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Path systems connecting forces, materials and robotic tools

Integrated computational design optimization and robotic fabrication workflows

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Abstract

This paper discusses the role of path systems within an integrated framework that involves computational design optimization and robotic fabrication processes. After a brief and general discussion on complex systems and their modeling approaches, as well as their impact on architecture, the paper emphasizes on path systems, a special type of complex systems that can be similarly found in non-living and living nature. Then, a discussion on the way these are interpreted in the work by Frei Otto is developed, formulating at the same time our proposed framework for integrating path systems into a seamless workflow where forces, materials and robotic tools can be potentially connected. This discussion is further enhanced by presenting two research case studies on toolpath development based on form-finding of systems that carry certain properties derived from structures' loading conditions and materials. At the same time, their effectiveness to be used as integrated computational design and fabrication process is discussed with the aim to improve existing workflows.

Keywords

Path systems; Forces; Materials; Robotic tools; Computational design; Robotic fabrication

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1. Introduction

The investigation of path systems can be identified as part of the broader research on complex systems, where the interaction behavior between automata and their environment at local level is examined, evaluating at the same time the behavior of the system at global level. This can be characterized as an interactive relationship between "automata", "agents", "particles" or any other form of "individuals". A theoretical discussion on such interactions can be found in the work A thousand plateau: Capitalism and schizophrenia by Deleuze and Guattari, where the term "molecular population" is introduced, particularly in "People are now at its most molecularized: a molecular population, and people of oscillators as so many forces of interaction" (Deleuze and Guattari, 1987). Evidently, interactions at the level of "molecular populations" that lead to complex systems, can be part of a broader field of study that deals with collective intelligence in natural and artificial systems as well as with the way these interactions can be modelled using computational processes, aiming at emergent and self-organized behavior (Williams and Kontovourkis, 2008). This field of study has different directions and objectives including, among others, works in the area of Cellular Automata, Swarm Intelligence and Agent-based modeling. In each case, observations regarding the behavior of organisms and their interactive relationship are transferred on the computer based on specific simple rules, achieving their simulation, as close as possible to their natural behavior.

The example of Cellular Automata, first examined by John von Neumann (1903-1957) and Stanislaw Ulam (1909-1984), is characterized as a dynamic descried system consisting of cells with a finite number of states (Flake, 1998). Such systems have been used to simulate emergent behavior in physical, or artificial, organisms evolved through time based on a simple set of rules with unpredictable results. Another simulation approach is Artificial Life, which, as in the case of Cellular Automata, employs individual components called "agents" to achieve dynamic self-organized behavior. In this case, the result is described as continuous. In this direction of modeling, natural behavior and self-organized phenomena, found in living systems like school of fishes, flock of birds and ant colonies, can also be included. As in the cases described above, such systems have been initially introduced to examine organisms that exhibit a complex behavior, such as the foraging patterns developed by ant colonies based on their movement behavior in space (Bonabeau et al., 1999). Similar principles can also be found in flocking behavior modeling, initially examined in the work of Reynolds (1987), where the interaction between "boids" enables the simulation of bird movement with simple flocking rules like "separation", "cohesion" and "alignment". In another case of behavioral modeling with routes found in nature, namely that of social insects, the simulation of individual particles such as ants and termites, which interact with each other within a given environment based on "stigmergy" and "sematectonic communication", was examined in the work by Resnick (1994).

Since the first development of complex systems, their role in architecture has also been examined with pioneering applications to include, among others, the work on the use of Cellular Automata for the development of the Universal Constructor by John Frazer at the Architectural Association School of Architecture (Frazer, 1995) and the work on spatial growth of cities by Michael Batty at the Center for Advanced Spatial Analysis, UCL (Batty, 2005). Also, other examples include the work on emergent movement patterns for configuration analysis of space by Paul Coates at the Centre for Evolutionary Computing in Architecture (CECA), University of East London (Coates and Schmid, 1999), and the work at the same institute by (Carranza and Coates, 2000), where Swarm Intelligence was applied to achieve interaction with the environment following a collision detection algorithm based on the flocking movement approach introduced in the work of Reynolds (1987). Similarly, in design and construction field, the interaction between particles and their potential was

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discussed in the paper Swarm Tectonics by Neil Leach (2004), within the framework of a conference undertaken at the University of Bath in 2002 under the title Digital Tectonics (1). In this work, parallelisms between Swarm Intelligence and structural design were drawn, identifying structures as "self-organized" systems involving "a 'population' of smaller, nomadic components operating within the logic of swarm intelligence" (Leach, 2004).

