Responsive Systems and Surfaces in Architecture – Design and Challenges

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1 ABSTRACT

In the last two decades, the impact of digital technologies has dramatically changed the way of thinking in architecture. Following the overall development of digital media and computation, the process of generating forms has become more automated, with the use of algorithms and scripts. Moreover, computational design approach created new groundwork for the new, time-depended systems in architecture – responsive facades and structures. Responsive systems react to the surrounding by changing its surface in order to adapt the architectural form according to predefined influences. An example of such design approach are media facades, artistic based installations etc.

Challenges are mainly oriented towards forming a user-architecture connection. Such bonds are formed between sensors and actuators, via programming board and language. Adaptive qualities of such systems are based on sustainability principles as well, utilizing alternative energy sources in situ. In this paper, design and challenges of responsive systems are analyzed, evaluated and applied on a case study in particular.

Simultaneous use of above approaches is applied in the design of the structure that is located in Novi Sad's central core. The structure is optimized to use the maximum input of solar energy and adapt to it, while limiting the spatial openness of public squares and increasing human interaction. Resulting design is presented in this paper. Further exploration of responsive generative systems can contribute to financial benefit and better quality of given architectural solutions in the near future.

2 INTRODUCTION

Architecture has always been dependent on the medium and drawing tools in order to facilitate projects. Since the early ages and throughout the history, paper and pen were mostly used to upgrade and express ideas in architectural discourse. However, in the last two decades, the impact digital technologies had, in reference to the form generation as well as design tools, considerably changed the way of thinking in architecture.

Computation control has three levels.[1] The first one is oriented towards imitating the moves and actions architects make, in order to speed up the design process and provide a certain degree of automation. Later on, as the technology advanced more, so did the thinking process. Next step implied use of computational tools not just for drawing in computer aided design programs, but also for making connections between geometrical entities themselves. This design process, parametric modeling, insured the development and further implementation of automation in architectural practice. Also, non geometrical information was assigned to geometrical entities, further defining their qualities as parameters, used in BIM technologies.

The greatest degree of computational control, however, was achieved through algorithmic modeling, as the next step in the architectural design development. With use of algorithms and scripts, the automation process was ascended to a higher level, changing the way architects were thought to perceive space and design itself. By abstracting traditional design tools and actions and focusing mainly on the logic of the design process itself, emphasis was shifted towards programming languages as primary design tools. The spatial

[1] Kotnik, T., Algorithmic Architecture, Master thesis, ETH, Zurich, 2006

representation of forms was thus changed from geometrical to algorithmic, offering new ways of exploring architectural form. [2]

At the same time, whilst upgrading the computational process altogether, implementation of other sciences and CGI (Computer Generated Imagery) software introduced time as a new dimension in architectural design process. Use of time was expressed through series of form iterations.[3] That meant that architects were actually choosing the best form as a result of algorithm use, thus finding the form from a number of given resulting solutions and not making the form by drawing.[4] Although, such approach gave vast opportunities for form exploration, it left the finished projects inert and often alienated from its surrounding as well as the people. However, it did set groundwork for the new time dependent architecture. No matter which computational degree of control was used, such forms or structures, as finished projects, were optimized to adapt and interact with their surroundings.[5] Since they adapt to changes in their surrounding and respond to a certain influence, they are called adaptive or responsive systems and surfaces. This can be considered as an answer to the question Cedric Price posed in 1960's – "What if a building or space could be constantly generated and regenerated?" [6]

This paper will focus on the design and challenges of responsive systems, and the classification of different input and output information. Also, it will implement the topic of sustainable architecture and use of alternative energy sources used in powering such surfaces, leaving them completely self dependent and self organized.

3 CONCEPT OF RESPONSIVE SYSTEMS

Responsive systems are a fairly new approach in architectural design. The significance they impose on the architectural discourse is centered on responsiveness in real time. In a way, they mimic human behavior, by reacting to outer influences and adjusting themselves according to a predetermined set of rules. Before the technological advancements and the digital era, responsive surfaces could only be comprehended via analog approach. A fair example of an analog approach in the digital era is a part of Juan Subercaseaux's Master of Architecture Dissertation, done at Emergent Technologies and Design, AA School of Architecture, London in 2006. By using a moisture sensitive sensor, the adaptive unit, window based, can open and close, depending on the precipitation. This component changes the porosity of the building envelope without any electronic or mechanical control. By using CMC gel, in the actuator, the responsive system is able to function like an analog system. However, a better degree of interactivity could be achieved using digital components and programming languages. Further expansion of computation process can advance architectural design by automating adaptive qualities to suit variable factors.

