Biomimetic Reciprocal Frames

A design investigation on bird's nests and spatial structures

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Reciprocal Frame (RF) is a constructive system typically applied with timber, since it is composed by discrete elements with short dimensions. It allows the construction of large spans and complex geometries. This kind of structure has been addressed by recent research projects that aim to produce it using computational tools and digital fabrication techniques. Moreover, the enhancement of these technologies enabled the integration of simulations of biological processes into the design process as a way to obtain better and optimal results, which is known as Biomimetics. This paper describes the development of a spatial structure that combines the principles of RF and the assembly process of natural agents, such as birds, in a digital environment. The tools used for the generation of the structure were Rhinoceros, Grasshopper and different add-ons, such as Culebra, Kangaroo, Pufferfish and Weaverbird.

Keywords: *Biomimetics, Reciprocal Frame, Nexorade, Computational Design, Agent-Based System*

INTRODUCTION

Wood is one of the oldest materials used in construction, and often its first applications are confounded with the origins of architecture itself, as stated by Laugier (1755), in his primitive hut theory. Some timber constructive systems were created with the purpose of solving technical limitations, for example, the Reciprocal Frame (RF) or Nexorades (BAVEREL et al., 2000). Dated from the neolithic, it was firstly applied in primitive huts, and its application enables the construction of large spans (LARSEN, 2014; PUGNALE; SASSONE, 2014) with relatively short elements. This kind of structure has appeared in different places and cultures throughout mankind's history, e.g. a roof typology known as Mandala, in China and Japan, during the 12th century; Sebastiano Serlio's studies and Leonardo da Vinci's schemes, in the 16th century; during the early 20th century, in Pier Luigi Nervi designs and within the development of specific systems, such as Zollinger's (WINTER; RUG, 1998; TOUSSAINT, 2007; LARSEN, 2014). It is possible to notice that the use of RF has usually coincided with periods of great technological advancement, such as the one we are living nowadays, which is already being called the 4th Industrial Revolution.

Presently, with the availability of new digital technologies, many researches are exploring RF, bringing a deeper knowledge and a more scientific approach to it. One of the main interests is the possibility to achieve a higher level of formal complexity by using simple linear or planar elements with short dimensions (BAVEREL; LARSEN, 2011; PUGNALE; SASSONE, 2014; MESNIL et al., 2018). Hereby lies the sustainable approach of RF structures, since its components take better advantage of timber, reducing material waste, on top of wood being a renewable material (WINTER; RUG, 1998; GUTIERREZ; FLORES; PRECIADO, 2016).

Over the past few decades, computational design and fabrication methods have been introduced into architectural design, enabling processes that encompass the geometric differentiation of building components (KNIPPERS; SPECK, 2012) as well as the integration of material, form and structure (OXMAN; OXMAN, 2010). Commonly disregarded by traditional design and production methods (OXMAN, 2014), this integrative approach is noted in the hierarchically structured world of natural organisms (WEGST et al., 2014), which enables the direct exchange of information between the scientific fields of Architectural Design and Biology (AHLQUIST et al., 2015). Resorting to Nature has been a recurrent topic in the history of Architecture (BAHAMÓN; PÉREZ; CAMPELLO, 2008; STEADMAN, 2008). In a first moment, Nature was taken as a source of inspiration for visual representation. Gradually, Nature was also used as a philosophical analogy. With a deeper understanding of natural processes, it has been possible to develop artifacts based on natural mechanisms; recent computational advances in design, simulation and fabrication allow biological processes and natural phenomena to be comprehended as methodological strategies to achieve technical solutions (KNIPPERS; SPECK; NICKEL, 2016). This approach is commonly named Biomimetics.

Given the importance of sustainable design approaches to economic and ecologic criteria in view of the worldwide concern on climate change and energy resources, this paper examines if architectural design could undertake Nature's strategies into a RF design process in order to emulate the structural and material performance of complex structures found in Nature. In this sense, the objective of this paper is to develop a digital spatial structure with discrete irregular elements, such as a pavilion, based on both RF principles and accounting assembly strategies performed by natural agents, such as birds.