2. Path systems in the work of Frei Otto

Path systems can be characterized as a type of complex systems whose role in architecture has been extensively discussed among architects and theorists. In particular, their importance has been emphasized, describing them as a special form of interactive systems composed of vertices and edges similar to networks. According to the work Occupying and Connecting (Otto, 2009) by Frei Otto (1925-2015), a pioneer architect and structural engineer at the Institute for Lightweight Structures (IL), University of Stuttgart, path systems can "assist in the communication of animals and humans, the movement of individuals, groups and herds, and the transport of masses and forces, often made easier by various aids". In the same work, path systems were distinguished into the ones that can be found in non-living and living nature. Specifically, non-living nature examples include among others branching that might be generated by water transportation, path systems made from spread of light where materials and forces are transported, and sound waves that allow travel and transport of energy. As Frei Otto stated, such examples "show forms of distancing or attractive occupation" (Otto, 2009). Examples in living nature include, among others, fluid paths that serve the transportation of micro-organisms, plant fluid transport systems that operate similarly to energy transport and path systems generated by the movement of animal colonies (ants, termites and bees) that leave traces for air supply, food provision and transport of building materials (Otto, 2009); a complex behavior that has also been discussed in the sub-section above.

References to similar systems, and their relationship with architectural examples, can be found in the field of biomimetics or biomimicry (Pawlyn, 2011), particularly regarding the way path systems derived from non-living and living organisms are interpreted as architectural and construction systems. This can be done either based on their behavior or their properties, mostly to fulfil a task or to express usefulness, effectiveness, optimality, etc. (Otto, 2009). A direction of investigation that dates back to the well-known and significant work On growth and form by D'Arcy Thompson (1966), where various examples of natural systems are discussed, draws analogies with man-made structural systems. More precisely, discussion on the form and branching can be generated, for instance, through the example of blood-vessels, whose form and arrangement help circulation with minimal effort and with minimum of wall-surface, investigating at the same time, the angle of branching so that the least possible loss of energy can be achieved (Thompson, 1966). Furthermore, discussion on the form and mechanical efficiency, particularly with regard to the structure of bones, evidences that the specific line arrangement in the interior of bones achieves a match between density of bone filament and concentration of stresses (Pawlyn, 2011). Moreover, in the example of birds sculls (Pawlyn, 2011, Finsterwalder, 2011), the economy of materials and their lightweight nature increases the ability of birds to fly, formulating, at the same time, a three-dimensional system of beams in the interior of bones (Finsterwalder, 2011).

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In addition to the search for path systems found in nature, the work by Frei Otto (2009) concentrated on physical experiments, by following "analogy research", where, apart from "optical comparison of forms and objects", investigation on "physical origination processes" was conducted, similar to chain hanging modelling techniques by Antoni Gaudi (1852-1926). Within this framework, Otto's work on "optimal path systems" attempted to generate minimal path systems, ideal for traffic routes (Otto and Rasch, 1995), using wool threads as the material of implementation. Specifically, starting from direct path systems with all target points around a circle which, in this case, were represented as houses, connections were made by stretching the threads between start and end-points. After the threads were loosened at 8% of their actual size and dipped into water, they were stuck together resulting to the development of a system with "minimal detours", showing that "the area needed for the transport routes to be constructed and their overall length is significantly smaller" and "only 30-50% of the direct path system" (Otto and Rasch, 1995) (Figure 1). In addition, following similar principles of "analogy research", investigation into occupation area occupation has also been conducted by Frei Otto and his team, in this case using bar magnets that were dipped into water based on repulsion and attraction forces enabling, in this way, the investigation on distancing and attractive occupation of spaces (Otto and Rasch, 1995; Otto, 2009). In his work NOX: Machine architecture, the architect Lars Spuybroek (2004) followed and discussed Frei Otto's work on path systems and described the process as "analogue computing"; a machine of design in which materials act as "agents" with certain flexibility and a certain amount of freedom, achieving restructuring from a liquid to a rigid system through interactions among elements in time (Spuybroek, 2004).

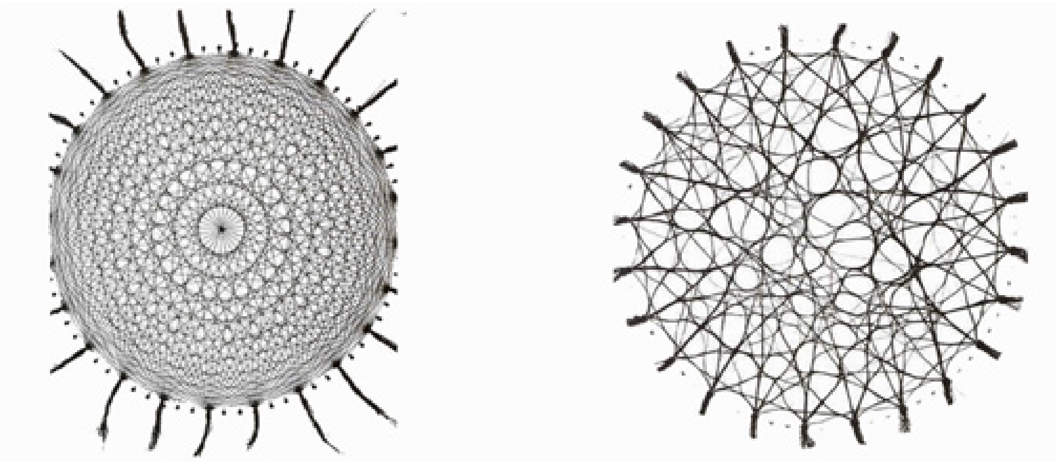

Figure 1.
Direct and optimal path systems
(Otto and Rasch, 1995)

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3. Computational methods for path systems form-finding

Almost two decades after the conference on Digital Tectonics at the University of Bath (1), the role of complex systems in architecture and construction industry, and the way these are observed and interpreted, continue to essentially influence how architectural and construction systems are developed and implemented. This is because architectural and construction systems, from the conceptual design to the fabrication stage, involve dynamic interactions between a large number of individual components which, in most cases, carry contradicting parameters and objectives that can be seen as forms of complex systems. Nowadays, more than ever, architectural investigation on such systems is reinforced by advanced computational tools and robotic fabrication processes, aiming at a more unified connection between the two initially separated design and physical implementation parts.

