling). There are four main respiration systems; (a) integument – where the exchange of gas occurs in the water directly through their integument; (b) gills – external tissues with many enfolding that increases the surface area for gas exchange. Organisms which live in water have this type of system for gas exchange; (c) lungs – the system is located inside the body connected to the outside by a pathway. By moving the muscles of the chest the air is sucked inside through the pathway to fill the lung. The lung has a great surface area of gas exchange due to its tiny protrusions inside; and (d) tracheae – the system is divided into a lot of small tubes that are in contact with muscles and organs. This kind of system functions in bodies less than 5 cm in length. Body movements increase the diffusion of gases inside.

3. **The skeleton of a sea sponge**: the fibers of the skeleton are overlapped or overlaid in a regular or crisscross pattern, with diagonal fibers to reinforce the skeleton. When increasing the diameter of the sponge skeleton a spiral pattern is emerged to be stronger. According to Reichmanis (2005) the sponges are formed in a perfect way with the exact amount of material for optimizing the design. Understanding how their structures evolve could help in design processes.

4. **The surface of a sea sponge**: sponges have an extraordinary surface features. They don't have organs, muscles or nervous system. They only have specialized cells for different purposes. The sponge can increase its volume and by that it increases the inner and outer surface area. It generates a water flow by a nonstop beat and movements of flagella (a long slender projection from the cell body) which is part of the choanocytes (collar cells in the sponge). The water flows into the shafts through the pores in the body wall. The sponge also consist of oscules (outgoing of the channel system permeating the sponge) that close and open.

### 3.1 Principles Abstraction

<table>
<thead>
<tr>
<th>System</th>
<th>Keywords</th>
</tr>
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<tbody>
<tr>
<td>Ascoinoide sponge</td>
<td>Circulation, membranes, sucking, expelling, atrium, cells, chambers,</td>
</tr>
<tr>
<td></td>
<td>pumping, absorption.</td>
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<tr>
<td>Respiration systems</td>
<td>Gas exchange, tissues, enfolding, surface area, pathway, muscles, sucking,</td>
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<tr>
<td></td>
<td>protrusions, division, tubes, movements, diffusion, expansion, contraction.</td>
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<tr>
<td>The skeleton of a sea sponge</td>
<td>Helix like structure, overlapping, overlaying, crisscross pattern, diagonal,</td>
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<tr>
<td></td>
<td>fibers, skeleton, increasing/decreasing, optimization.</td>
</tr>
<tr>
<td>The surface of a sea sponge</td>
<td>Differentiation, nonstop beating, movements, shafts, pores, close/open,</td>
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<tr>
<td></td>
<td>channel system, permeable.</td>
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From studying and analyzing natural systems that perform ventilation or circulation processes, we had...
abstracted the principles and methods that these systems are based on. And we summarized the main keywords in a table (Table 1) as a reference for our work. Different methods for ventilation (gas exchange) are used in the living organism. In the living organism we can see that the gas exchange is performed through a series of actions which is related mainly to parts movements influencing the air pressure to create a flow against the exchange tissues. The surface area of the exchange is greatly expanded in such natural systems, by dividing the system into many small parts, chambers or sub-branches. The gas exchange process is happening continuously, and it depends on the pressure changes. Integration patterns are based on simple basic geometry to create more complex functionality of the system.

3.2 Principles Transformation
Based on the principles and methods abstracted from the natural systems, a breathing skin for buildings was designed (Fig. 1). In our work we will refer to the following methods:
1. Generating gradient pressure by parts movements.
2. Increasing and decreasing the volume to result in sucking and expelling.
3. Dividing the system based on hierarchy.
4. Controlling the air-exchange by designing the surface pattern (sea sponge).

These methods provide the base-line for our development, where during the transformation we keep and follow these methods in order to create the new system based on natural principles. By this transformation we consider the envelope of the building as a ventilation system that improves the functionality of the building skin.

3.3 Transformation Results

We developed a skin that reacts to changing conditions and influences the air pressure on the surface to perform a process of inhaling and exhaling. It provides an extended surface area for air exchange created by a lot of small active units (a basic component). Increasing the exchange surface of the skin improves the ventilation through it.

The designed skin is a system where local changes occur to create global behavior. The system is created by a specific arrangement of a basic component, to utilize the space and the materials in an efficient way. The orientation and the geometry of the components allow deformations in order to perform the inhaling and exhaling process which results in regulating the interior microclimates.
3.3.1 Basic Component

The component presented in Fig. 2 is produced from elastic membrane that allows it to be flexible. The component cross section consists of three hierarchical parts: opened, semi permeable chamber, and a closed part. This hierarchy is important to create three chambers with different air pressure. The changes in the geometrical state of the components allow the air to flow in and out. The rate of air-exchange depends on the velocity rate of the component changing shape (deformation). Sensors are attached to the inner side of the skin, which give signals (through a control system) to the component to increase or decrease the deformation velocity. The middle chamber allows the air to flow in one direction. Hence it functions as a lung allowing air to flow in both directions (in and out). A more detailed explanation of this lung like chamber is discussed later in the paper.