BEHAVIORAL BASIS

As stated by Gherardini and Leali (2017), the guidelines established by Biomimetics are known as ways of perceiving environmental, economical and/or structural efficiency and functionality. Although emulating natural processes does not necessarily result in aesthetic value, Allen and Zalewski (2009) suggest that there is a human fascination in natural principles of form, such as in the idea of "ordered disorder" and "natural growth". This means that an aesthetical value might be attained by exploring the intrinsic relationship between natural structures and their mathematical principles. In this sense, RFs mathematical principles, such as mutual equilibrium, can be found from basic geometry until complex biological structures (PIZZIGONI, 2009). Exploring these principles encompassing material properties, construction logics and integration of design, fabrication and assembly might be a way to obtain optimal results and innovative solutions. Therefore, in order to develop the design of a spatial structure of this kind, it was necessary to understand the behavioral basis of both birds' nests assembly process and the RF essential mechanisms.

Agent-Based Systems

Through the emulation of natural phenomena and biological behavior it is possible to achieve some level of integration between form, process and ecosystem, providing optimal solutions under certain restrictions (BENYUS, 1997). In nature, living organisms may be considered as systems that achieve their degrees of systemic complexity through the interaction of external pressures of the environment and their own internal components. Their maintenance is done by adaptive evolution and by shifting specific behaviors (PEDERSEN ZARI, 2007; MENGES; WEINSTOCK; HENSEL, 2010). Thus, biomimetic approach requests an integrated design methodology that encompasses material properties, development tools, fabrication equipment and an environment that provides active inputs into a bottom-up process. These inputs enable an adaptive behavior that perceives the optimal self-organization of the organism, which is a way of exploring emergent and unexpected complexities. A computational data processing method capable of translating and integrating these demands is the *Agent-based System* (BAHARLOU; MENGES, 2013; BAHARLOU; MENGES, 2015). Based on the behavioral pattern of natural agents, it consists of a collection of autonomous decision-making digital entities that follow simple local rules that trigger the interaction with the environment (GILBERT, 2008).

The behavior of every agent arises from a starting set of rules that defines certain strategies in response to recurring new situations and guides the decision-making processes (HOLLAND, 1995). This basic set of rules can be modified by agents along the process by acquiring environmental information over time and, hence, generating new sets of rules and promoting dynamic adaptations (BAHARLOU; MENGES, 2015; CASTI, 1997; BAHARLOU, 2017). Furthermore, unexpected and new events may emerge from individual or collective behavior of agents. When an agent is involved in the process of form generation, it is considered as an individual being, such as a bird building its own nest (BONABEAU, 1997).

The bird nest can be considered one of the best examples of RFs in Nature, since their structural and mathematical principles are the same of artificial RFs. It is remarkable that both are made from simple discrete elements and create a narrative and aesthetic expression, as stated by Song et al. (2013). Nevertheless, while artificial RFs present a highly symmetric pattern and similar fans, natural RFs are made from completely irregular, non-symmetric and inaccurate elements.

Reciprocal Frame: Structure and Elements

RF are also known as Nexorades, which implies in the term nexor, referring to the individual elements that constitutes this kind of structures (BAVEREL et al., 2000; PUGNALE; SASSONE, 2014). Larsen (2014) points out that each nexor is characterized as short linear or planar element, that integrates closed and complex systems. RF essential concept relies in the relationship between supporting and being supported simultaneously and symmetrically. These functions do not constitute a structural hierarchy and a single connection point of a nexor cannot overlap the same function. Moreover, each nexor has always four different connection points (two supporting and two supported), located along the element. The region established by the encounter of nexors is called fan and it is considered as the elementary geometric pattern of these structures. At least three nexors are necessary to constitute a fan. More recently, Araullo (2018) has suggested the term "DNA" as a biological analogy. The spatial configuration generated by the fans implies in overlapping of nexors eccentricity, which refers to the smallest distance between the axis of two connected elements (BAVEREL et al., 2000, DOUTHE; BAVEREL 2009, SÉNÉCHAL; DOUTHE; BAVEREL, 2011 , THONNISSEN, 2014, MESNIL et al., 2018).