In order to achieve this, fully operational workflows are required, where forces, materials and robotic tools can be inseparably connected to transfer information as accurate as possible, from the design to the fabrication stage. Such investigation can take different directions which include, among others, computational design for form-finding, and later on, robotic fabrication by direct transferring of complex design results to a sort of computer-numerical control (CNC) machines for physical execution. The first part, i.e., that of design through form-finding and analysis steps, has been extensively discussed in literature, especially in connection with the simulation and investigation of the static behavior of structural and construction systems.

3.1 Form-finding

As mentioned above, computational form-finding techniques follow the pioneering work on physical models conducted by Antoni Gaudi and Frei Otto (1995). The further development of those techniques, through the use of computational design tools and simulation approaches, undoubtedly, offers the possibility for the investigation and analysis of structures accurately and close to their natural behavior, but also for the analysis of their performance under the influence of particular forces. The work of Phocas et al. (2019) gives an overview on the use of computational techniques which, on one hand, deals with geometrical development and physics-based simulation of systems and, on the other, allows numerical analysis of results, with special emphasis on their application in advanced tensile and bending active systems, including tensegrity, tensile and bending-active structures. In this case, two main form-finding approaches are distinguished, the Force-density (Schek, 1974) and the Dynamic relaxation methods (Day, 1966; Barnes, 1998). In the first case, the equilibrium state of any structure consisting of nodes and edges is described based on the force-length ration or force-density that is applied to every single element while, in the second case, the static equilibrium state is achieved by the gradual finding of the motion of structural nodes (Schek, 1974; Day, 1966; Barnes, 1998). The investigation on geometrical development, conducted at the early design stage, along with the simulation of forces and material behavior, are today more feasible and simplified due to the rapid development of parametric design programs and the physics-based computer modeling approaches. Such tools, as the Kangaroo plug-in for Grasshopper (4), a parametrically controlled physics-based engine (Piker, 2013), offers an ideal environment where form-finding of structures can be investigated through a range of physics-based rules such as the well-known particle-spring technique based on Hooke's Law of elastic stress-strain behavior (Kontovourkis et al, 2013; Ahlquist and Menges, 2011). By applying gravity and self-loading to particles and by assigning spring behavior, stiffness and damping properties to lines, the geometry consisting from nodes and edges can gradually find its equilibrium position in space.

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3.2 String effect based on virtual forces

Within the framework of the author's doctoral research, entitled "Computer-generated circulation diagrams" (Kontovourkis, 2009; 2010; 2012), conducted at the University of Bath under the supervision of Dr. Chris J.K. Williams, a computer program, based on the idea of "virtual forces", was developed to describe people movement behavior. Specifically, the "virtual force" model simulates, in real time and in parallel, a continuous movement of people in space, based on forces, real or virtual, which are acting upon each individual (the term individual represents particle, agent, etc. that might be used in different research works), motivating their motion and interaction behavior. The model is coded using C++ language with OpenGL graphics and it consists of a number of movement behavior rules that represent effects, which include the repulsive effect, the obstacle avoidance effect, the boundary avoidance effect (Figure 2), the attractive effect (Figure 3), the string effect, the sigh effect (Figure 4a and 4b), etc. Different types of individuals are subjected to different virtual forces (effects) at local level, accelerating their movement or interaction with other individuals and the environment. The summation of all forces, or effects, acting on each individual results in an overall behavior at global level, generating circulation diagrams based on the movement performance of people in space. In this context, different phenomena emerge; for instance, the application of the repulsive effect in cases where a large number of people move in opposite directions causes self-organized movement; a real situation phenomenon called stripe formation, which was discussed in the pioneering work on crowd simulation by Helbing et al. (2005).

As part of this research investigation, an attempt to simulate Frei Otto's work on path systems (Otto and Rasch, 1995) was made that was called string effect. In this case, strings consist of lines and particles were arranged randomly in the perimeter of a circle, which represented wool threads. Virtual attractive forces were applied, accelerating motion of particles. Specifically, particles in the same string attract each other due to the tension of strings and particles from different strings attract each other by surface tension under a certain distance (Kontovourkis, 2009; 2010; 2012) (Figure 5).