"This new research proceeds from the recognition of architectural constructions not as singular and fixed bodies, but as complex metabolic and intelligent material systems that have a finite lifespan, that are interlinked as part of the environment of other active systems, and that can be symbiotically related to the flow of energy and material in the systems and processes of the natural world."[7] The basic and most common architectural element used for applying responsive systems on, is a facade. The term media facade is in use today in defining such systems. The most common example found today is media facades which are illuminated at night, creating a particular light show or displaying information. Regardless of the approach in particular, these systems are all dependent on two things:

- Physical components that make them adapt and respond
- Computer programs that provide information on what to do

[2] Tepavcević, B., Influence of Geometrical Representation on Contemporary Architecture, Doctoral Dissertation, University of Novi Sad, Faculty of Technical Sciences, Novi Sad, 2010
[3] Fasoulaki, E.: Integrated Design: A Generative Multi-Performative Design Approach, Master thesis, MIT, 2008
[4] Hensel, M., Menges, A., Weinstock, M., Emergent Technologies and Design, Towards a Biological Paradigm for Architecture, 2010
[5] Fox, M., Sustainable Applications of Intelligent Kinetic Systems, Massachusetts Institute of Technology, Department of Architecture, Cambridge, MA
[6] Quoted by Bullivant, L.: Introduction. In: Architectural Design, 4D Space, Interactive Architecture, Volume 75, No 1, Jan/Feb 2005, page 5
[7] Emergent Technologies and Design, page 20

This logic, embedded in the responsive system design, has certain requirements and predispositions that will be evaluated in the following chapters.

3.1 Physical components of responsive systems

All the hardware and devices required for generating responsive systems can be defined as physical components. Despite the diversity in function, all hardware components have the same aim, which is to generate a valid interactive system. Responsive systems function by receiving outer influences, both human and environmental, through sensors. Those influences get changed into information, computer units can understand, called input information. Once information is introduced into a computer, specifically the programming boards, a predetermined set of rules converts the information into desired output information. This kind of information is necessary for the system to respond to its surroundings via actuators. The general idea behind responsive systems is a circular, repetitive loop – a strain where one action evokes a reaction, which in turn starts the whole process again, similar to a repetitive cause and effect phenomena. Otherwise, such systems would merely react and not interact, as they should. An insight into each of these requirements will be explained in the following chapters.

3.1.1 Input information

The first step in designing any responsive system is establishing an influence it responds to. Those can differ, but they can generally be classified as human and environmental influences. Importance lays in recognition of the diversity that exists and the applicability in architectural practice. Since there are a great number of phenomena in nature, influences responsive systems can react to can be extended to meet those demands, by using sensors, limited to its interactivity and practical exploitation. Sensors are devices capable of receiving any number of different influences, such as solar insolation, human touch, air movement, temperature change etc. They measure the amount of any given phenomena, thus converting it into numeric values that can be computed. This information is called input information and represents the initial factor in the computing process. Influences that can be used for interactive responsive systems in architecture are presented in Figure 1. Most of them are similar to human senses, such as touch, light, movement, while others are natural phenomena that are immeasurable by human senses - weather changes, electromagnetic field, invisible light detection etc.

