Robotic Prototypes Optimization

Incorporation of optimization procedures in the design process

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Abstract. The use of computer-aided design combined with robotics and evolutionary principles of optimization, during the architectural design process, is discussed in this paper. The research is based on the examples of four case studies out of six projects designed during the Experimental Design Studio: ROBO Studio and a parallel seminar on optimization techniques on Architecture for Society of Knowledge Master course at Warsaw University of Technology, Faculty of Architecture. The project's main goal was to combine robotic prototypes construction with an optimization process executed in parallel within one design procedure. The results of the course and the discussion about the impact of both factors on the architectural design process are presented in this paper.

Keywords. Genetic algorithm; optimization; robotics; Galapagos, Firefly, digital fabrication, design integration, kinetic structures.

INTRODUCTION

Design process has been a subject of study in design methodology and theory for centuries. Whether the designer should rely entirely on his intuition or follow some prescribed way of thinking when creating an artefact or a building was a question raised by many theorists. The concern was also about the coexistence of the object and its’ environment and the influence of one on another. In recent times a question of the role of computers in the design process was added to this discourse. With the rise of cybernetics and robotics in the mid 90’s the connection between the two and architecture was also established. The use of computer-aided design combined with robotics and evolutionary principles of optimization, during the architectural design process, is discussed in this paper. The research is based on the examples of four case studies out of six projects designed during the Experimental Design Studio: ROBO Studio and a parallel seminar on optimization techniques on Architecture for Society of Knowledge Master course at Warsaw University of Technology, Faculty of Architecture. The project’s main goal was to combine robotic prototypes construction with an optimization process executed in parallel within one design procedure. The results of the course and the discussion about the impact of both factors on the architectural design process are presented in this paper.

Designing is a creative, problem-solving process resulting in a ‘form creation’. Project, in order to meet present demands, has to fit the context as good as possible and to remain in “effortless contact or frictionless
coexistence” with it (Alexander p.19). In each design task there are external and internal requirements that has to be met. These are specified by the certain context conditions, formal requirements, functional needs, etc. and these very in amount and quality from one case to the other. Every factor has some influence on the other, they can be in a positive or negative relation with each other. A good design searches for the best fit between all the variables, but - depending on the complexity of the task – usually it is not possible to be solved by the designer in mind. The more factors to be considered the more intuition the designer uses to create a form. Complicated designs like town planning or high-rise buildings are beyond individual’s mind capacity. Because of the constant changes and growing complexity of the design conditions, like environmental, social, technical factors, the information necessary for designers to comprehend is distributed and great in number. Therefore is a need of multidisciplinary design teams or multifaceted project development. This includes introducing experimental techniques into the design process, such as optimization procedures, design simulations, prototype building, digital fabrication, etc.

The idea of a ‘binary code’ representing the form-making process described by Alexander (pp.38-41) implies the possibility of amending the process by the use of computer programming. He characterizes a system, where each of the imagined interconnected lights represents one variable. Every variable can be in just two states: fit or misfit. The system is constantly changing during the design process, when some factors meet the requirements and some still needs correction. A good design is created when the system gains equilibrium, which means that all the variables are in state 0, representing good fit between the form and the context. Balance of system with a great amount of requirements, which influence one another, is almost impossible to achieve. If one variable gains the 0 value, then dependent variables can be affected, thus destabilizing the whole arrangement.

Similar principle underlies the evolutionary algorithms, in which the genotype, responsible for the individual form or behavior, is usually written in a form of a string of values. The process of finding the best possible individual - in a limited time - is performed over a number of generations consisting of a group of individuals. At first random in form and quality in terms of the fitness objective, the individuals evolve towards the best solution.

THE TASK

The Faculty of Architecture in collaboration with the Faculty of Mechatronics at Warsaw University of Technology organized a three-week workshop, during which six groups of students were working on a subject of designing a Recharging Station for Electric Cars. Each group consisted of four students of architecture and one student of mechatronics. Their task was to design a so-called “reCHARGE Station” augmented by the appropriate additional function and with the possibility of adapting to certain external factors. These factors could range from environmental adaptation, interactivity to mobility and reconfiguration. Students were expected to construct a working prototype, which was to incorporate sensors and actuators controlled with the provided Arduino Uno microcontroller board. As a part of the Design Studio, a workshop on interactive design principles with the use of Arduino Boards was conducted. The students were also equipped with the basic knowledge of robotics during the lectures preceding the project.

