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Environmental Feedback and Spatial Conditioning

abstract: This paper illustrates responsive systems, which focus on the implementation of multi-objective adaptive design prototypes from sensored environments.

The intention of the work is to investigate multi-objective criteria both as a material system and as a processing system by creating prototypes with structural integrity, where the thermal energy flow through the prototype, to be understood as a membrane, can be controlled and the visual transparency altered.

The work shows performance based feedback systems and physical prototype models driven by information streaming, screening, and application.

1 Introduction

1.1 Dynamic response in architecture

With changing perspectives on the implementation of technology into architecture, an understanding that everything in relation to buildings is dynamic in character and that it therefore is necessary to develop more sustainable, environmentally orientated architectures; we are now looking at the possibilities within responsive structures, responsive environments, and potentially complete responsive architectures.

In this line of research, there is a growing interest to construct physical systems which have the ability to actively respond to local climatic and social environments, allowing inhabitants to experience higher degrees of personal comfort, both physically and mentally. This ability to continuously inform and adjust local climates and their enclosures from both phenomenological and functional perspectives calls for new design approaches that place spatial performance and perceptional issues at the core of design methods and models.

1.2 Responsive architectures

While the above change of perspective catalyses the development of responsive research and practice in architecture, it, in fact, has been conceptually implemented since the 1960s through the ideas of Nicholas Negroponte, investigating the application of cybernetics to architecture through a computational processing unit *(Negroponte, 1975).* Since then, more works have been produced, in both theoretical and design research in a wide spectrum of application. The surface, Aegis Hypo-Surface (2003) by dECOi, shows a dynamic surface structure, with a complex mechanical organisation *(Liu, 2002; Sterk, 2003)*, while Calatrava's simple mechanical operations within the Milwaukee Art Museum (2001) create a remarkable change in both building expression and building porosity (Nichols, 2004). How to work with non-mechanical, steam responsive systems has been illustrated by the Fresh Water Pavillon (1997) by NOX (Spuybroek, 2004) and the Blur Pavillon (2002) by Diller+Scofidio (Sterk, 2003). The projects listed are recognized for their ability to produce aesthetical and phenomenological effects through their responsive behaviours with, perhaps, less emphasis on functional performance.

In pursuing response in relation to environments with the objective of functional performance models, we find the works of ORAMBRA, Office for Robotic Architectural Media & The Bureau for Responsive Architecture, investigating potential material organisations, such as tensegrity structures and system behaviours *(Sterk, 2006).* The work reflects an idea of material optimisation through production techniques and its geometrical organisation with embedded sensors and actuators. A similar functional approach is seen in research conducted by Michael A. Fox, at the Kinetic Design Group, MIT, discussing material systems and system logics *(Fox, 2005)* to clarify and develop knowledge within kinetic systems, methods, and models.

1.3 Research approach to responsive architecture

The research presented here attempts to combine both functional and phenomenological aspects of responsive systems by exploring physical prototypes and processing adaptive behaviors that respond to thermal as well as social parameters. In doing so, the intention is to move from a responsive domain, to a time based adaptive domain, applied through learning algorithms classified as 'intelligent' responsive systems *(Sherbini & Krawczyk, 2004)*.

The intention is to move towards performative multi-objective adaptive architectural models in the field of environmental architecture through mechanical movements with potential energy savings and improved thermal and phenomenological spatial conditions.

2 Performative Responsive Systems

2.1 Framing responsive prototypes

Current architectural applications illustrate various approaches to responsive systems, its architectural scale, and its implementation as an embedded, deployable, or complete system *(Fox, 2005)*. Within the latter, the response is visible in the way a given architecture is transforming itself. An indication of design intention can be observed in the above mentioned examples, where one can see responsive architectures applied as an element to an existing formal language, as is the case with the Milwaukee

Art Museum, or with the intention to completely alter the understanding and immediate function of the building's appearance and expression, as is the case with the Blur Pavillon 'dissolving' into a cloud.

A possibility for complete transformation seems logically to be the most effective and holistic path as a performative responsive strategy to any environmental alteration. A complete transformation is however, contrary to the Blur Pavillon, in need of a control system which precisely regulates environmental conditions according to sensor feedback and performance benchmarks, if aimed at being a functional application to architecture beyond the aesthetical qualities.