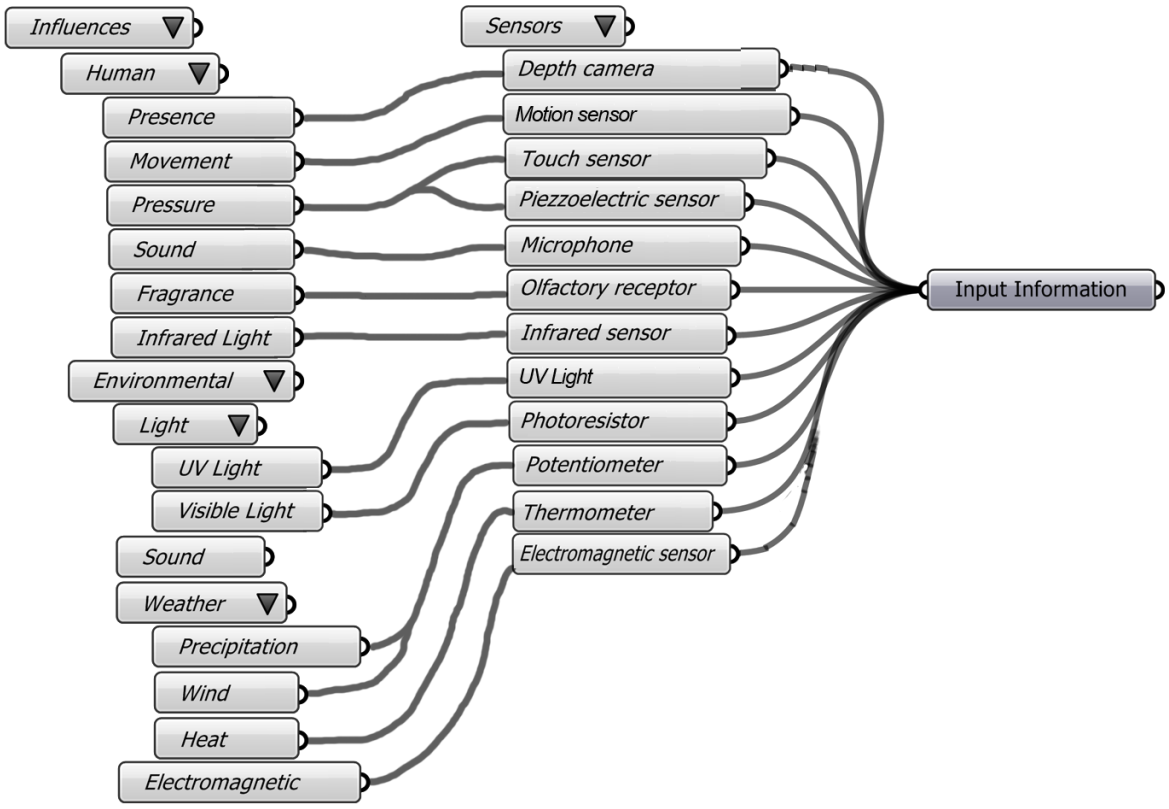

Fig. 1: Input Information Diagram.

A significant amount of designs are renown by Haque Design and Research, a centre, specializing in the design and research of interactive architecture systems. They thrive on dynamics and responsiveness, making their projects an excellent groundwork to build upon. The project which uses a most unusual approach and sensors altogether is Usman Haque's Scents of Space, where the designer says "that smell can be used spatially to create fragrance collages that form soft zones and boundaries that are configurable." Actually, by using an array of fans and diffusion screens, a continuous laminar airflow can be generated, making parts of the space selectively scented. Therefore, influence of the scented airflow and use of fragrance and scent sensors, along with illumination created a unique interactive system.

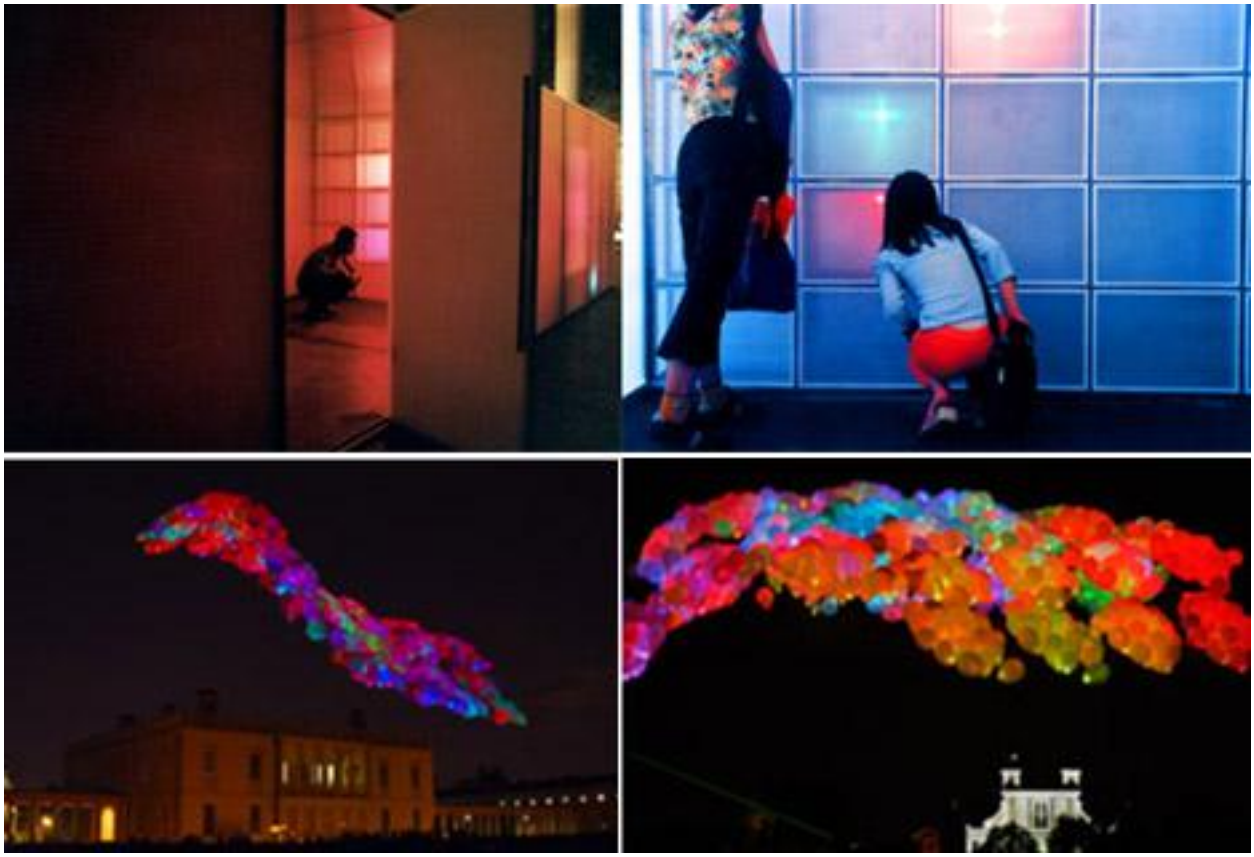

Fig. 2: Haque Design and Research examples. Scents of Space on the upper, Sky Ear bellow.