DESIGN SOLUTIONS

Feasibility of the design ideas to which students came at the beginning of the workshop was tested during the remaining part of it, when the building, programming and testing of robots phase began. The prototypes behaviour and construction were programmed in Firefly and Grasshopper plugins for Rhino software, which then communicated with the Arduino boards. The majority of robots’ structural components were custom made by students and built with the use of digital fabrication tools, such as a laser cutter. Some groups used paper-folding structures for their design realization.
The designs proposed by students included solutions such as:

1. Kinetic canopy over a parking and EV charging station (City Carpet project).
2. Movable city lamp with integrated a charging slot (reCHARGE lamp).
3. Sound-reactive urban landscape (DISCOMOTO project).
4. Installation integrated with municipal charging stations system (Fuzz-ball).
5. Multi-storey car park with kinetic façade system (Robotic Façade).
6. Folding roof over individual charging slot.

Case study 1: reCHARGE lamp
Project’s aim was to adapt existing infrastructures in the city to new functions. Students decided to use an everywhere present street lamp for the purpose of the project. Their new lamp design would combine both functions and have an additional informative layer. The movable biomimetic structure placed at the top of the lamp moves accordingly to the state of its energy supply. Simultaneously with the on-going process of vehicle charging its position will change towards the vertical direction. Achieving the full vertical position will indicate that the car battery is fully charged.
**Case study 2: City Carpet**

Kinetic, performative aspects of design and the principles of robotics are combined together in the City Carpet project. The goal was to design a shelter for Electric Vehicles charging points, that would serve as a roofing and in the same time would create some characteristic environment beneath it. Their aim was also to make a visible representation of EV charging process in the city, and thus promote reducing the carbon dioxide emissions.

“City Carpet” is a modular tessellated structure, which thanks to its customizability could be applied to any plot in the city. At the beginning students were planning to use rigid origami folding surface, but during the design process the idea evolved towards a kinetic fabric based on rigid triangles and articulated nodes. Pillars moving vertically support the whole structure. Several alternative sequences of movement were proposed and programmed in the prototype. The structure in the mock-up is modified on the basis of mechanical movement of pillars controlled by individual servomotors.

**Case study 3: DISCOMOTO**

DISCOMOTO project concentrates on the promotion of ecology connected to electric cars. The project involves creating an interactive environment in which the electric cars, which are connected to the charging points, are moving and shaping the urban space. Principles of moving the vehicles are the main subject of the project. Few prototypes were constructed in order to test the different types of movements and stimuli.

Two sound sensors are reading sounds from the environment and send the input to Arduino board by analogue pin. Possible readings have a range of one kilobyte (values between 0 - 1024 bits). The program reacts on sounds that exceed 700 bits. Then the values from both sensors are compared and the higher value involves the reaction of a corresponding servomotor. The robot turns 30 degrees in the direction of sound impulse (the closer servomotor moves backwards, the other forward) and moves for one second towards it (both servomotors move in one direction).

**Case study 4: Fuzz-ball**

The research is based on the idea that electric cars should be used mostly in tourism. The rant-a-car sightseeing has the biggest potential in Poland due to the changing weather conditions. The project involves the creation of a network of rental and charge stations along the slope of the Warsaw. Within the
project one sample location was designed in detail. Each charging slot is equipped with so-called Fuzz-Ball structure, which indicates the charge level and forms a distinctive element for the whole network. The form is inspired by origami, which can fold and unfold with the use of a pneumatic piston. The whole structure consists of a series of modules, which are connected together. The piston is attached to the central module, which movement is transferred to all the other elements.

OPTIMIZATION PROCEDURES
Lectures and seminar on the subject of optimization techniques were conducted in parallel with the design workshop. In particular, the students were taught about the theoretical basis and applications of Genetic Algorithms in architectural and urban contexts. In practice they were using a Galapagos plugin for Grasshopper / Rhino or Processing programming language to create and control their own Genetic Algorithms. During the Design Studio students were using Firefly plugin for Grasshopper, therefore the for the optimization phase they used the Galapagos plugin, because of the ease of connecting both steps and create a comprehensive design environment for building, manipulating and optimizing their robotic prototypes.

