RESPONSIVE BUILDING ENVELOPE AS A MATERIAL SYSTEM OF AUTONOMOUS AGENTS

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Abstract. The paper represents the concept of an abstract model of the responsive building envelope (RBE), founded on pre-programmed material’s behaviour. The assumed model of the responsive building envelope is based on the idea of material autonomous agents that control default parameters of building’s energies like ventilation, humidity, light volume, radiation, temperature, etc., by materials’ geometry deformation. The agent is a material system, built with the electroactive polymers (EAPs) actuators which react to the environment’s fluctuations continuously and independently from other agents. The model of a responsive envelope is a cluster of self-reliant units which control the primary characteristic of the building environment in an analogous way to the homeostasis system of a living organism. By decentralization the system becomes more stable and reliable. The CFD simulation was created from the schematic model of the RBE’s performance to test the presented design concepts.

Keywords. Responsive system; autonomous agent; electroactive polymers (EAPs); homeostatic cycle; CFD simulation.

1. Introduction: Architecture as a Responsive System

Responsive architecture can be characterised as: a system which reacts on given stimulus in predefined way. The system’s state can depend on the interactions with the non-system events, thus the system’s reactions can be reliant on the outer actions and the current characteristics of the system.

In architectural context the term responsiveness can be divided in several types which can be collected in general into two main groups:

- presentational/form responsiveness – the building components react on the user or environment behaviour, not affecting the general characteristic of the building system (i.e. interactive facades, digital screens, kinetic elements, etc.);
- functional responsiveness – the building’s system characteristics change under external stimulus (i.e. automatic shading systems – internal temperature increase
under the solarisation – the system responds by changing his geometry to decrease a light volume and therefore a temperature, etc.).

Groups mentioned above can be divided into two additional subgroups (Addington and Schodek, 2005):

- **micro – level of responsiveness**: mechanism of adaptation changes system’s components material properties – i.e. thermophysical or optical material properties, energy state change – i.e. electricity to light due photovoltaic cells, or electricity to thermal radiation;
- **macro – level of responsiveness**: mechanism of adaptation changes geometry of building’s envelope by moving its components to demanded configuration (by folding, sliding, rotating, opening, inflating, etc.).

This article will concentrate on the second group of the responsive building envelopes only.

The **functional responsiveness** in contemporary architecture can be defined as (Ferguson et al, 2007):

system’s ability to adapt itself to deliver intended functionality under varying conditions through the design variables changing their physical values.

Cited definition can be rearranged and simplified for a building system to: a system that controls building’s energy balance by its elements manipulations. The design process of these systems focused on the **responsive building envelopes** (RBEs) development, where external environmental conditions (like ventilation, humidity, light volume, radiation, temperature) influence the interior parameters of the building (i.e. thermal and light comfort). The most common solutions are based on several specialized subsystems (like structural elements, sensors, mechanical actuators, membranes, control devices, etc.) that are responsible for changing the envelope’s geometry according to stimulus and programmed performance. The application of these systems concern on the solar shading systems and the bio-inspired building skins (manipulation of the ‘pore’ element to control the air flow between interior and exterior) (Figure 1).

The implementation of the responsive envelopes in contemporary realisations is very unique and rare. Responsive shading systems were applied in: i.e. Institute du Monde Arab in Paris by Jean Nouvel, or more current Al Bahar Towers in Abu Dhabi by Aedas (more examples can be found in Anshuman, 2005; Loonen, 2010). The responsive ‘pore’ system hasn’t been implemented in full scale project yet, and it is still in conception (i.e. Dutt and Subhajit, 2012; Doumpioti, 2011) or prototype phase (i.e. ‘Bloom’ installation by Doris Kim Sung, 2012).
2. Responsive Distributed System and Material Auto-responsiveness

Current responsive building envelopes (RBEs) are based on hierarchical relations between system’s elements with a central control device which maintains system’s behaviour. Although the overall performance can be effective, the stability on the unpredicted perturbations can be low, reliant on system’s central scheme (i.e. local failure of the actuator mechanism, or sensor will effects the whole system). The decentralisation of the scheme can increase the system’s local and entire performance and makes the system more reliable to external disturbances. The result of distributed system scheme is the subsystems’ elements multiplication (i.e. sensor, mechanism, control devices, etc.) and therefore growth of energy consumption.

The system simplification with the energy reduced consumption can be achieved by the minimisation of the subsystems and their elements. The design scheme is based on the *material auto-responsiveness* paradigm – the material is being programmed to react on the stimulus in defined way. The behaviour is independent from other system’s components and based only on material embedded properties. The material reaction for the application of external impulse is a shape deformation that can be converted into a functional responsive mechanism.