A transformation, which ultimately alters the expression of the building, is naturally a complicated undertaking as it will need to be the very building itself that transforms. Such buildings becomes an almost unpredictably complex organisation of material elements if approached through a mechanistic system, as seen with the Divertimento project, by ORAMBRA in 2005 *(Sterk, 2006)* or the Hybgrid (2004) by Felipe and Truco, which through local actuations achieve desired forms *(Felipe & Truco, 2006)*.

Building envelopes functions clearly to separate the external and the internal environment as a crucial part in regulating environmental conditions. However, when becoming very large envelopes, and thus framing large spaces, it becomes increasingly difficult to regulate locally, as microclimates will merge within the internal enveloped environment, like cold and warm water merging into a new mixed temperature within a glass.

The research presented here takes the less complete architectural approach of merely constructing experimental prototype structures and systems in order to explore the modulation between two defined environments.

2.2 Understanding spatial environments

With the aim of searching systems and material organisations for modulating spatial environments which have the ability to both improve thermal functionalities and social parameters, an understanding of the environments must be created. Thus, technical and conceptual/ perceptual understandings must be determined.

Technically, a system must understand its environment through sensors, involving a series of electronic elements with explicit functionalities in the same way as a light sensor only understands light levels etc.

Conceptually, the designer is in need of understanding spatial parameters and their effects, such as light and shade relations, spatial enclosure, system-human interactivity, user motions etc. to implement this into the sensing system in order to activate and contextualise the spatial awareness created.

2.3 Negotiation

Those conceptual aspects create a series of design and operational objectives. As for instance the desire to affect the way people move within a space or how they are visually oriented in certain directions through the responsive system. On a more functional level, one might want to thermally cool an environment to improve the user's productivity level, based upon studies of activity in relation to temperature data.

The negotiation of physically measurable elements through electronic sensors are thus turned into conceptual elements which introduce a sort of meta-responsive-design inserting a hierarchical structure in order to fulfill more objectives than 'simple' thermal regulation, such as a radiator.

In effect, this means that the double objectives, thermal and social, unfold unto a series of sub-objectives determined by spatial strategies by the designer through computational negotiation of information streaming and screening.

3 Information Flow

3.1 Information understanding

Reception, organisation, and distribution of information are in many ways similar to the way nature uses sensing mechanisms and actuating mechanisms as seen within the Venus flytrap responding to stimulation with the objective of capturing insects *(Darwin, 1875)(Forterre, 2004).* In electronics, it is as described above, broken into a sensing element (electronic sensor), a processing unit (computer or microcontroller), and an actuating element (typically being a rotational motor, linear piston or linear 'muscle'). Equal to sensors being affected by the designers objectives, are actuators affected in their functioning by properties, via actuation speed, intensity, duration etc.

Information is thus seen as a source, which should be used subjectively in order to reach multi-objective answers by asking—what are the preferred holistic responses to a dynamic environment, rather than a singular regulation to a singular objective question.

3.2 Feedback and hierarchies

With multiple sensors, as shown in the diagram (Figure 1), a screening of the streamed information is applied in the models through hierarchical arrangements within the processing unit, which according to environmental strategies, transfer and transform information. In doing so, actuation is activated, which modulates the spatial environments and potentially the behaviour of the users. The modulation is registered by the sensors, closing the continuous feedback loop towards constant responsive environments.

By using a real time continuous feedback between environment and model, the research strives to obtain a performance-based, form-finding system as defined by Oxman *(Oxman, 2009)* but as a post-optimisation to the environment through dynamic formations.

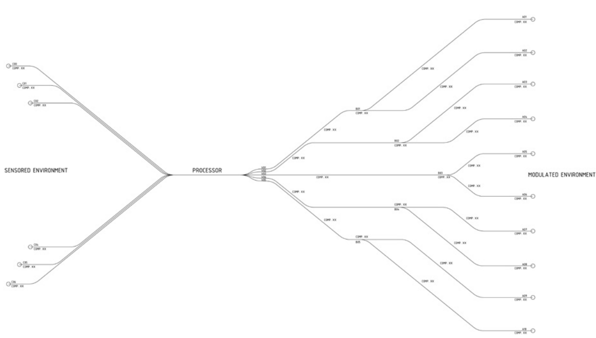

Fig. 1. The diagrammatic representation illustrates the sensored information funnel into the processor and the branching actuations.