Case study 1: reCHARGE lamp
In the reCHARGE lamp project, an optimization procedure was introduced into the design process, in order to prevent possible light pollution and protect the constant light changes in the environment during the lantern movement. A simplified 2d scheme of a lamp deflector was created and modified by the genetic algorithm. The phenotype was created by a polyline with 10 control points placed within the base arc of the lamp shape. For the purpose of the optimization process only the two most extreme conditions of the lamp movement were examined – when the lamp is completely bent and fully straightened. The genotype was controlling the geometry of the inner surface of the lamp, by adjusting the distance of the polyline control points from the centre of the base arc. Length and rotation of the base arc and the range of rotation of the lamp head in the upright position were also encoded in the genotype. The optimization goal was expressed by the sum of the total number of rays of light falling on the designated plane and the inversed number of the sum of rays that do not fall into the plane, brought to values between 0 – 1. The fitness function was calculated for both positions of the lamp and then added together. By maximizing that number the best deflector’s shape was generated.
**Case study 2: City Carpet**

The optimization objective was the minimization of the motors’ energy use. The work performed to lift the structure is proportional the energy use. In order to optimize the structure the amount of energy was compared to the total volume beneath the roof surface. The relation of both parameters expresses the fitness function, which is to be maximized by the Galapagos solver over the evaluated generations of objects. Finding the maximum of this coefficient (\( e = \frac{V_{\text{max}}}{E_{\text{max}}} \)), which is determined by the relation of volume and the sum of distances that the ten supports must pull out, approximates the energy used by the engines. The larger the ratio of volume to the aggregate length of distances travelled by each support, the less energy is used by the whole structure. The optimization was performed over generations of 50 individuals, with the initial boost factor of 2, which means that the first population consisted of 100 individuals.

![Diagram](image-url)

**Figure 7**
DISCOMOTO project – prototype construction scheme. Authors: Ewa Stankiewicz, Maciej Burdalski, Michał Grzymała, Andrzej Miłosz, Jan Rubel.

**Figure 8**
DISCOMOTO project – optimization process cycle. Authors: Ewa Stankiewicz, Maciej Burdalski, Michał Grzymała, Andrzej Miłosz, Jan Rubel.
Case study 3: DICSOMOTO
The Project involves optimizing the behavior of the robot in relation to constantly changing external factors, to which the robot reacts. Optimization is usually carried out on the basis of computer-modeled factors. Here the analyzed conditions were changing constantly and therefore the fitness value was being changed during the optimization process. The possibility of manually controlling the mutation level of the genetic algorithm in the Galapagos plugin played an important role in this process. Once achieved the optimal solution, under changed conditions may no longer provide valuable individuals for further development. Adding some random individuals to the population is important to prevent the population from sticking in the local optimum, once the external factors change.

For the purpose of the optimization task a new robotic prototype was built. It consisted of a light sensor, Arduino board and a servomotor attached to the shading element. The Arduino board was controlled by a Firefly plugin in Grasshopper and the behavior of the system was dynamically optimized by Galapagos plugin. The light sensor was constantly sending values to Grasshopper through the Arduino output monitor in Firefly. Its’ readings were acting as a dynamic fitness value.

In order to facilitate data analysis, proper system reaction and another clear sensor reading, a timer was introduced to slow down the data flow. The optimization goal was to optimize the rotation angle of a shading element controlled by a servomotor in order to get a maximum shading over the light sensor in the changing light conditions. The rotation angle of the servomotor, which is the modified genetic information, was connected to the Firefly plugin controlling the behavior of the robot.

Case study 4: Fuzz-ball
The optimization procedure of the origami form aimed to find the proper angle of rotation of each point in the structure, and thus the optimal distance over which the piston, attached to the central module of the form, was pushed. The fitness function was described by the ratio of the volume to the area of the surface. The fitness function was being maximized over the generations of populations of 50 individuals. The first generation consisted of 100 individuals, in order to maximize the diversity of genes for further reproduction.

SUMMARY
The conducted design experiments during the Experimental Design Studio workshop were an attempt to combine multiple computational methods in one comprehensive design process. The greatest emphasis was put on the development of the robotic prototypes of the designed kinetic structures. The complexity of the project required incorporation of computational tools to a large extent. Students were using scripting environment to handle their design from the conceptual stage to final form gen-
eration and robot control. The layer of optimization acted as a realistic constraint and brought additional complexity to the projects. The same scripting environment was used to create the genetic algorithm, and to modify predefined forms. Few projects concentrated only on the physical optimization of the designed objects, such as optimization of the ratio of volume to surface area; some were aiming to optimize the energy usage of the system; one project was dealing with the dynamic optimization of the robot, by continuous analysis of the external conditions, to which the structure reacted. The experiment of combining multiple computational tools within one design task proves to be a valuable attempt towards creating a multidisciplinary design environment for complex problem solving.

REFERENCES