In regards to structural aspects, RF main effort demands are from axial and flexion loads, and due to its very complex behavior, Finite Element Analysis techniques are the most common strategy adopted to obtain the best structural configurations. Mesnil et al. (2018) have demonstrated that this type of structure has very peculiar properties, which should not be treated through conventional techniques. Brocato (2011) suggests that the optimal configuration of RF may be found by reducing the axial forces and increasing the bending, which is the opposite of what is usually done in shells or gridshells. On the other hand, Kohlhammer and Kotniki (2014) point out that, by analyzing each nexor, their individual behavior is very close to traditional beams.

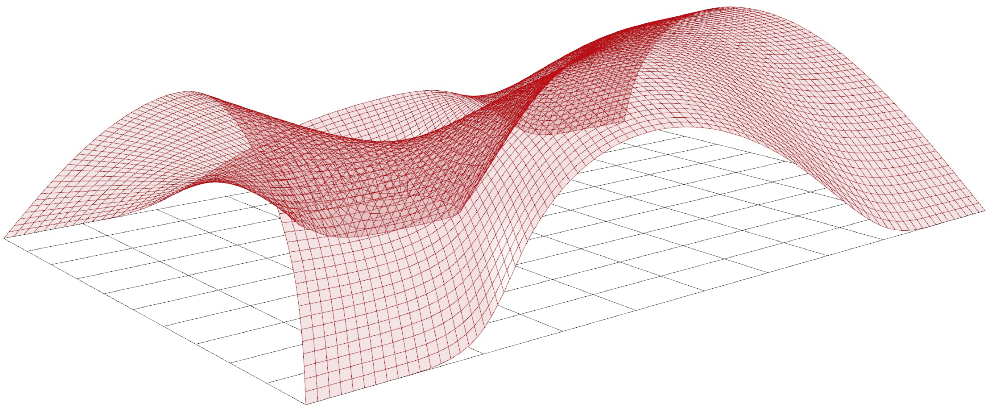

Figure 1
Generated geometry of the Pavilion, using Form-Finding Techniques. Font: Authors, 2019

INTO THE ALGORITHM

The design process was developed using Grasshopper algorithmic modelling tool for Rhinoceros 3D, with specific add-ons for the emulation and analysis of the design. The process consisted in three different stages: (1) initial setting, (2) *Agent-Based System* simulation, and (3) RF setting. The first step consisted of defining a rectangular mesh (30x20m) with an internal cutout of 1/5 of the total area (6x4m). Considering the four boundary points of the mesh, as well as the internal rectangle as supports, the global shape for the pavilion was generated with form-finding techniques with Kangaroo Physics add-on (Figure 1).

Decoding Nature

In the second design stage, the process of a bird's nest assembly was translated into a design construction algorithm that emulates the building behavior of such natural agent. In order to achieve that, it was necessary to set the *Agent-Based System* with the aid of Culebra 2.0 add-on, which enables dynamic interactions between multiple agents in hybrid systems within a behavior library, computing data in two or three dimensions. Besides the geometry from the previous step, there are three main settings that must be defined in order to start the simulation: (1) agent set, (2) behavior set and (3) visual resources.

The bird's nest assembly process started with a single wood stick. It is a three-dimensional structure without a precisely geometric boundary, so the initial settings of the agents were matched with these criteria. Also, the agents' movement adjustment defines maximum and minimum dimensions and angles of each stick, which are very irregular in the whole natural structure. The initial settings for the simulation were defined as: Spawn Settings: 1, Dimensions: 3D, Bounds: None; and for movement configuration: Initial Speed: 1.0 m in axis Z, Maximum Speed: 3.0 m/s, Maximum Force: 0.3 m/s^2 , Velocity Multiplier: 1.5 units.