Another design system, entitled Sky Ear, also by Usman Haque, utilizes electromagnetic sensors in helium filled balloons, alongside mobile phones, which trigger the LED , illuminating the balloons in different colors. The design is not an issue, it's the experience of it that matters. The whole phenomenon is similar to northern lights, where people are more than users – they are participants. By using their own mobile phones, they can call the phones in the installation, and listen to the electromagnetic sound of the sky. However, since their call is influencing the local electromagnetic field, it is changing the color of the balloon cloud itself, making the whole thing interactive. To achieve an immense effect, the process of information has to be fast and accurate, which is handled by programming boards.

3.1.2 Programming boards

The main unit of any computer is its programming board. Since it converts all the data and sends out information on executing actions, it is the essential component of any responsive system. For the purposes of this paper, an exemplary programming board, along with accompanying software, will be used to explain the conversion process – an Arduino board.

Arduino board is a well known, open-source, programming board available on the market. Open source implies that every piece of information regarding it is free to explore and use, regardless if it is scripts, board schematics or anything else. The importance lays in upgrading and improving existing components through a distribution network online. Amongst all components, the most important are pins, which represent ports where input information is sent to. Arduino board has several analog and digital pins, which provide a fair

amount of information to be used. Analog pins have a range of 0 to 1023 or 2^{10} variations, whereas digital pins have only two variations, 0 and 1. Range can be perceived as resolution.

The wider the range, the finer the transition and resolution is. However, many designers find that low resolution contributes to the design process as well to the experience, in a fair manner. An example of a low resolution system is Ron Arad's Millennium House project, including a living room and a family dining room. His contribution is seen in the programmable floor, "that can be instructed to move in a certain pattern or frozen into a given 'landscape'. Talking of the way things operate in the interactive business, Arad observes that 'we are always fighting to increase the resolution, but sometimes you discover the beauty of low-res'."[8] Sensitivity is an important factor when choosing and implementing a certain sensor in the responsive system. In order to properly receive data, its range has to match the one needed for a certain responsive system. Also, the minimum requirement needed to start the sensing process needs to be calibrated in the right way. Adequate connection between the sensors and the board also depends on the speed of response, operating life, cost, size, weight, etc which are not primary in this analysis.

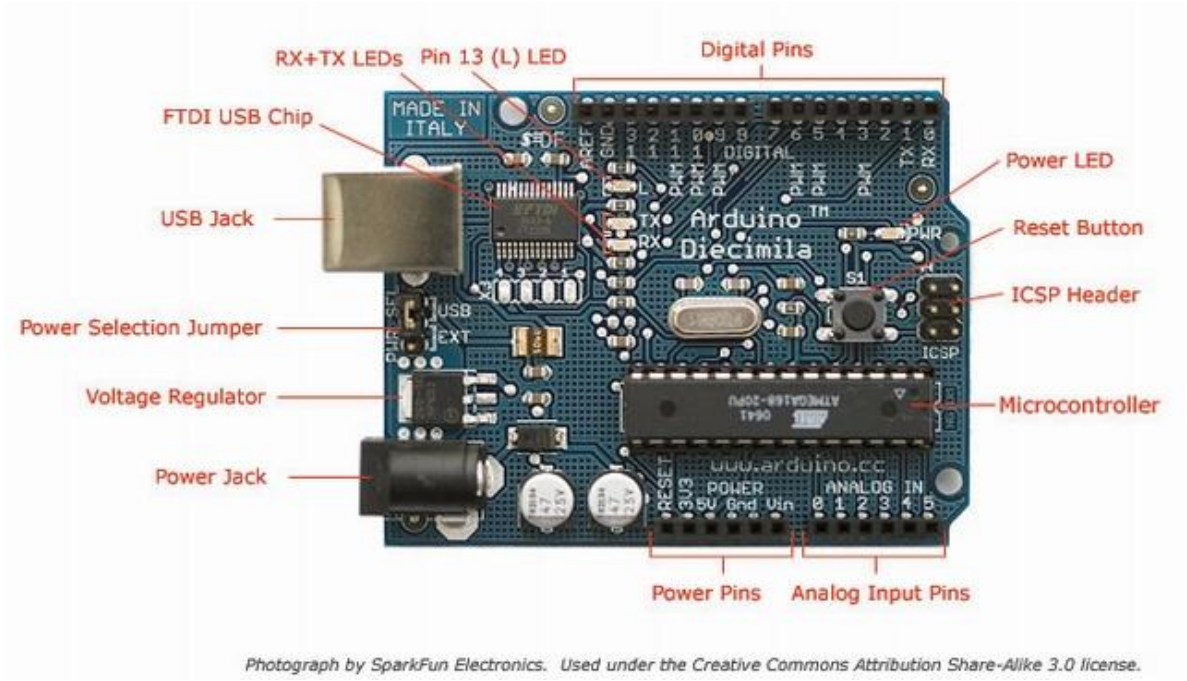

Fig. 3: Arduino Programming Board. Review of Arduino components.