The implementation of the mechanism can be achieved by using the components based on the shape memory polymers (SMPs) – particularly the electroactive polymers (EAPs).

3. Electroactive Polymers (EAPs) Materials

From the various types of the active materials (i.e. shape memory alloys, bimetals, piezoelectric, ceramics, polymers, etc.) EAPs dielectric elastomers (DE) have the most applicable performance parameters (strain, reaction speed, efficiency, low energy of actuation, operating temperature range, etc.) for application into the
RBEs’ components (Bar – Cohen, 2004; Lochmatter, 2007). The principle characteristics of the EAPs DE to shape changing under the electric stimulation can be used to react on a relatively small and rapid environmental conditions change (i.e. temperature, humidity, light volume, etc.) with the pre-programmed geometry change (up to maximum strain), which is difficult to achieve using on the previously mentioned active materials due to their properties limitations (Madden, 2005).

The material properties of the EAPs DE allow to design components which will deform in predicted way. The material displacement can be used into development a soft mechanical actuators for the responsive building envelopes (RBEs). The calibration of the material performance can adjust the previously mentioned paradigm of the material auto-responsiveness in which the material system behaves in the way of a well-tuned device. For the purpose of this article a simplified model of the EAPs DE component behaviour was developed. The EAPs DE elements are represented by element’s geometry deformation before ($G_0$) and after ($G_E$) application of an external stimulus.

4. Homeostatic System: Material Homeostatic Cycle

Definition of the term homeostasis can be described as (Moioli, 2008):

a successful adaptation of the system to dynamic environments.

The general definition of homeostasis can be formulated as the ability of the system to maintain its parameters in a defined range to keep the system in a state of equilibrium. The grounded idea of homeostatic system (a system with ability to conduct homeostasis) can be related to the term of the functional responsiveness and further with the material auto-responsiveness. Based on the SMPs (EAPs’) material properties it is possible to design an element (sub – system for a responsive envelope) that controls system’s parameters in balance directly by the material homeostatic cycle.

The material homeostatic cycle is a continuous process in which pre-programmed material performance controls attributed system’s domain parameters: if the system stability is interrupted by external change (i.e. defined range of the internal temperature is crossed) the system reaction is geometrical deformation of the material/component element (auto-responsiveness) in the way that allows to return to system’s equilibrium. The reaction occurs without any external control devices and is eternally based on a material/component embedded properties (Figure 2).

The material homeostatic cycle (homeostatic cycle’s steps: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow [1]_{virtual}$) can be used as the basic principle for the responsive envelope development (RBE). Furthermore, buildings (or any architectural object with the embedded maintenance of physical parameters) can be seen through the paradigm of buildings as: a continuous homeostatic process.
5. Autonomous Material Agents System

The primary scheme for responsive skin performance is a collective of pre-programmed material agents that control set-up of building environmental characteristics. Material agent definitions came from the computer science background where term *agent* is described as (Stamatopoulou et al, 2005):

> an encapsulated computing system that is situated in some environment and is capable of flexible, autonomous actions in order to meet its design objectives.

In more general definitions *agent* can be defined as *autonomous* object (Weiss, 2000):

> that takes sensory input from the environment and produces an output actions that affect it.

From the various types of an agent samples (i.e. intelligent, smart, learning, etc.) the most suitable model for the application in the material systems is a *reactive agent*. The reactive agent’s behaviour is based only on its present situations with a simple rule scheme (adopted from Weiss, 2000):

\[
\text{Action: Perception } \rightarrow (\text{Reaction (Action)})
\]
Agent’s behaviour is without any reference to the history of the previous actions and its decisions are purely autonomic (no communication amid other agents).

For the purpose of the responsive envelope development an agent was adapted as a material system that inherits a similar reactive agent’s model of performance with a rule that allows to conduct the continuous homeostatic process. The material agent system is: an autonomous unit that responses only on stimulus from surroundings and controls only its parameters. The autonomous material agent can be a single element, or a cluster of elements (that retains listed before properties). Their common feature is the possibility of an asynchronous behaviour (cluster’s cells behave in synchronous way but in relation to different clusters on the same domain their states can be various) which is caused by different stimulus from the environment (i.e. various temperature range for the same domain) (Figure 3).

Autonomous material agents due to their independent performance and control (every agent is controlled by itself) provides a steady and reliable responsive system – i.e. if one of the system’s unit has a defect its responsibilities are intercepted by the others. Although overall system’s performance is lower – the principle of homeostasis stabilizes its parameters on the defined levels.