4 Adaptation

In this pursuit, the research extends concepts of adaptation beyond initial descriptive response rules, by applying a calibrating algorithm. This creates adaptive robustness within the developed responsive prototypes. The application of strategies of location and adaptation moves the behavioural information processing from a position of simple regulation, that of a thermostat to that of a Homeostat *(Cariani, 2008).* The Homeostat is a simple adaptive system that gives the internal processing logic the ability to construct new behavioural patterns from various locations and thus optimise its performance according to different environmental information patterns than it initially was designed for.

5 Experimental prototypes

5.1 Test platform

Test prototypes illustrated below are selected from an intensive workshop, which examines the idea of the above discourse in responsive architecture by investigating the informational processing systems, material properties, and environmental responsive strategies. People from architectural, engineering, and media technology were put together in cross-disciplinary groups in order to amplify the knowledge field and thus the creation of responsive structures and systems.

5.2 Areas of investigation

As recognised by many practitioners and researchers working with dynamic structures, are many factors necessary to be resolved simultaneously. This is valid in structural elements that are measured against material properties, material organisation, material production, structural integrity, flexibility, kinetic assembly, kinetic movements and force transfer in joints to name just a few. In developing responsive systems a highly integrated process of interlocking relations emerge, as parts only can be applied if thought in the way of the functionality of the whole system.

Some influencing factors in the organisation of dynamic material systems and dynamic behavioural systems are listed here.

- Modularity of parts (Production methods, material use, re-fit elements)
- Transfer of forces through joints (Force distribution through moving joint)
- Material properties (anisotropic/isotropic, elastic/plastic etc.)
- Processing unit (Physical boundary conditions, movement optimisation, adaptation)
- Assembly logic (Linkages, fast-fitting, reassembly, transportation)
- Environmental Strategy (Daylight, ventilation, radiation, temperature, humidity, precipitation)
- Kinetic strategy (Linkages, movement transformation, amplification, expression)
- Surface strategy (Directing energy, absorbing energy, releasing energy)
- Actuation strategy (Movement directions, speed, amplifications, rotational or linear)
- Sensing strategy (Location, sensitivity, shielding, direction)
- Aesthetics (Expression, perception, understanding, interaction)