3.3 Structural and topology optimization

Form-finding techniques offer the opportunity for rapid geometrical development of structures at an early design stage, necessary to be accompanied by a more accurate static analysis of structure performance through the use of Finite Elements Analysis tools (SAP2000 (2), Abaqus (3), etc.). In addition, Topology Optimization, a method for optimizing material distribution in structures based on given space and boundary conditions, enhances a more direct relationship between static analysis and generated geometry, aiming at reducing material while maximizing static performance. Well-known techniques include, among others, the Solid Isotropic Microstructure with Panelization (SIMP) and the Evolutionary Structure Optimization (ESO) (Gardan and Schneider, 2015; Donofrio, 2016). Furthermore, tools like Ameba (5), a plug-in for Grasshopper based on Bio-directional Evolutionary Structural Optimization (BESO) (Li et al. 2018; Xia et al. 2018) offers a more direct rela-

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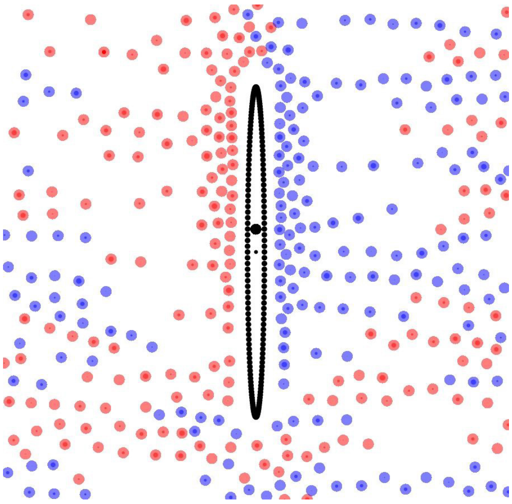

Figure 2.
Boundary avoidance effect (Kontovourkis, 2009)

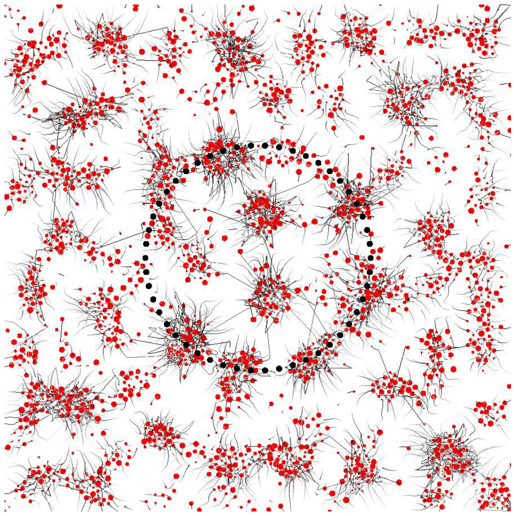

Figure 3.
Attractive effect (Kontovourkis, 2009; 2012)

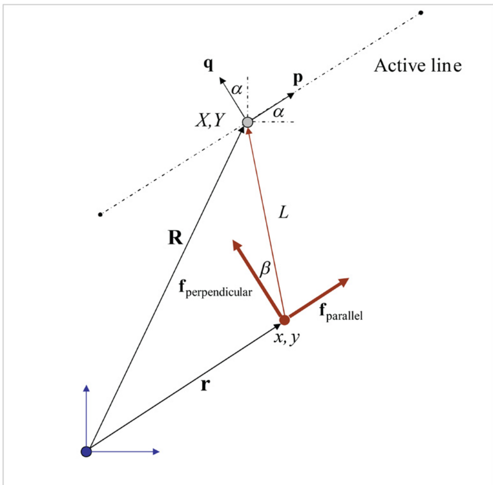

Figure 4a.
Model that describes individual-sign geometry (Kontovourkis, 2009; 2010; 2012)

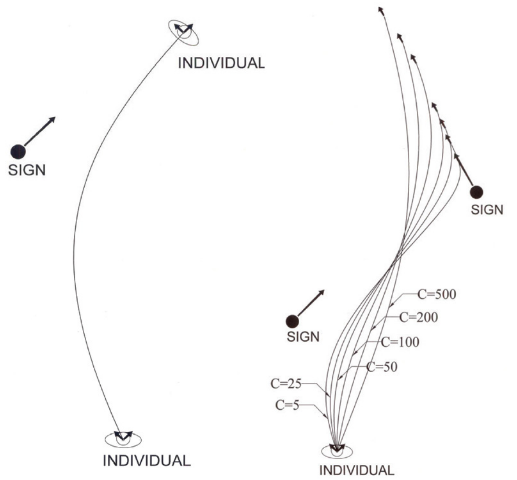

Figure 4b.
(Left) Path curve produced by sign effect (Kontovourkis, 2009; 2010; 2012) , (Right) Path curves controlled by different parametric values (Kontovourkis, 2009;)

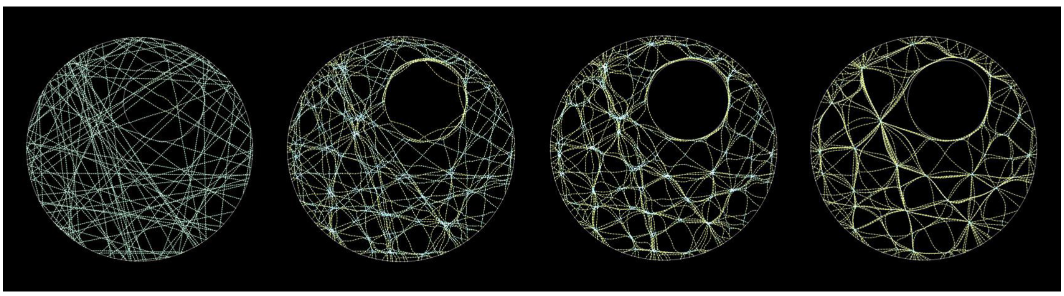

Figure 5.
Path system generated using string effect (Kontovourkis, 2009)