3.1.3 Output Information

Once the numerical input data has been processed and computed into information that is usable as a responsive, output information, mostly medium resolution numerical data, it is sent to actuators. Output numerical data, for example, ranges from 0 to 179 for servo motors, 0 to 255 for DC motors, or 0 and 1 as digital outputs. Actuators are devices capable of receiving information and acting upon them, either by moving, illuminating, playing audio, etc. There are an infinite number of combinations possible for intertwining sensors and actuators as a responsive system. However, it is the right combination and interrelating feedback that the focus should be on. For instance, the project Electro Clips, Teater am Turm in Frankfurt, utilized changes in light projection on the sensors in the room with audio feedback. A single man, dancing in such space, can trigger multiple sensors and evoke certain predetermined musical patterns to play, as if conducting a virtual orchestra.

Feedback has to active and suit human physiology and senses. In reference to this, the whole range of human senses, excluding taste, can be applied, from visual pictures, audio, touch, and even smell. Most importantly, responsive systems can make a feedback in biological way as well. The best project that demonstrates the implementation of architecture and an actual human adaptation is the Hormonorium, by Philippe Rahm, presented at the 8th Biennale in Venice in 2002.

[8] Arad, R., There Has Always Been a Connection Between Design and Technology, Architectural Design, 4D Space, Interactive Architecture, Vol 75, page 60

Hormonorium incorporates several key aspects that make it a unique biological adaptation system. It's important to grasp the concept of using body adaptation through hormone secretion as a responsive feedback. First, the sun light imitation, with both UV-A and UV-B light, positioned in the false floor, is impossible to avoid and thus influences awareness and mood. Second, the elevated nitrogen levels and lowered oxygen levels, influence people's behavior, from confusion to euphoria, while changing the blood saturation as well. The interactivity level of this project may be classified as minimum. Nevertheless, its concept is applicable and notable for future study and application in responsive systems.

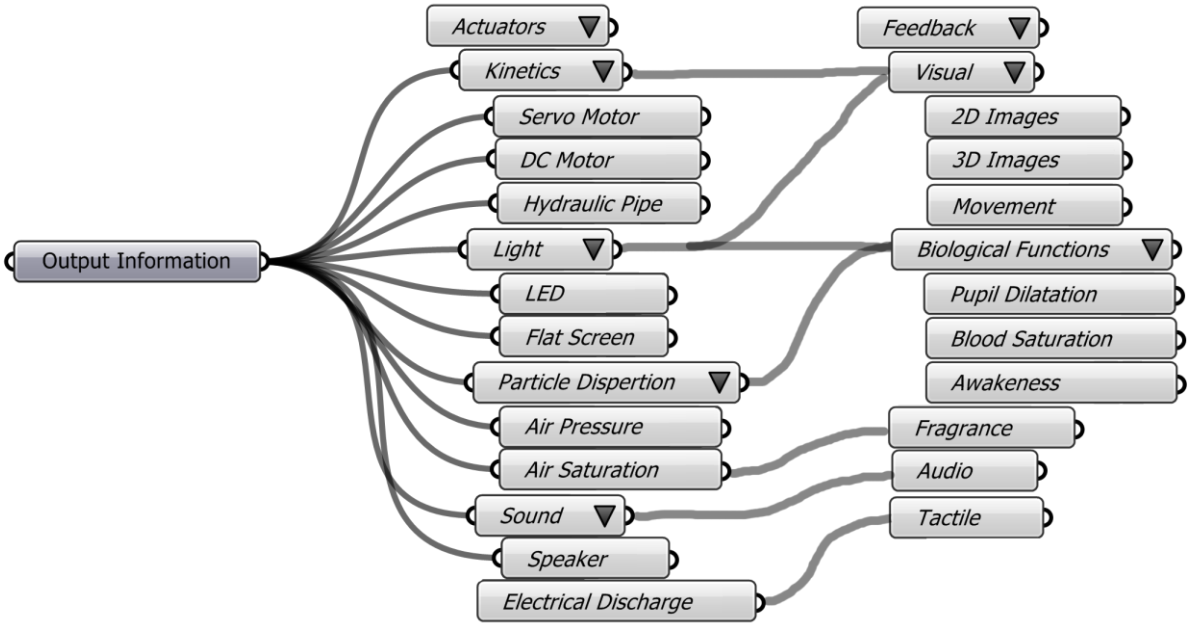

Fig. 4: Output Information Diagram.

Amongst all the responsive system projects, most of them rely on illumination and kinetics as actuator systems in order to produce the most appealing feedback. Human senses react to quick motion better, since it sharpens the reflexes and exerts euphoria. Actions like changing pictures, silhouettes, colors or the entire topography of a surface in 3D is more interesting to cope with than slow reacting systems. An example of a real time responsive system is dECOi's Aegis Hyposurfaces. It makes use of many sensors, sound, presence, light and movement to evoke a single reaction – the change in the surface topography. It also stands as a result of using kinetics in architecture.