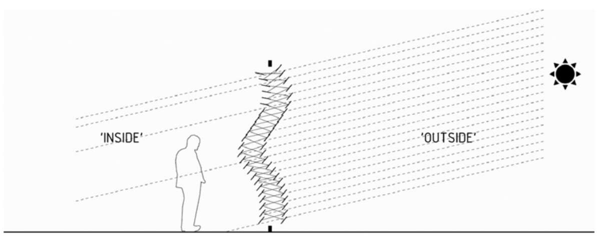

Fig. 2. Physical environments

Fig. 3. Prototype 1 with rotational servomotors and actuated discs

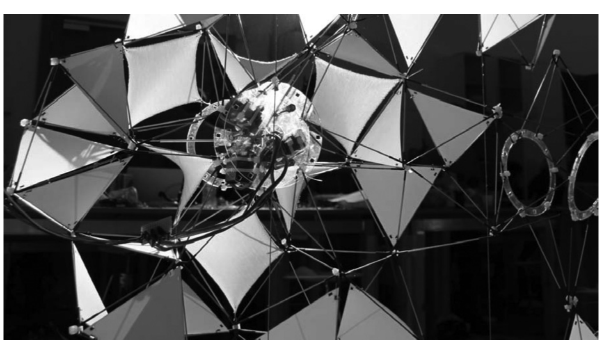

Fig. 4. Prototype 1 with surface implementations

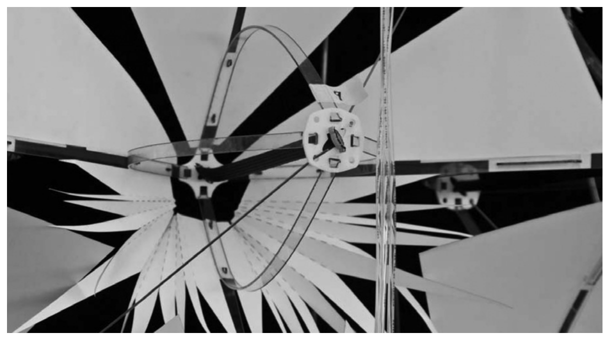

Fig. 5. Prototype 2 with linear actuated air muscles

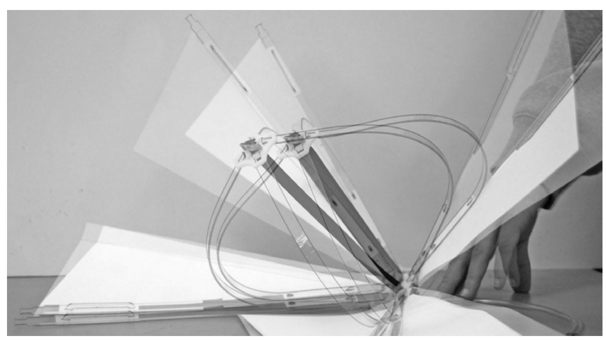

Fig. 6. Prototype 2 with surface alterations according to local alterations

Fig. 7. Prototype 3 with air muscles actuation creating surface contraction

5.3 Prototypes

All prototypes are placed in a way that separates/ connects two different environments (Figure 2). The informational flow of the prototypes are illustrated in Fugure 1. The digram illustrates the flow of information and the hardware components used: sensors for light, temperature and motion; an Arduino microcontroller for processing responsive behaviours in relation to environmental strategies and adaptation to location; and lastly servomotors, air pistons, and air muscles for actuations. The prototypes are described through a) the general concept and b) the responsive behaviours.

Prototype 1

General concept

Two discs with three rotational servomotors connecting them construct the core movement functionality. By rotating the three 'arms' attached to the discs through the servomotor, full control of angling between the discs are made. The discs extend through a triangulated grid to other discs, which as a joint system alter the global configuration of the structure.

Responsive behaviours

By changing the discs placements a regional area of the structure will create a convex/ concave formation, which slightly alters the local surface orientations to change the shade/ light penetration of the structure. Additionally, this will create a global formation of the model stretching into either of the two environments it is connected to.

Model 2

General concept

A component system is developed, which through a linear air-muscles actuation, alters the components geometrical organisation, with subsequent controlled movement of the neighbouring components. Material parts are organised as an interlocking assembly kept together by the material properties and the applied actuating force.

Responsive behaviours

By contracting a series of components, by pneumatic pressure, the global form creates a controlled convex or concave form to either of the environments to extend the exposed surface area and to simultaneously create porosity through the structure by 'unfolding' the component.

Prototype 3

General concept

A scissor grid serves as the structural organisation, with an implemented surface folded to follow the grid, which is actuated by pneumatic air-muscles. In contraction of several muscles, the grid compresses and the structural surface alters in density by the moving structure and by the changing folding and unfolding surface elements.

Responsive behaviours

The prototype attempts to construct a dynamic densification of the structural elements and applied surfaces to precisely adjust the penetration of light through the structure. In doing so, the surface becomes a pixilated organisation of small open/ closed components.

Prototype 4

General concept

A tetrahedron based component structure is developed based upon a complex modular material assembly to construct triangular rigid forms, while maintaining flexibility within the structure. By changing the relation between the tetrahedral organisation are alterations in the general form and porosity created based upon both rotational actuation from servomotors and linear actuation from air-muscles.

Responsive behaviours

By altering the density of the tetrahedra components and internal surface restructuring surfaces are created. This is partly done by contraction of the system as a whole and partly by rotating the system in relation to sensored information in order to construct various visual connections through the structure.