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tionship with design investigation through parametric control and results of Topology Optimization. Either form-finding, structural or topology optimization techniques, all refer to the digital exploration of structures and their static analysis, or configuration, in order to achieve their geometric and static viability. At the actual construction phase, problems often arise, especially during the construction of non-conventional architectural and structural systems. In these case, the implementation of robotic processes could allow the reduction of construction time and cost, and at the same time, it could provide a higher degree of accuracy compared to conventional construction approaches.

4. Integrated computational design optimization and robotic fabri cation

The design development and physical construction of architectural and structural systems through integrated approaches have a number of advantages over other processes, where the two parts are operating independently, particularly when referring to non-conventional forms. Thus, integrated approaches achieve precision, flexibility, economy and time efficiency since computational design optimization informs robotic fabrication and vice versa.

Within this framework, two case examples are summarized in the section below. Specifically, reference is made to projects undertaken in the research laboratory for Digital Developments in Architecture and Prototyping – d2AP (5) in the Department of Architecture at the University of Cyprus, where the development of path systems plays an important role in shaping the methodological frameworks towards robotic construction. In the first case, the particle-spring technique, based on Hooke's Law of elastic stress-strain behavior, determines the form-finding process in case of tensile mesh structures using polyurethane elastomeric threads, a process that interrelates with the static behavior of systems and the toolpath that robotically-driven end-effector mechanisms can follow for their physical realization (Tryfonos, 2018; Kontovourkis and Tryfonos, 2016; 2018a). In the second example, Topology Optimization principles are used as mechanisms to optimize material distribution. Then, hexagonal infill patterns are applied and pass through a form-finding procedure in order to allow possibilities for redefining their infill geometry according to the optimal distribution of material; in this case, clay-mixtures. Finally, generated infill patterns are employed to control the robotic toolpaths and the material for the 3D printing of building components (Kontovourkis et al, 2019). Path systems are used as a common feature in both cases, whereby they are translated into robotic toolpaths, through form-finding as an approach for computational design optimization, aiming at developing sustainable and efficient design and fabrication workflows.

4.1 Robotic additive manufacturing of tensile mesh structures

In the first case, an integrated approach that investigates the design, simulation and robotic fabrication of elastic tensile mesh structures has been developed. In parallel, an innovative custom-made end-effector tool has been introduced and tested (Tryfonos, 2018; Kontovourkis and Tryfonos, 2016; 2018a). In particular, the need for high precision manufacturing of complex elastic systems, due to their geometrical characteristics and the elastic behavior of polyurethane elastomeric material, has led to the design exploration of systems through form-finding, static analysis and optimization. This has been done in order to achieve pretension control of the elastic threads, while transferring the information easily and effectively to the robot and the end-effector tools for physical execution. To this end, a weaving elastic mesh geometry has been proposed, which has been form-found, statically analyzed, and finally optimized in order to find the best fitting results that satisfy geometrical, struc-

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tural, and robotic fabrication requirements. Important parameters include the weaving typologies used for additive manufacturing, the elasticity and diameter of material, as well as the capabilities of the robot and the end-effector tools.

At the level of design, the weaving patterns have been parametrically defined and controlled in Grasshopper environment (Figure 6). The physics-based software Kangaroo (Piker, 2013) has been applied to the same platform for form-finding using particle-spring behavior in order to simulate thread relaxation. The application of pretension forces on threads has enabled the deformation of the tensile mesh structure and its stabilization (Figure 7). Finally, the static analysis software SAP2000 (2) was used to evaluate the results derived from the form-finding process. Due to the large number of parameters and the complexity of the process involved, the results have been optimized using multi-objective genetic algorithms (Deb, 2002), whereas best fitting solutions for robotic fabrication have been selected based on the Pareto front graph by taking into account static and geometrical criteria. At the physical prototyping level, an industrial robotic arm, the ABB IRB2600 with IRC5 controller and the custom-made end-effector tool, were applied for the additive manufacturing of elastic threads, evaluating, at the same time, the ability of fabrication mechanisms to accurately execute specific tensile mesh systems with specific pretension behavior and toolpaths (Figure 8a and Figure 8b).

3.2 Robotic additive manufacturing of building components

In the second case, a methodological framework that describes the form-finding and the robotic fabrication of building components has been conducted. This was done through robotic 3D printing, using specific clay-based material mixtures (Kontovourkis et al, 2019). At the same time, the current role of 3D printing in construction-scale applications is discussed, particularly with regard to construction time and cost; two aspects that are associated with material minimization and structural efficiency. In this direction, the design development and static analysis of construction components has been achieved through topology optimization and form-finding principles, aiming at optimizing infill patterns for 3D printing execution and at finding solutions that satisfy geometrical, static and fabrication criteria. In this case, path systems in the form of hexagonal infill patterns played an important role during the process due to their ability to act as structural and construction systems.

