DESIGNING FOR THE UNPREDICTABLE

Novel model for the design of emergence through real-world behavior

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ABSTRACT: Most current approaches to unpredictability, within architectural discourse, lie either in the design of unbuildable emergent shapes or in performance simulations to test already designed outcomes. Even though some recent explorations have enabled the construction of emergent shapes, the unpredictability of real-world behaviors as the rules’ source for the unpredictability of shape generation remains unexplored. This paper proposes a novel model for the design of unpredictable buildable shapes, based on real-world behaviors. Initially, current methodologies are studied in order to find how they deal with the unpredictability of shape generation and real-world behaviors. Finally, a comprehensive novel model is proposed and tested through an empirical experiment, to show how it can be applied in architecture.

KEYWORDS: Unpredictability, emergence, simulation, folding structures

Résumé: Les approches les plus récentes sur l’imprévisibilité dans le discours architectural concernent soit le design de formes émergentes non constructibles, soit des simulations de la performance de projets qui sont déjà conçus. Même si certaines explorations récentes ont permis la construction de formes émergentes, l’imprévisibilité du comportement dans un monde réel reste non explorée en tant que source de règles pour l’imprévisibilité dans la génération de la forme. Cet article propose un nouveau modèle pour la conception de formes imprévisibles constructibles, basé sur des comportements dans le monde réel. Au début, les méthodologies courantes sont étudiées pour découvrir comment elles traitent l’imprévisibilité de la génération de formes dans un monde réel. Finalement, un modèle de compréhension est proposé et testé par une expérimentation empirique, pour démontrer comment il pourrait être appliqué en architecture.

KEYWORDS: Imprévisibilité, émergence, simulation, structures pliables
1. INTRODUCTION

Unpredictability, from a creative design point of view, lies in assuming that design process is closely related to situations of uncertainty, uniqueness and conflict. Designers begin with uncertain and indeterminate situations, which they, through the process of making or “bringing new things into being”, discover and transform into determinate ones (Schön 1987). In the beginning the final outcome is always unpredictable and designing is a continuous process of definition and discovery in a constant loop of construction, analysis, criticism and reconstruction. From an engineering design perspective, unpredictability has to be reduced, as possible, in order to forecast the real-world behavior and performance. In this case, the designer uses descriptions and models in order to simulate and thus been able to change “existing situation into preferred ones” (Simon 1996). Even though, the designer uses simulation according to real-world known laws, the implications of a certain design, particularly on systems behavior, might be unknown. The loop of definition and discovery, of those unknown factors, can also be related to creativity, within the boundaries of engineering design.

The general objective of this paper is to combine the creative design approach with the engineering design one, to propose unpredictability as a concept of great potential to envision new emergent buildable shapes based on real-world behaviors. It is possible to find several explorations, from different disciplines, which deal with unpredictability in its different manifestations: from a more creative and artistic perspective of unpredictability, as the generation of emergent shapes, to a more instrumental and scientific approach, as the emulation of real-world phenomena. This paper will analyze three methodologies, which have different degrees of commitment to creative or instrumental perspectives to unpredictability within design process: (1) Emergence of Overall Shapes, as the design of unexpected shapes through the repetition of simple rules, such as adding, subtracting or reconfiguring elements. (Knight 2003), (2) Simulation of Real-world Behaviors, as the digital emulation of physical constraints, such as movement, flexion or foldability (Killian 2006) and (3) Learning by Recording Cases, as the use of physical artifacts to compute real-world behavior when no mathematical descriptions of the phenomena are possible (Winston 2003).

The Emergence of Overall Shapes (EOS) has been widely applied in architectural practice and education in the last years, generally in initial stages of the design to produce unexpected outcomes and thus fostering creativity. Even though, in most cases, EOS has been used to create free-form shapes through geometric transformations in the digital space, there are some explorations on material, buildable and real-world emergent shapes, such as the Materialization of Shape Grammars (Saas and Oxman 2006) and the Computer Evolution of Buildable Objects (Funes and Pollack 1999). Similarly, the Simulation of Real-
world Behaviors (SRB) has also been lately accepted and promoted as a tool to aid architectural design. Yet generally, the simulation is incorporated in latest stages of the design process to simply analyze the final outcome performance. Still, it is possible to find explorations which exploit real-world behaviors possibilities in early stages of the design process. The Structural Form Finding Tool (Killian 2006) and the Hoberman's Foldable Structures (Hoberman 1990), are clear examples of how to incorporate structural constraints and rigid-body behavior to creative design processes. Finally, as regards Learning by Recording Cases (LRC), it has not been applied yet in architectural explorations. Even though this technique has been mainly applied, as an instrumental solution, into task-level robots (Aboaf 1988), there are some examples in toy product design, such as the Topobo Tangible Learning toy (Hayes 2004) in which it is possible to envision potential contributions to architectural design.