3.3.2 Basic Component Deformation and Integration

The deformation of the basic component is continuous. It deforms from phase a. to phase b. and vice versa (as shown in Fig. 3, left). At phase a. the component is opened to the outside and closed to the inside, but this state is changing all the time at different velocities depending on the conditions of the interior space. The system is an integral part of the building envelope. The active ventilating components with their arrangement and geometrical integration create the protective envelope for the building, not just a protective layer but also an adaptive system based on bionic principles. The arrangement of the components creates an envelope that has the ability to perform dynamic continuous changes. Dynamics are produced due to geometry and material hierarchies. These dynamics generate gradient air pressure which in turn creates process of inhaling and exhaling, performed at the same time. While some components are performing inhaling other components are performing exhaling.

The components are made from membrane materials that are able to receive signals from sensors and
respond by changing their geometry, this change will enable the air to permeate the lung-like-chamber from one side and expel it from the other side during the geometry change of the component.

3.3.3 Lung-like-Chambers Arrangement in the System

![Fig. 4 the Pattern of the Lung-like-Chambers Net](image)

The position of the lung-like-chambers is fixed in the basic component. As mentioned earlier in Fig. 3, there are fixed points in the basic component during their continuous changing. The chambers are based in the middle of the basic component cross-section, where the basic component is fixed and no movements occur. They are arranged in a diagonal crisscross pattern (as presented in Fig. 4) to optimize the stability of the system. This net is the basic support of the dynamic system, where the basic component is attached to this net too. The two different color scales of lungs in Fig. 4 imply the direction of air flow through the system. The air flows from outside to inside or from inside to outside through the lung and it doesn’t flow in reverse direction through the same lung-like-chamber.

3.3.4 Piezoelectric Material Application

![Fig. 5 the Expansion of the Lung-like-Chamber](image)

The lung like chamber is designed on base of principles and methods abstracted from respiration systems, surface of the sea sponge and the asconoid sponge, which were presented earlier.

The lung like chamber consists of two surfaces attached to each other at their edges creating a specific volume in the basic component (as presented in Fig. 5a). Piezoelectric wires are attached on the sucking surface of the lung like chamber. The sucking surface is controlled separately (Fig. 5b & 5c). When a voltage is applied to the piezoelectric wires on the sucking surface, the lung expands and increases its volume and by that it increases the inner and outer surface area. A low pressure is created in the lung which results in sucking the air inside the lung (Fig. 5b). The air flows into the lung through shafts on the

surface of the lung. The shafts are designed in a way that allows the air to flow in one direction; valves are attached to the inner surface of the shafts, when the air pushes on the inner surface towards out, the valves are contracted and closed. Stopping the voltage from the surface results in contraction and creating over pressure (Fig. 5c), which results in expelling the air out of the lung like chamber through the other side, where the air pushes on the inner side of the expelling surface and results in opening the valves. By this action the air flow is controlled to flow through the lung in one direction.

3.3.5 Lung Expansion and Contraction combined with Basic Component Deformation

Fig. 6 the Process of Air-Exchange that occurs in the New Skin

In natural respiration systems air circulation is generated by a nonstop beat or movements of the muscles or different parts of the system. These movements create over/low pressure where the air is sucked or expelled, as already explained and summarized before.

Based on sections 3.1 and 3.2, the expansion and contraction of the lung-like-chamber is combined with the movements of the basic component (Fig.6 a-d). When a voltage is applied to piezoelectric wires on the lung, results in the expansion of the lung, and at the same time the basic component deforms and opens to create a bigger volume on that side where the lung had expanded (Fig.6 b). Creating a bigger volume increases the low pressure and increases the air sucking from the surrounding environment. Stopping the voltage will result in contracting the lung and creating over pressure inside (Fig.6 c), at the same time; the basic component is deforming and closing the side where the air was sucked inside the lung, and opening the other side (Fig.6 d). Creating the bigger volume in the basic component creates low pressure which will result in improving the air expelling from the lung to the other side, And so on. In this way the skin sucks air from one side and expels it to the other side. The skin consists of lung-like-chambers that take air from outside to inside, and lung-like-chambers that take air from inside to outside. In this way the air is exchanged continuously.

4. Conclusions

We had developed a skin that performs a gas exchange process which can be integrated into structures with the property of adaptation, based on principles abstracted from natural organisms.

With installing and integrating services in the envelope for building renewal, we result in less interference with the interior spaces. And by moving the old services from the interior, an extra space is provided. By developing the presented breathing system we are not dealing with a separate ventilation system, but with a system that is an integral part of the building envelope which functions as a protective layer too. In this way we save material and energy and thus improve the sustainability of buildings.

The developed skin has a unique geometry and integrity, which allows it to react to the environmental changes. The elastic material used for the skin is important to make it possible to react and change continuously. Utilizing advanced materials in the design, which are not common in the building industry,
opens new opportunities for better solutions for building envelopes. Currently we are running simulation tests to investigate the behavior of the ventilating system for structures with different requirements in order to optimize their functionality. We also intend to test a prototype of the developed system based on the required improvements (from the simulations). Our vision includes a new class of building envelopes which are self-adapting systems that can behave “intelligently”. This class is a result of ideas transformed from nature, with the property of adaptation to changing environmental conditions. And can be the solution for the major problems in integrating new services for the existing stock of buildings.

5. References