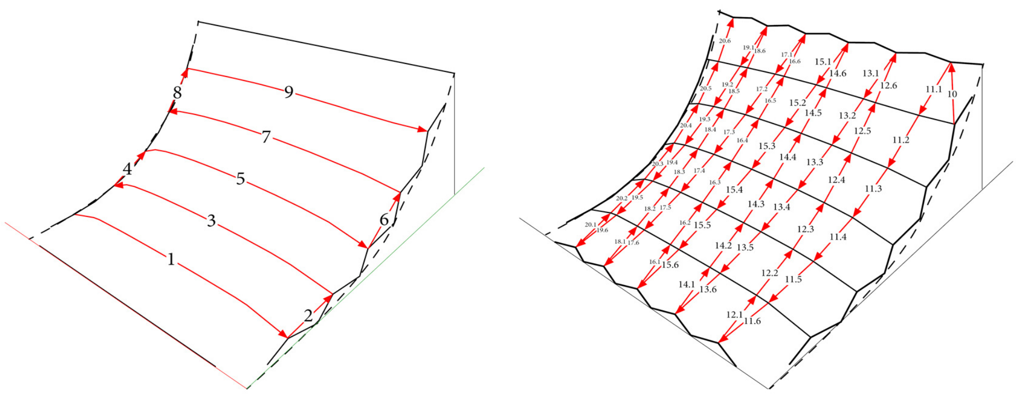

Figure 6.
Weave sequence (Tryfonos, 2018; Kontovourkis and Tryfonos, 2018a)

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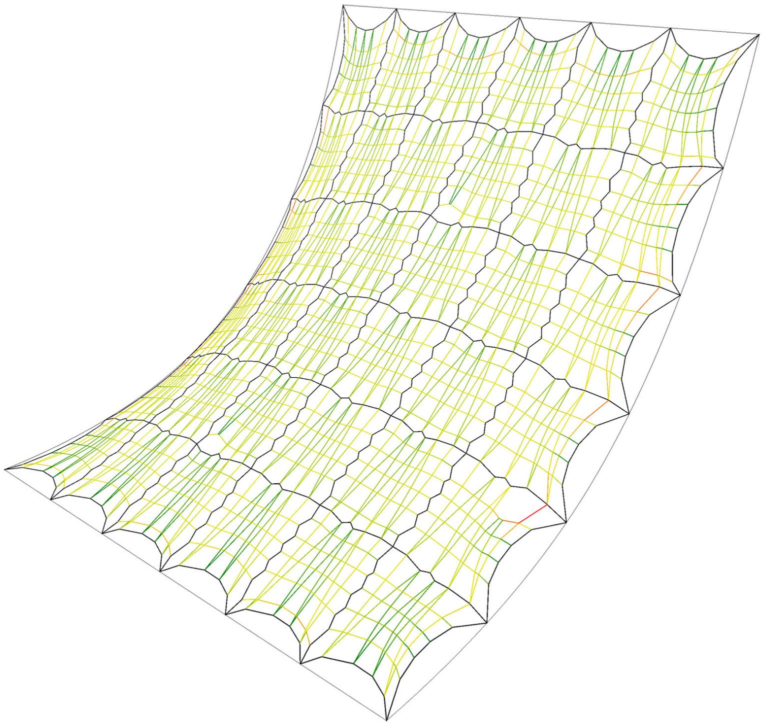

Figure 7.
Tensile mesh structure (Tryfonos, 2018; Kontovourkis and Tryfonos, 2018a)

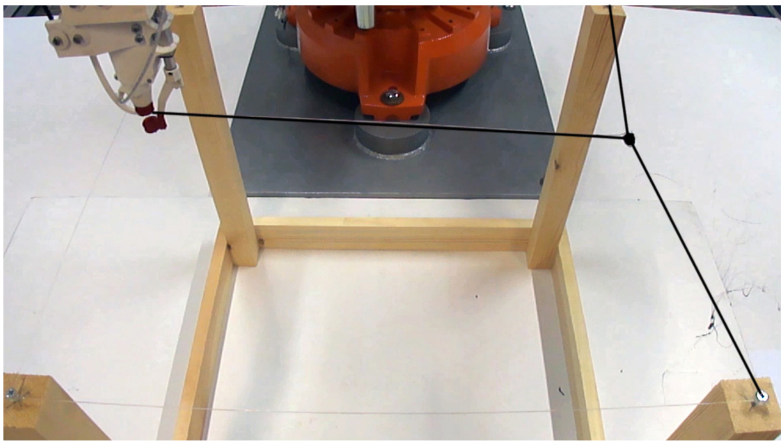

Figure 8a.
Additive manufacturing of an elastic thread (Tryfonos, 2018; Kontovourkis and Tryfonos, 2018a)