The assembly process of a bird's nest has some level of linearity, since the order is set by the first stick in connection to the next one, then in a loop. However, there is an unexpected randomness generated by the dynamic interaction of the elements. When a bird's nest is analysed, the inner and outer boundary are irregular because of the dimensional tolerances of each stick. Moreover, at times these sticks might be much larger or smaller than expected (Figure 2). These characteristics should be translated into the al-

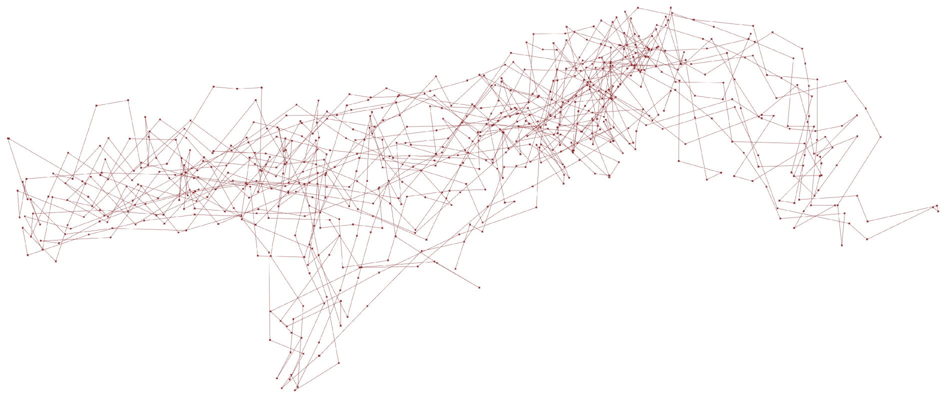

Figure 2
Agent-Based System trail and cloud points representation in Rhinoceros and Grasshopper. Font: Authors, 2019.

Figure 3
Fallen bird's nest. Some of the sticks go much farther than the whole structure boundary. Font: <https://commons.wikimedia.org/wiki/ File:Nedfalt_-fuglerede.JPG>. Accessed in: 14/05/2019.

gorithm through the Behavioral Settings. First, the tracking behavior should incorporate the desired geometry and its expected dimensional tolerance, such as the outer projection distance. At the same time, the wandering behavior should simulate direction and dimensional unexpected randomness, showing that it is possible to have a certain level of order and control. The tracking behaviors were defined as the Pavilion Form-Found Geometry, Another Agents Detection Limits: 1.5m, Projection Distance: 2.5m and Radius Projection Distance (Multiplier): 1.45 m; and for wandering behavior: Randomness Control: 100 units, Wander Radius: 15.0 m, Wander Distance: 15.0 m, Rotation Trigger: 6.0 m.

At last, it was necessary to calibrate the visual representation of the simulated system, enabling a graphical output, such as a sequence of lines connecting a point cloud, which should be the final geometry of the *Agent-Based System*. After more than 700 iterations, the output of this stage was the simulated bird's nest trail based on a cloud of more than 700 points (figure 3).

Reciprocal Frame Conversion

Since many of these points were too close or too far from each other and it would not be possible to ensure every element's connection in four vertices, it was necessary to reduce the total number, considering the proximity between them, defined as a minimum of 0.5m. At the same time, it was imperative to embed some restrictions to the behavior of natural agents into actual RF segments, and one of them was the definition of fans made by four different nexors. Although this might not be the best structural option, it is the most precise configuration to assure the number of connection points, due to its grid similarity. With every point defined, they were splitted between UV coordinates according to the pavilion shape, and were connected by lines. With the help of add-ons such as Weaverbird and Pufferfish, some of the geometric relations were improved, reducing distortions of fans and establishing a defined boundary for the most external nexors.