The main question to be answered in this paper is how to design unpredictable buildable shapes according to unpredictable real-world behaviors. Even though current explorations of EOS, SRB and LRC methodologies have tackled this question, each one proposes a particular solution according to its own perspective to the problem. Likewise, although, some of those explorations have enabled the physical construction of unpredictable shapes, real-world behaviors as the rules’ source for the generation of those shapes remains unexplored. The hypothesis is that, through relating these three methodologies, using the different perspectives and advantages of each, it will be possible to construct a novel model that creates emergence based on rules taken from the real-world. This paper will study EOS, SRB and LRC methodologies in order to understand their underlining structure and extract, from there, their strengths and weaknesses. Consequently, the proposed model will be constructed by combining strengths of each one to cover the weaknesses of the others.

This paper will be organized in four sections. In the first three Sections, each model, EOS, SRB and LRC, will be described and analyzed. For each model, an example will be presented as well as a disclosure of the model underlining structure, in order to understand how the model works and to find what its
weaknesses and strengths are. In the last section, a general model will be proposed according to the analysis of previous sections. This proposed model will be finally related to an experiment conducted by the author to exemplify how the model works, and again finding new problems which will lead to future research.

2. EMERGENCE OF OVERALL SHAPES

The concept of Emergence is nowadays accepted and promoted as a creative design methodology within architectural education. The Emergence of Overall Shapes (EOS) methodology has been applied in creative design, through different computational models such as genetic algorithms, cellular automata and shape grammars, in order to explain or create unpredictable shapes and behaviors through simple rules iteration (Knight 2003). Using locally decentralized rules, unexpected behavior or outcome may emerge. The designer writes the rules, computes, gets outcomes, analyzes, criticizes, changes rules and runs the process again until he is satisfied. This loop, based on Schön’s creative design process (Schön 1987), has been widely used in architectural design, mainly since architecture schools support and promote the use of scripting and programming as an extension of traditional modeling tools. Nowadays major CAD programs have extended digital design possibilities, through scripting platforms such as Max Script, Grasshopper and GC Script. Likewise, architecture schools have incorporated scripting and programming courses has part of their curriculum, shifting the role of designers from form-makers to rule-builders.

**FIGURE 2. FUNES AND POLLACK: COMPUTER EVOLUTION OF BUILDABLE OBJECTS.**

The Computer Evolution of Buildable objects (Funes and Pollack 1999) is an example of the use of genetic algorithms to design using EOS models. The research proposed an algorithm with a model of the physical reality with the goal to generate buildable structures, such as a bridge or a scaffold, using LEGO blocks (Figure 2). The rules are the mutation of the block and the crossover of already generated configurations. While mutation operates by random modifications of the block parameters, such as its size, position or orientation, crossover combines already tested and possible parent assemblies to generate
new child configurations. After the application of random mutation and crossover, outcomes are tested, in relation to fitness functions, in order to evaluate properties, avoid overlapping and then select or discard candidates consequently. The achievement of a certain goal, for example the creation of a longitudinal or vertical shape, can be set in the fitness function incorporating a certain distance, starting point and defined target. In those cases certain aspects of the shape are predictable, such as the longitudinal shape or the vertical one, yet the final path that the shape will describe between the starting point and the target will be still unpredictable.

By analyzing the example of buildable blocks, we can understand how the design process flows when using EOS models (Figure 3). The process begins by applying rules of transformation, in this case part selection or mutation as well as parts combination or crossover. This has to be computed in order to get an initial shape candidate. There is an inner loop, the loop of partial growth, in which each additional mutation or crossover is tested before its addition to the overall configuration. This process of partial growth, generally obscure to the designer, may become helpful if he wants to incorporate his judgment during the process. Partial goals, such as buildable feasibility or structural performance, are tested while the main goal, of arriving at the final target, is not yet achieved. Once accomplished, additional performance analysis may be included, to finally allow designers to judge and criticize. Then the process may be run again, first if the performance is not accomplished, according to general fitness functions, and second if the designer is not satisfied with the emergent overall shape.