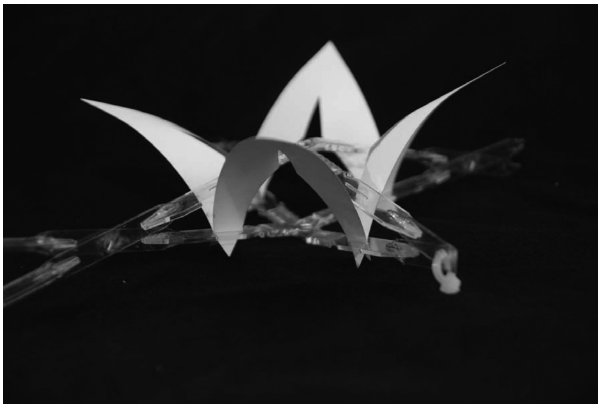

Fig. 8. Prototype 3 with surface expansion

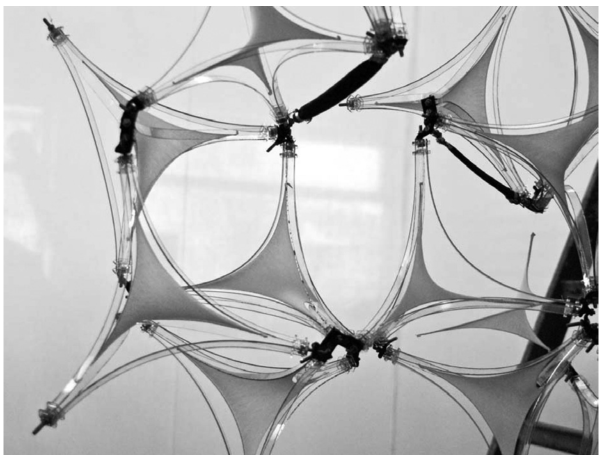

Fig. 9. Prototype 4 with linear cross component air muscles

Fig. 10. Prototype 4 with material assembly logic in joints

6 Conclusions

From experimenting with both processing algorithmic structures and material kinetic structures, it is evident that simple systems serve as more flexible, adaptable and robust organisations. A well-working performative processing system cannot perform without an equally agile and well-built material system. Focus to material systems supporting dynamic models, is thereby to be further explored in future works.

When applying multiple input information flows, funneled to responsive action via a complex adaptive algorithm to a series of actuators, a great versatility in response is constructed. However, simultaneously, is the danger of blurred performative processes equally present. Processing systems with simple adaptive rules tend to perform rather advanced operational functions, which also allow an easier understanding of the systems logic when implemented.

The research thereby suggests to maintain simple organisations as open systems, to which differentiated expression and dynamic readings of the structure will be created from the changing climatic and occupancy patterns.

The continuous research thus attempts to construct simpler, even more defined performative methods and prototypes, whose objectives remain to explore material, structural, phenomenological social and functional environmental aspects.

In doing so, future prototypes and models are developed within a described operational framework for response architectural typologies, with focus on three typologies; 'Discrete In-Direct Response', 'Hierarchical In-Direct Response' and 'Coupled In-Direct Response'. These approaches are all based upon separating the material system into a primary and a secondary system.

References

Arthur, W.B., & Durlauf, S.N. *(1997). Introduction, Process and emergence in the economy, The Economy as an Evolving Complex System II. Addison-Wesley.*

Arthur, W.B. *(1999). Complexity and the economy. Science, Vol. 284 (2).*

Cariani, P. *(2008). The homeostat as embodiment of adaptive control. International Journal of General Systems, Vol. 38(2), 139-154.*

Darwin, C. *(1875). Insectivorous plants, Murray, London .*

Forterre, Y. *(2004). Mechanics of the venus flytrap closure, XXI ICTAM, 15.21 August 2004, Warsaw, Poland.*

Fox, M. *Beyond Kinetics, Kinetic Design Group, MIT.*

Fox, M. *Intelligent Kinetic Systems, Kinetic Design Group, MIT.*

Liu, YT. *(2001). Defining Digital Architecture, Birkhäuser Basel; 1 edition.*

Negroponte, N. *(1975). Soft architecture machines, 'Intentionalities" 60-63 'Computer Aided Participatory Design,' 102-123, Soft Architecture Machines, Cambridge: MIT Press.*

Nichols, A. *(2004). Example Case Study: Milwaukee Art Museum, ARCH 631*

Oxman, R. *(2009). Performance based design: Current practices and research issues. International Journal of Computing, Vol. 06 (1).*

Sherbini, K & Krawczyk, R. *(2004). Overview of intelligent architecture, 1st ASCAAD International Conference, e-Design in Architecture KFUPM, Dhahran, Saudi Arabia.*

Spuybroek, L. *(2004) Machining architecture, Thames & Hudson.*

Sterk, T. *(2003). Using actuated tensegrity structures to produce a responsive architecture, ACADIA Connecting Crossroads of Digital Discourse Proc.*

Sterk, T. *(2006). CAAD for responsive architecture, Form Z – Joint Study Report 2005-2006*

Sterk, T. *(2006). Shape control in responsive architectural strcuctures – Current*
Reasons & Challenges, 4th World Conference on Structural Control and Monitoring

Truco, J. & Felipe, S. *(2006). HybgridA, responsive architectures – Subtle tecnologies, Riverside Architectural Press*