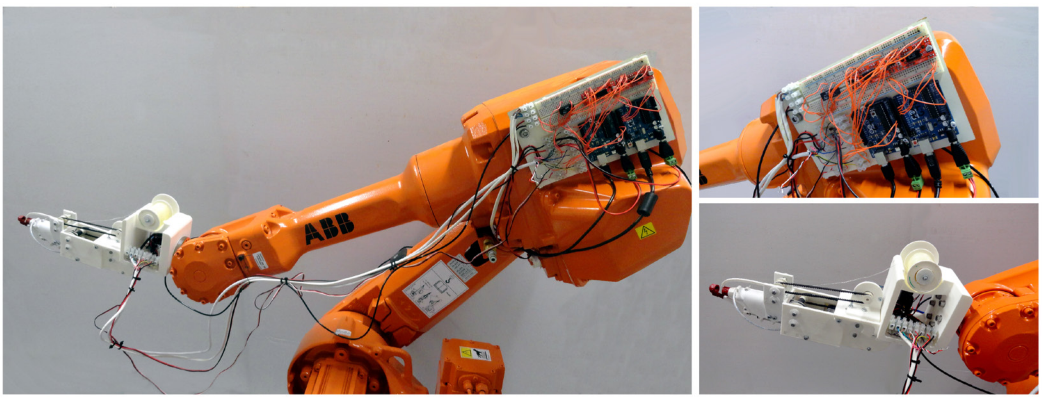

Figure 8b.
Custom-made end-effector tool (Kontovourkis and Tryfonos, 2016)

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At the form-finding level, the topology optimization tool Ameba, a plug-in for Grasshopper, which is based on Bio-directional Evolutionary Structural Optimization (BESO) was applied in the initial solid geometry in order to iteratively remove inefficient and add efficient material in the body of structure (Li et al. 2018; Xia et al. 2018). Then, hexagonal infill patterns were associated with the results obtained from optimization, which were further investigated in order to achieve the best distribution and minimization of material but also to preserve their static performance. Their development consisted of stretching and loosening the infill patterns for best deviation of their geometry in relation to the loading and material distribution areas using the Kangaroo physics-based engine (Piker, 2013). The programing of the relative speed of 3D printing followed in order to deposit thinner and thicker material filaments on hexagonal infill according to the results obtained from topology optimization (Figure 9a and Figure 9b). In order to verify the results, a finite element analysis in Abaqus was conducted, showing the allowable limits of compressive strength. At the robotic 3D printing level, the toolpath planning for robotic execution was achieved through a suggested parametric algorithm (Kontovourkis and Tryfonos, 2018b), which integrates the proposed geometry derived from infill pattern optimization with 3D printing extruder capabilities, particularly in terms of their nozzle diameter and 3D printing speed (Kontovourkis et al, 2019) (Figure 10a and Figure 10b).

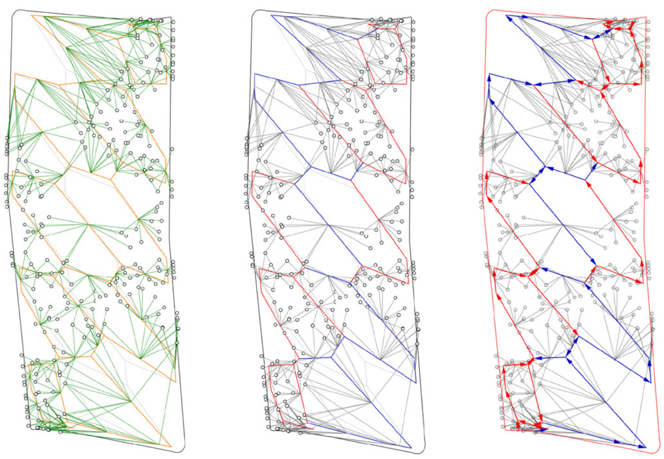

Figure 9a.
Material density mapping based on the results of topology optimization (Kontovourkis et al, 2019)

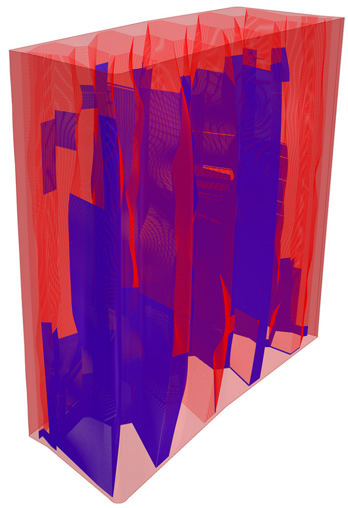

Figure 9b.
Overall toolpath development (Kontovourkis et al, 2019)

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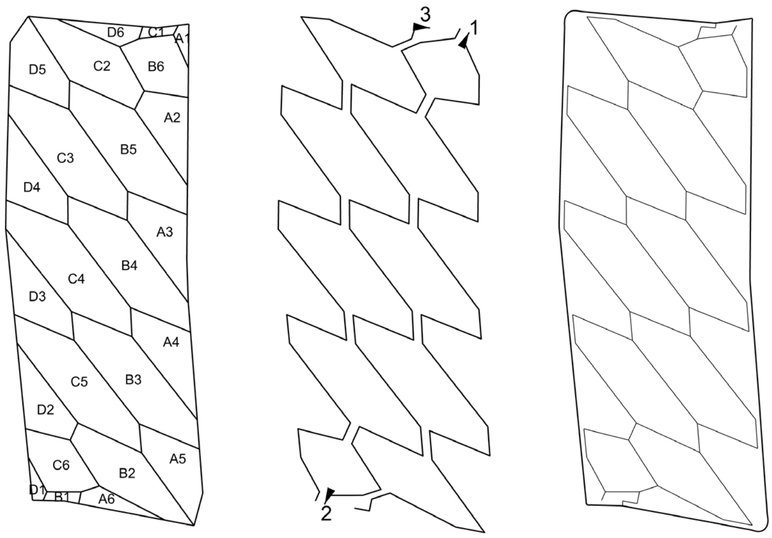