**FIGURE 3. EOS MODEL.**

Using EOS models allows the designer to obtain unpredictable shapes through rules definition, combination and iteration, in a loop of creative design, until the designer is satisfied with a certain outcome. In addition, this rule-based approach can be related to a certain goal, for example the bridge between two points, enabling the designer to have a certain control of the shape generation process according to a general idea of what he wants. The disadvantage of using EOS is usually related to the conception of invalid outcomes in terms of their feasibility, applicability and buildability in the physical world. Even in the
buildable blocks example, the algorithm is underconstrained, causing unnecessary and expensive computation, in which only some representations produce valid structures and many describe impossible overlapping ones (Funes and Pollack 1999).

3. SIMULATION OF REAL-WORLD BEHAVIORS

The Simulation of Real-world Behaviors (SRB) has been lately established as the engineering design process to imitate, predict and therefore deal with real-world constraints and behaviors (Simon 1996). Simulation processes require both a theoretical understanding of the real-world phenomena as well as working digital implementation (Killian 2006). It is possible to distinguish between two types of SRB tools used by designers. On the one hand there are tools for early stages of design to emulate physical and dynamic constraints, such as movement, flexion or foldability, and on the other hand simulation tools to test and analyze structural, environmental and programmatic performance of already designed models. The first approach, the simulation of physical and dynamic behaviors, will be the one to be addressed due to its implications for design engineering as a creative process. Parametric programs, such as Solid Works or Inventor, have been used mainly in engineering environments to simulate and design mechanical working systems. Likewise, animation programs such as 3D Studio Max and Maya have incorporated simulation tools to emulate dynamic behavior using inverse kinematics, rigid and soft body solvers.

**FIGURE 4. Hoberman: Radial Expansion/Retraction Truss Structures.**

_Hoberman's Foldable Structures_ illustrate how SRB, through parametric programs, can be used to deal with real-world mechanical behaviors. Hoberman structures are based on the repetition of a module called scissor-pair, which is composed of two rigid bars connected in the middle with a pivot assembly. In order to design three-dimensional foldable applications, such as geodesics, domes, arches, and helicoids, the design is aided by the mechanical simulation of the folding process through parametric programs (Figure 4). The
scissor-pair components are modeled, leaving rotation on the pivots as a variable parameter. During the folding process, because all scissor-pair components are linked, the rotation of one local assembly will affect the behavior of the entire structure. This principle of propagation is essential because it reduces the control mechanism to the rotation of only one component. It also determines the synchronized and smooth transformation between folding states (Hoberman 1990).

The methodology used to design through SRB methodologies, particularly parametric and rigid body tools, is illustrated in figure 5. In engineering design, as a creative process, the structure is also defined by a loop of construction, criticism and reconstruction. Yet, the overall shape might already be defined from the beginning, as in the case of the Hoberman’s three dimensional structures, such as a geodesic sphere. This initial overall shape, which has a defined geometry and size, has to be subdivided or tessellated according to size and quantity of the initial part that the designer is looking for, for instance the Hoberman’s scissor-pair component. The initial part can be parametrically modeled in an independent file, called part file, and then included in the assembly file according to the defined geometry. The computation process enables the simulation of the part and overall shape behavior, which can finally be tested to decide if the outcome is satisfactory. If it is not, the process can be processed again according to performance criteria, such as weight, structure, overlapping and folding requirements, as well as aesthetic designer criteria.

**FIGURE 5. SRB MODEL.**

The chance to play and interact with real-world physical phenomena is the principal advantage of the use of SRB to aid design processes. It is possible to design artifacts based on real-world constraints, which finally result in models that are feasible and buildable in the real world. Yet this great advantage may imply SRB’s main disadvantage, when no theoretical understanding of those real-world phenomena is possible. In some cases there are no mathematical descriptions and models to be translated into working digital implementations. Additionally, another disadvantage may occur when working on larger models. Simulating real-world phenomena, such as the rotation and the movement
propagation of scissor-pair components, may become computationally expensive and even unfeasible. In those cases the only solution is to test real-world phenomena in partial models, which restricts and limits designers’ freedom and possibilities during the design process.