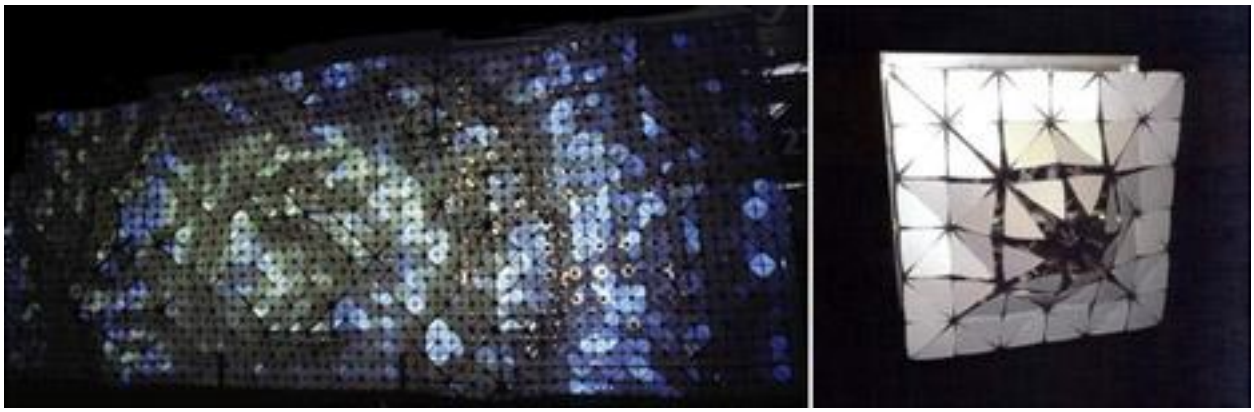

Fig. 5: Aegis Hyposurfaces, dECOi. Example of a real time kinetic responsive system

"Kinetics will be defined generally as either transformable objects that dynamically occupy predefined physical space, or moving physical objects that can share a common physical space to create adaptable spatial configurations. Robert Kronnenberg[9] defines such systems as buildings or building components with variable mobility, location and/or geometry."[10] The concept of responsive system thus has the ability to

[9] Kronenberg, R., Portable Architecture, Architectural Press, Oxford, 1996
[10] Fox, M., Kemp, M., Interactive Architecture, Princeton Architectural Press, New York, 2009, page 20

ascend to adaptive systems using kinetics. Adaption process guarantees possibilities that can be utilized on several levels. "We break down the application of kinetics into four general categories of use in architectural environments: spatial optimization, multifunction design, contextual adaptability and mobility."[11] The most relevant is contextual adaptability. By using dynamical components, a single architectural installation can have changeable form, depending on the influence at any given time, which can be seen on the example above. Multifunction design is a concept used on the Media House project by Guallart Architects. Not going into further details, the house was perceived as a computer, as a network itself. It was comprised of wooden/aluminum railings, which incorporated data and network flow through it. It generated a slender geodesic form, whose segments had opportunity to be multifunctional and inherit data from other parts of the house.

Responsive interactive systems are creating new ground for researching architectural form, since it can incorporate aesthetics and contemporary massive communication systems into one. "The interactivity incorporated within the physical nature of buildings means working at a new level of architectural complexity. But the greatest challenge of all is not scientific, nor technological. And neither is it even functional. No, the true challenge is, as always, of an aesthetic nature."[12] Responsive systems are a stepping stone to self-organized systems. However, to make them self-sustainable as well, architecture has to look into alternative energy sources and implementation of sustainability principles.

3.2 Computer programs

The Arduino board is unable to function without software. This particular software is based on Processing platform, and uses C/C++ programming language, which holds and defines a set of rules, needed for the computation process to take place.[13] It is determined by two functions:

- Setup() - a function, which is executed once at the beginning of the program and which initiates all the settings
- Loop() – a function which recursively repeats itself, until a predetermined criteria is met or until the board is switched off

The most important factor here is the loop function which provides the essence of the responsive systems concept, feeding the system information as a recursive process. The computation process takes place, after the data has been gathered. As a result, numerical data is generated and processed further to the end component of any responsive system, an actuator.

4 SUSTAINABILITY PRINCIPLES AND ALTERNATIVE ENERGY SOURCES

The demand for energy has always been increasing. Energy represents the sole necessity and an imperative in modern day architecture and construction. The technological advancements have not only benefited the form generation in CAD software, but also innovations in alternative energy sources and its exploitation. A lot of natural phenomena can find its use as an alternative energy source, provided that it can be converted as usable energy – mostly electric.