An algorithm capable to adapt RF into different surfaces, currently under development as a PhD research by one of the authors, was applied in order to transform the UV lines into RF elements. Basically this is possible through a set of geometrical and mathematical operations, such as rotating the lines in a certain angle, projecting the points into the intersection planes, connecting points in different heights (in order to guarantee the RF support logic and control the eccentricity), extending the extremities and defining the section dimensions. Since the structure was designed to be constructed with rods, the eccentricity and section dimension was almost the same (0.03 m), the extension of nexors was 0.07 m and the rotation angle in the center of each line of 7 degrees. The generated structure had a total of 820 nexors, with lengths ranging from 0.49m to 3.5m and around 200 totally different fan geometries (figure 4).

RESULTS

By one hand, this experience glimpses the potential by integrating the natural processes of assembly, such as birds nests, with the already known restrictions and demands of RF made by men. The use of biomimetic principles into the design methodology may ensure much more interesting formal solutions, and it might also provide a more efficient, structural and economical solution. The resulting structure for the pavilion has a high level of morphological complexity and variety. Each connection angle and geometry, nexor dimension and fan configuration is unique, which can only be produced using digital fabrication technologies.

By the other hand, one of the main issues is the connection system between all nexors. It is possible to design and even fabricate elements using simple dovetail or bridle joint systems, but the assembly process would be hard or even impossible, due to the relation support-supported and the global geometry. Actually, the connection system is considered an issue in multiple RF situations by many authors. As stated by Araullo and Haeusler (2017), the connection point in linear and in planar nexors implies in peculiarities that cannot be solved by using off-the-shelf standardized products. Nevertheless, the final structural condition of the structure was not verified,

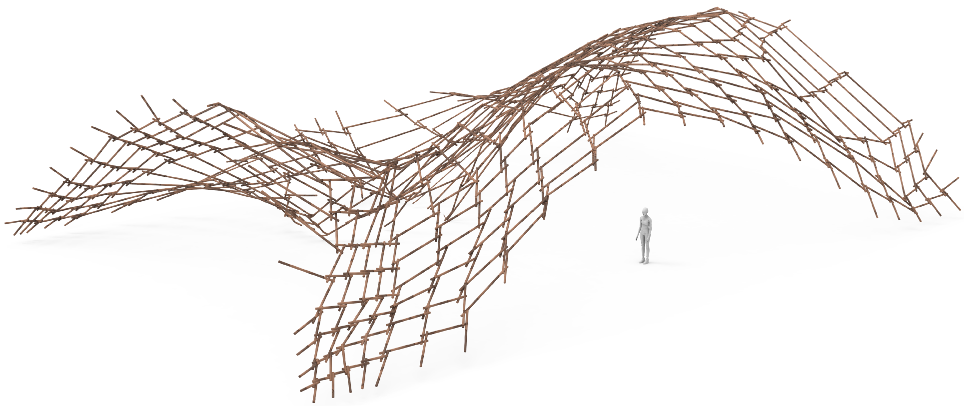

Figure 4
Reciprocal Frame Structure generated using the grasshopper alogirthm. Font: Authors, 2019.

nor the strategies that should be used to settle it.

Finally, the digital data generated from the simulated bird's nest structure and the one from the RF configuration look very similar, as it can be seen in Figures 3 and 4. However, the RF structure was generated considering only UV coordinates, while the simulated nest presented also used the W coordinate. In another words, the RF algorithm works undertaking any kind of surface, without thickness, but nature works with material-based elements. We expect this experience may encourage more research projects integrating RF theories and concepts with Bio-inspired methodologies, looking into other natural structures.

FUTURE WORKS

The discrete elements will be structurally optimized with the integrated use of structural analysis add-on Karamba3D for Grasshopper and built-in evolutionary solver component Galapagos, in order to assure the minimum displacement of the whole system.

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