The bottom – up approach that summarizes the scheme of the functional responsiveness of the building systems can be found below.

\[
\text{[material properties]} \rightarrow \text{[material auto – responsiveness]} \rightarrow \text{[material homeostasis cycle]} \rightarrow \text{[material agent]} \rightarrow \text{[responsive structure]} \rightarrow \text{[functional responsiveness]}
\]

Figure 3. Scheme of material agent unit and cluster of material agents units in RBE’s domain.
6. Application of Autonomous Material Agents System into Responsive Building Envelope

The studies of the plants stomata mechanism helped in developing abstract model of the responsive building envelope. Stomata is a complex system of pores that regulate gaseous exchange process in plants. Stomata performance depends on regulation of the size and the opening of the pore to control the amount of gas exchange between internal air space and external atmosphere. The responsive behaviour of the stomata structure depends on inner chemical equilibrium which is a main factor of the pores shape change (Kramer and Boyer, 1995) (Figure 4).

The abstract scheme of responsive building envelope was developed as an implementation of stomata self-regulation mechanism. The model presents simple fragment of the responsive envelope with the regular grid of pores. The pores scheme is an application of autonomous material agent system: in designed arrangement every single pore is a material agent with embedded responsiveness scenario. The applied behaviour can be expressed as a simple conditional statement (2):

\[
Pore: \text{If}(t_i > t_m) \rightarrow \text{Open(Pore)} \quad \text{Else} \quad \text{Close(Pore)}
\]

\[t_i\] - internal temperature in pore’s surroundings; \[t_m\] - maximum default temperature in pore’s surroundings in relation with external environment.

The responsive scheme model is designed to stabilize the internal temperature in the default pore’s surroundings: if the temperature crosses default value – the

Figure 4. Tomato leaf stomata
pore will open and allow heat to transfer from the environment with the higher temperature to the lower. The autonomous material agent system grounded on the EAPs and their composites is able to maintain internal conditions on default level with this reduced rule-based procedures. At this stage of the research the behavioural model is simplified to single binary logic and the most common situation (indoor temperature > external temperature or indoor temperature < external temperature). The more complex situations will be considered in further research.

7. CFD Simulation of Schematic Responsive Building Envelope Performance

For this research purpose, the CFD (computational fluid dynamics) simulation of responsive building envelope was made. The schematic of the interior model was assumed with the responsive building envelope containing ‘stomata’ elements. The assumed interior’s dimensions were: 3x6m, ‘pore’ element’s width – open: 0.10m (total cluster’s opening: 30% of the façade), - closed: 0.00m. The ‘pore’ element

Figure 5. CFD simulation of responsive building envelope’s ‘pores’ opening performance (a fragment of room with the schematic RBE). The pores open when the temperature in the pointed measurement is (t_i > 22°C) and close when (t_i ≤ 18°C).
performance was an autonomous agent with the embedded control scenario (2). The element controls the heat flow between mediums with open or close state. The temperature measurement point was done for ‘stomata’ cluster: 5.0m from the cluster and 1.5m form the floor in one local point. The ‘pore’s’ boundary temperature was set: for $t_m = 22^\circ C$; for $t_{\text{exterior}} = 15^\circ C$. The interior air was heated by a circulated heat stream (heat source with power 30W/m$^2$ localized in the middle of the ceiling) with the initial interior’s temperature $t_{\text{interior\_initial}} = 18^\circ C$ on the closed ‘pore’s’ state. The heat source is set – up to turn on when a temperature in the default measurement point is ($t_i < 18^\circ C$) and turn off when ($t_i \geq 23^\circ C$). For the simplification of the simulation process the wall’s thermal conductivity was set to 0 [W/(m$^2$K)].

The simulation showed that the ‘pore’ elements performed synchronously (as a cluster), according to their default pointed temperature measurement: if the temperature ($t_i$) was higher than the boundary temperature ($t_m$) the element changed its geometry (open state) to enable a heat flow (Figure 5).

The study of the CFD simulation showed that the performance of the RBE’s model is able to reduce an interior temperature ($t_i$) to the initial level ($t_{\text{interior\_initial}} = 18^\circ C$) which implicates the ability to control the system’s temperature state in the homeostatic cycle (Figure 6).

8. Conclusion and Further Work

The RBE’s schematic model founded on the material auto-responsiveness presented in this paper reveals potential for further research for the stage of physical implementation. The studies showed that the multi-layered system behaviour of
RBE’s model can be simplified to a set of subsystems that control the ambient interior climate condition autonomously (*material agent or cluster*). Implemented in RBE’s model distributed system of building’s energies control contributes stable and efficient structure’s performance. The next step for the RBE’s model development should be intensive studies on CFD simulation that analyses various scenarios of the building energies environmental exchange (heat, humidity, air flow, etc.) under diverse conditions. Simultaneously the research on physical models should be conducted to compare the results with the computational models and optimize them according to their efficiency and constancy of operation.

**References**