Sun is the most affordable alternative energy source, since it is present everywhere. Depending on the insolation and the sloping angle of the Sun, by utilizing solar panels, it's possible to harvest energy from any place on Earth, using photovoltaic effect. Wind turbines exert a lot of space, but they produce plenty of energy, depending on size. Since urban environments are small, the energy is produced accordingly. Waves can be used as excellent energy sources, provided the proximity of seas and oceans or any kind of water or precipitation, for that matter, can be used to produce energy. Applying piezoelectric effect, it's possible to harvest energy even by walking. A public space tiled with such technology could power itself. Geothermal sources, located all over the world, can provide much more energy from one location than all other alternative energy sources, since it is based on the preheated material, whose qualities can be utilized appropriately.

Sustainability principles are implemented in contemporary architectural design. However, they wield a state of stasis. Therefore, it is imperative to form a synthesis between architectural design, structural integrity and

[11] Interactive Architecture, page 31
[12] Architectural Design, page 27
[13] Raes, C., Fry, B., Processing: A Programming Handbook for Visual Designers and Artists, MIT Press, 2007

adaptive qualities of sustainable principles. Implementation of these aspects into requirements of modern society is sure to yield improvement in the quality of life and built environment. Such an approach is applied on a case study, presented in the next chapter.

5 SUSTAINABILITY BASED INTERACTIVE RESPONSIVE SYSTEM

We approach this problem by focusing on responsive systems in terms of in situ adaptability. The location is a large public square, Liberty Square, in Novi Sad, the centre of northern part of Serbia. We base the responsive system on variations in light emission and photon trajectory. Using kinetics, the whole surface is optimized to respond to perpetual variation in light exposure. The approach consists of three stages:

- Utilization of simulation analysis tools to determine insolation and find a suitable location
- Form adaptation by means of algorithmic representation of space and spatial implementation
- Generation of kinetic actuator network, based on solar panels and servo motors

5.1 Analysis

Autodesk Ecotect insolation analysis tool was utilized in order to procure a viable representation of surfaces exposed to light in a predetermined analysis grid. We examine the issue of exposure to Sunlight by observing two distinct extremes – the summer and winter solstice.[14]

During the summer solstice, the solar elevation angle is blunt, therefore exposing the majority of the public square's surface to direct Sunlight for a greater duration of day. However, on the winter solstice, the solar elevation angle changes to a sharp angle. In conjunction with the square's enclosing elevations height, most of the surface remains shadowed. By overlapping these analysis grids, we are able to settle on the optimal location for this specific responsive system.

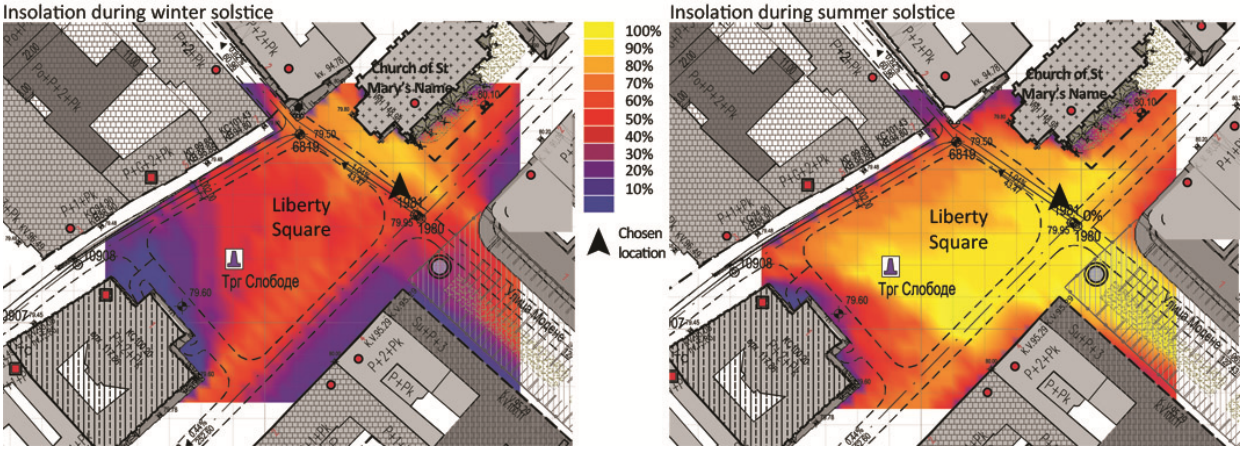

Fig. 6: Insolation Analysis. The figure dispalys solar insolation in winter and summer solstice, on the left and right, respectively

5.2 Form adaptation and implementation

Given the lack of distinctive spatial boundaries that outline and enclose the chosen location on Liberty Square, our approach tends to solve this issue by generating it artificially. Spaces that are to open negate the visual psychological limitation of the brain to grasp small clusters of visual information at a time. For that reason, we extend the psychological comprehension of Liberty Square's spatial elevations with surfaces, while at the same time creating curiousness and time-lapsed imagery through walking. The end result provided us with the experience of space through time as well.