4. LEARNING BY RECORDING CASES

Learning by Recording Cases (LRC) is a methodology used in Artificial Intelligence (AI) to achieve a prescribed goal when it is not possible to build an optimal model of it (Winston 1992). In this case the theoretical understanding of the real-world phenomena is assumed as incomplete and unpredictable, and therefore no simulation models are used. Instead, the physical artifact is designed to be able to self-sense, record its own behavior, gather data and after applying learning algorithms, enhance its performance by practice. LRC is a methodology which has been applied to the design of task-level robots, such as moving an arm, swinging a pendulum and throwing or juggling a ball (Aboaf 1988). The undertaking of such design requires the combination of diverse computational methods, from robotic simulation techniques, sensors and actuators technologies, to programmatic and learning algorithmic implementations. Even though LRC works directly under the assumption of unpredictability, the goal is predictable for the designer. There are neither reliable initial data nor models for simulation, yet the learning process seeks a satisfactory performance according to a predictable and desired goal.

A Robot Arm moving its hand along a given trajectory is a good example to illustrate LRC methodology. In order to reach the goal, the parameters that need to be predicted are the angle and torque variation for each pivot assembly. Even though there are mathematical models to calculate the rotation, the torque is difficult to compute due to additional real-world factors. The solution is to record real world behavior and to learn through iteration (Winston 1992). The Robot Arm begins with random and erratic movements. Consequently the data is recorded and then related to the desired trajectory. Learning algorithms are
used to make classification and predictions and then, by iterating the whole process, which is called practice, the robot arm is able to progressively improve its performance reaching a satisfactory result (Aboaf 1988).

The diagram shown in Figure 7 provides us with an understanding of how LRC works and the factors that the designer has to consider when designing for unpredictable behaviors. Even though in this case the loop of learning and practice is not related to creative design, it is still helpful because it illustrates the designer’s task of setting the physical model and the algorithms to address unpredictable behaviors. The designer has to define the entire system which has to be able to perform, to sense, to learn and finally to achieve the designer’s goal. As shown in Figure 7, the process launches with an initial state, movement or physical action. The physical performs according to its own initial inputs in relation to real world constraints. This process, which can be seen as a physical calculation or computation, is sensed by the model itself and then recorded. The data is related to the desired goal and then classified using learning algorithms. This new data will serve to optimize the initial state in the next loop until the desired behavior is accomplished.

**Figure 7. LRC Model.**

The principal advantage of using LRC in design processes is that enables the designer to find a possible solution, even in situations were physical behavior is not possible to be predicted by computer simulation. The designer can exploit this methodology in several stages of design process through the use of traditional physical models that incorporate sensing, recording and learning procedures. Likewise, part of the computation can be left open to be self-defined in the real-world by the physical final outcome. The designer can envision an artifact which once built is able to perform the desired goal, through confronting its own unpredictable behavior to real-world unknown phenomena. Even though this great advantages, of aiding designers to deal with unpredictability, LRC methodology is peripheral to design process. Its weakness, in relation to creative process, lies in the fact that is not actually part of it. In order to be a real contribution to design process LRC models have to be extended as, or related to a loop of construction, criticism and re-construction.
5. PROPOSED MODEL: EMERGENCE THROUGH REAL-WORLD BEHAVIOR

The major goal of this paper is to propose a novel model that combines the creative design approach with the engineering design one, in order to create unpredictable shapes and behaviors based on real-world phenomena. This objective is tackled through the analysis of existing models which deal with the unpredictable. Different models, from EOS and SRB to LRC, have been studied in order to understand their underlining structure and extract from there their advantages and disadvantages. Each model can contribute from a different design perspective to construct a balanced model, through combining the advantages of each one to compensate the disadvantages of the others. Figure 8 shows the relation between the advantages and disadvantages of each model. It is possible to appreciate that each model’s weakness is potentially offset by the strength of the other model. The proposed model is then, simply a straightforward combination and complementation of strengths of the previous analyzed models.

FIGURE 8. EOS, SRB, AND LRC ADVANTAGES AND DISADVANTAGES.