Figure 10a.
Continues infill toolpath planning
(Kontovourkis et al, 2019)

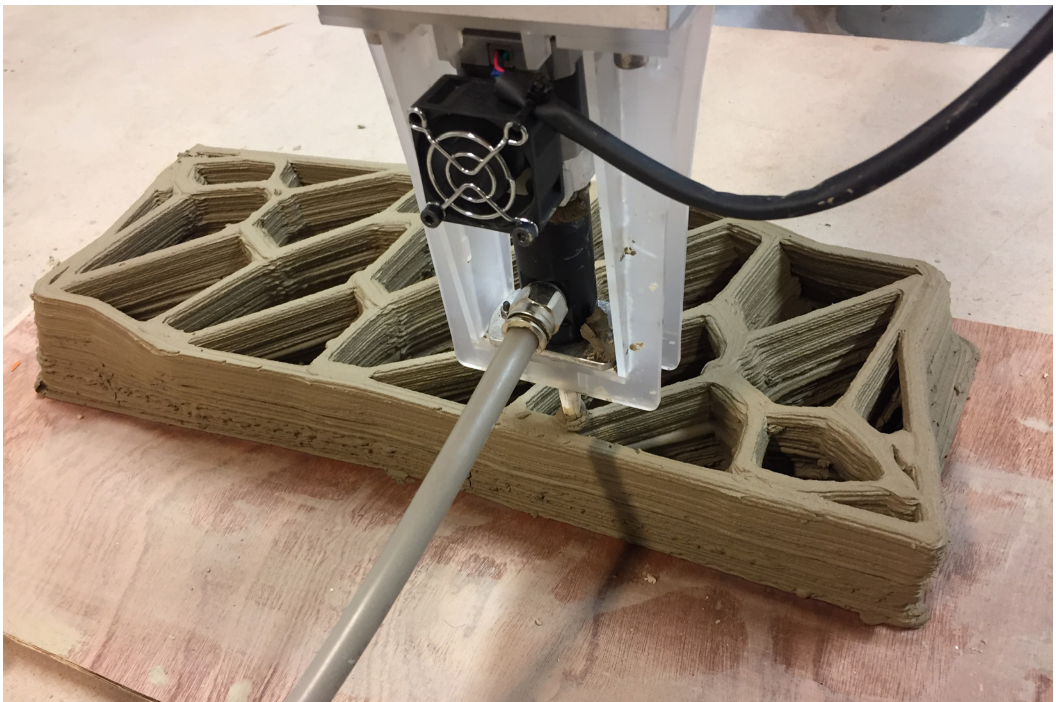

Figure 10b.
3D printing execution (Kontovourkis et al, 2019)

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5. Conclusions

In this paper, the role of path systems within an overall framework that includes computational design optimization and robotic fabrication is briefly reviewed. With references to Frei Otto's pioneering work, where such systems were extensively investigated using physical models, the paper discusses a number of available capabilities to be introduced within an integrated framework of computational design optimization and robotic fabrication. The latest developments in computational processes, especially in the first part of the investigation where form-finding procedures are implemented, as well as the rapid development in the area of robotic fabrication, formulate the framework under which new and more integrated fabrication processes driven by automated mechanisms can be developed in construction-scale examples. Although several years have passed since their first introduction in architecture, the discussion on issues related to complex systems, with emphasis on path systems, shows their potential to be continuously considered as a dynamic mechanism that can be investigated through contemporary means in order to achieve an effective interaction between forces, materials and robotic toolpaths.

This is evidenced through two research projects developed in our research laboratory for Digital Developments in Architecture and Prototyping – d2AP. The first refers to an integrated form-finding and multi-objective optimization approach that informs tensile mesh results complied with geometrical criteria, material constraints and robotic fabrication possibilities. The second project refers to an approach for robotic 3D printing, where building components are explored in terms of material minimization by investigating and optimizing infill patterns. In both cases, common aspects are correlated to path systems used as pathways where robotic tools execute the given assignments while, at the same time, they function as mechanisms for force and material distribution with the aim to achieve an optimum balance between material minimization and structural adequacy.

Notes

(1) Digital Tectonics: http://www.bath.ac.uk/digitaltectonics/
(2) SAP2000: https://www.csiamerica.com/products/sap2000
(3) Abaqus: https://www.3ds.com/products-services/simulia/products/abaqus/
(4) Grasshopper: http://www.grasshopper3d.com
(5) Ameba: https://ameba.xieym.com/index_en/

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