Algorithmic level of computation allows for programming the form as well as responsive capabilities. In this particular case study, these two aspects are merged into one, in a joined attempt to maximize the input. Form is generated by use of optimization algorithms, to adapt to the Sun's motion throughout the year.[15] The surface is enclosed with solar panels, following the curvature of the form. Solar tracking algorithms based on

[14] Arora, S., Saxena, S., An Evolutionary Architecture: Adapted, interactive, and effectively integrated design, PLEA2009 - The 26th Conference on Passive and Low Energy Architecture, Quebec City, Canada, 2009

[15] Mark, E., Optimizing solar insolation in transformable fabric architecture: A parametric search design process, Automation in Construction, University of Virginia, School of Architecture, United States, 2011

photo-resistors as sensors, control the panels, where perpendicularity to solar rays is obligatory in order to ensure the efficiency of solar energy.[16]

Therefore, the entire surface is flexible.[17] We decided on dual axial tracking, to provide for all input variables and light directions.

Fig. 7: Spatial Implementation. Difference in spatial awareness and comprehension of visual clusters of information between the existing state above, and the proposed state bellow, respectivately

Fig. 8: Time lapsed imagery through walking. An experience of spatial awareness and surface implementation

5.3 Kinetic actuator network

Solar cells are the essential component of any solar panel. In order to transcend the common rigid and opaque solar panel configuration, we decide on transparency as the main forte. By using an orthogonal network of solar cells on the surface of translucent materials, we are able to secure constant energy production, as well as a larger degree of spatial awareness. The responsive system is thus self-organized and self-dependent in terms of energy consumption. The struggles of constructing and designing such systems therefore ease the economical aspect. However, it is important to grasp the ratio of electricity being used to

[16] Landau, C., Optimum Orientation of Solar Panels, MACS Lab, Inc., April 2011
[17] Kronenburg, R., Flexible: Architecture That Responds to Change, Laurence King Publishing Ltd, 2007

respond and the electricity being produced. Responsive system is based on servo motors' motion, which use direct electrical current to align the solar panels. Since solar tracking is a slow process, servo motors needn't be responsive in real time, but calibrated to respond in larger time scales, hourly at best, in order to actually produce more electricity and be self-sustained. Otherwise, if their respond rate is a real time adaptation, more electricity is necessary. Utilization of the later concept can be exploited in nocturnal illumination.

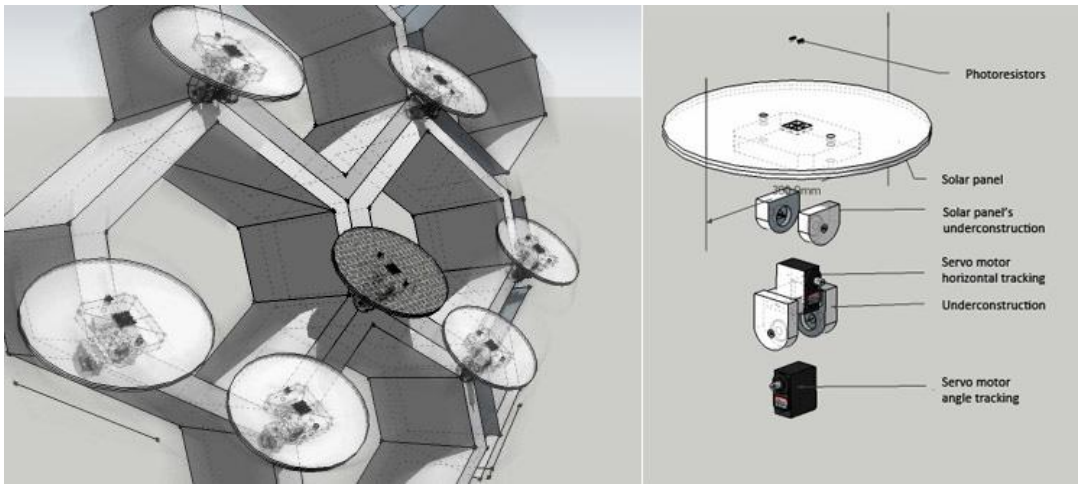

Fig. 9: Solar tracking concept. Part of the responsive surface, with solar panels on the left and a concept of the solar panel on the right. Input is received via photo-resistors and the panels responds via a set of two servo motors

6. CONCLUSION

Architectural practice has always served as a representation of social order in life and scientific advancements. In reference, the contemporary architectural design follows the modern society's thriving on mobile networks and rapid information flow in order to achieve multiple tasks. Utilizing modern technology achievements, the financial and ecological benefits of using algorithmic computational degree of control in both design and exploitation is presented and proved effective. Moreover, such an approach guarantees improvement of architectural solutions in the near future. Classification of different input and output information diagrams presented in this paper serve as a guideline to future design approaches and upgrades. Research and development should be centered on the combination of responsive, adaptive systems and sustainability principles in contemporary architectural discourse. By doing so, the structure doesn't only move, it dynamically adapts to generate the best possible solution in situ, the optimized form.

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