The proposed model, which we will call Emergence through Real-world Behavior (ERB), is based on EOS creative design loop of construction, criticism and reconstruction. The difference lies in the rules, which are, in this case, extracted from the SRB model. LRC is related to the model, first through using physical prototypes when simulation is not possible and second through setting future real-world feedback on the built artifact. This complementary organization is shown in Figure 9. Each sub-model is considered a black-box to which we know the inputs and outputs. However, we do not need to know the details of how it works internally. The process begins with the local simulation of real-world behavior through a digital parametric model. If that predictability is not possible, the designer uses the LRC approach, through building a physical prototype. This physical prototype does not have to be the whole structure, but a representative part of it based on future modularity and repetition. The behavior and different shape generation, either of the local parametric model or the physical prototype, has to be generalized and then abstracted into
simple rules. For example the rules may be extracted from the following questions: What states or shapes can be produced? How can we combine them? Is the behavior, between those states, linear or possible to be extrapolated? Once the designer has the rules he is ready to apply emergence to compute and transform those local rules into overall shapes. The number of rules and gathered samples dictates the quantity of possible unexpected emergent shapes the designer may get. The process, then, can be run again at its different stages, simulation, recording or emergence, until the designer is satisfied with a certain outcome.

**FIGURE 9. ERB PROPOSED MODEL.**

The model described above can be exemplified through an experiment, called Robotic Dome Structure (RDS) I conducted as part of my master’s dissertation at the Design and Computation Group at MIT. From the beginning this project dealt with unpredictability problems. First in relation to its behavior and second to the different shapes it was able to generate. The RDS experiment is a constructive system for a transformable dome structure. It is composed of identical rigid components joined by pivot assemblies (Figure 10). The structure is able to define different shapes, through the rotation of its pivot assemblies and thus the re-organization of its components. The use of simulation tool is the main approach to the design of the RDS experiment. Yet at a certain stage of the process, on the one hand local physical behavior is possible to be neither simulated nor controlled, and on the other hand, this initial unpredictability is traduced in the impossibility of overall shape generation. The only solution is building the real-world prototype and, from there, understanding its global and overall shape and behavior. Nevertheless, again the process is unproductive since building the whole physical artifact is time consuming, expensive and difficult to modify. The design process demands flexibility, in order to test different alternatives on local behavior and local shape, and be able to reveal the overall outcome.
Figure 11 illustrates how the RDS experiment can be related to the ERB model to address unpredictability, and thus enabling the design of emergent and buildable shapes based on real-world behavior. The RDS digital model is parametrically constructed in Solid Works software. Even though, it is possible to test local behaviors, the overall shapes are too expensive to be computed. In addition, it is hard to control the reaction of the parts and therefore the generation of possible states. Therefore, a physical prototype is built, which incorporates potentiometer sensors and servo-motor actuators in each pivot assembly of the structure. The system is run by an Arduino microcontroller which enables the recording of all real-world pivot rotations and the translation of data to the digital space. Then the data can be generalized according to the proposed model in order to define the rules, which through combination and iteration generates the emergence of an initial overall shape. Several versions may be produced, but the process will run in a loop, first in order to learn and gather enough data from real-world behavior and second, until the designer is satisfied with the outcome.
The main advantage of the model is that it simplifies the process through subdividing the computation into two complementary parts: (a) the gathering of the behavior, using SRB or LRC methodologies, through a partial representative part or module, and (b) the generalization of data in order to be able to generate the rules and then through iteration and combination generate the overall shape. Since each part demands different degree of detail and representation, the computation is minimized. For example, while SRB and LRC demand high detail representations of physical properties and assemblies, EOS can be represented simply as points and lines relaying the data extracted from reality. Yet, if the data from real-world behavior is not gathered nor generalized properly, the model will not work. In order to design for the unpredictable, it is not enough to use each part independently. The Emergence through Real-world Behavior is based on diverse models which, in order to work as a whole, have to be properly interrelated.

6. CONCLUSIONS

The challenge of this research was to propose a new model to foster the creation of unpredictable buildable shapes based on real-world behaviors. The approach was, as well, guided through two sorts of unpredictabilities: While, on the one hand some unpredictability lies in our incapacity and limitation to envision uncertain possible shapes, on the other hand, in our endeavor, we may encounter technical problems that cannot be instrumentally solved. Three methodologies from different disciplines were analyzed in order to, through exposing their structure and advantages; combine them in a new comprehensive model. Even though, the ERB model constitutes a contribution as an initial step, it is still a collection of three autonomous methodologies that can be further investigated. In that sense, a deeper understanding of the technical requirements and implications of each analysed methodology is necessary, with the purpose of reducing them to their basic features. From that initial reduction it will be possible to relate processes, blurring the boundaries between each and therefore been able to automate the process as a coherent whole. Future research will be conducted in that direction in order to build up a sufficient and automated model to deal with unpredictability in its different manifestations: a computational implementation used to relate unpredictable local real-world behaviour with a digital ruled-based system, to iterate and generate unpredictable overall shapes.

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