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Topological Design and Optimization of Robotic Additively Manufactured Cable-Nets

Daniel TISH*, Wes McGEE[a], Tim SCHORK[b], Geoffrey THÜN[a], Kathy VELIKOV[a]

*University of Technology Sydney, University of Michigan
2000 Bonisteel Blvd, Ann Arbor, MI 48109
dantish@umich.edu

[a] University of Michigan
[b] University of Technology Sydney

Abstract

Advances in additive manufacturing have availed the possibility to directly fabricate the results of topological optimization processes, especially those carried out by hard-kill methods such as the BESO process. However, a much less established area of research is the use of topological optimization for flexible forms and cable-nets through the use of elastomers in the additive manufacturing of their constituent geometries. Robotic additive manufacturing of cable-net structures with elastomeric material enables methods of topological design and topological optimization which are capable of embedding new formal, behavior, and performance properties in the cable-net material system. These capabilities are demonstrated and discussed through a series of case-studies realized by the authors.

Keywords: Additive manufacturing, robotic fabrication, topological optimization, topological design, cable-net, form-finding

1. Introduction

Large-scale additive manufacturing technologies have begun to transform the predominant approach to fabrication and construction processes from specifying and assembling standardized building components made from homogenous materials towards the aggregation of highly bespoke assemblies made from specifically designed materials. This shift and advancement in fabrication methods has occurred in tandem with the development of topological optimization methods that aim to minimize the overall weight of a structure through the determination of connectivity, shape, and voids (Deaton and Grandhi [1]). While topological optimization methods are well-researched and widely used in structural engineering, their use in the early stages of architectural design is also continually increasing. Simultaneously, the capacities enabled by additive manufacturing have made it more feasible to directly produce the irregular geometries that are typically the result of topological optimization processes (Tam and Mueller [2], Gardiner [3]). Current research on metamaterials in the material sciences have also leveraged additive manufacturing to produce material constructs in which novel mechanical behaviors or other properties not normally attributable to the raw material itself are ingrained into a material through deliberate structuring at the nano- or micro-scale (Lee et al. [4]).

The BESO method, developed by Querin, Steven and Xie [5], and other hard-kill methods of topological optimization translate particularly well to additive manufacturing fabrication methods since the system is defined by voxels that are constrained to either solid or void conditions (Brackett [6]). On the other hand, density-based methods of topological optimization, exemplified by the SIMP method developed separately by Bendsøe [7] and Zhou and Rozvany [8], typically employ a penalization process to drive intermediate material densities towards binary distinctions, but often leave some voxels just shy of fully solid or void definitions. This necessitates additional post-processing before the additive manufacturing stage for single material prints, but density-based methods without penalization have already been

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employed successfully for multi-material prints capable of producing a continuous range of densities (Michalatos and Payne [9]).

In addition to the research on topological optimization processes, there has been much work done on the impact of topology networks on form-active structures such as cable-net and tensile membrane structures. In cable-net structures, the individual edges clearly define a line of force in the structure and as such the topological network impacts the flow of force between elements and subsequently the form of the structure at a micro and macro level (Otto [10]). The form-finding of these form-active structures is typically undertaken through the method of particle-spring physics simulation such as those developed by Kilian and Ochsendorf [11] or Piker [12]. Employing this method, Ahlquist and Menges [13] have demonstrated the effect that topology can have on simple cable-net structures and argue that topology is the primary input in particle-spring systems.

Despite such interest in cable-net and tensile membrane structures, there is little existing research that investigates the design opportunities afforded by large-scale robotic additive manufacturing to fabricate highly customized mesh topologies. This paper presents three realized case studies that develop different approaches to topological design as the critical medium for form-active structures due to its ability to produce novel properties for formal, behavioral, and structural considerations, likening it to other metamaterial constructs.

2. Case Studies

2.1. Infundibuliforms

The first case study, entitled Infundibuliforms, is a 30m^2 lightweight kinetic cable-net that is controlled by cable-robotics (McGee et al. 2018 [14]). The aim of this case study was the design of kinetic systems capable of desired gross deformations and involved the study of material systems that would allow for such a multiplicity of forms with a wide range of surface areas, which resulted in the development of a robotic additive manufacturing system for thermoplastic elastomers.

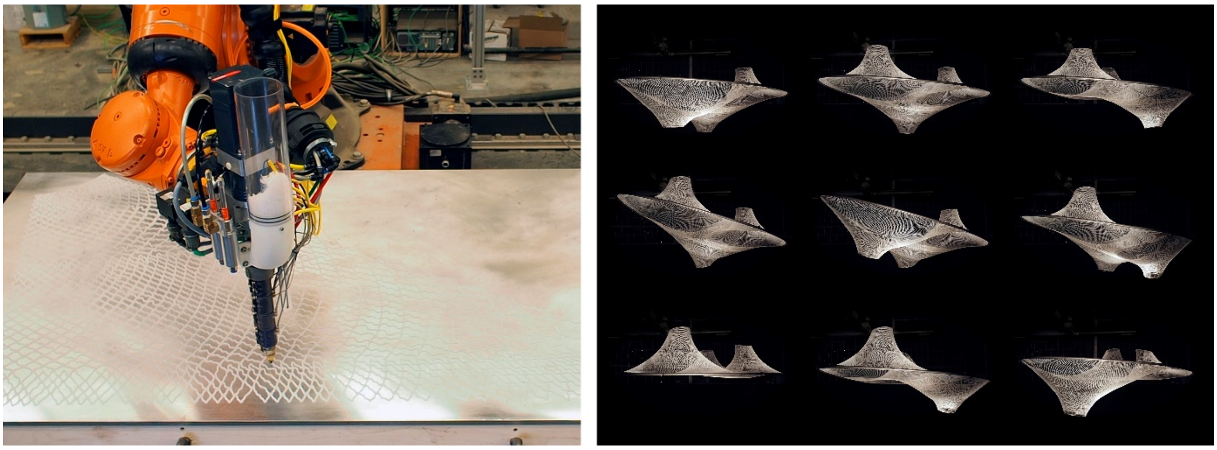

Figure 1: Robotic additive manufacturing work cell and process (L); Nine different positions of the Infundibuliforms installation exhibiting a variety of forms and surface areas while always remaining taut (R).

As part of the research, the authors developed a custom pelletized thermoplastic extrusion end effector for a 6-axis industrial robot, as well as a 1200mm x 2400mm heated aluminum table that was required for the additive manufacturing process of thermoplastic elastomers (McGee et al. 2017 [15]). This robotic work cell and pellet extruder enabled the production of bespoke elastic cable-nets by allowing the authors to take advantage of the scale and precision of industrial robots in addition to a wider range of thermoplastics than those available in filament form. For this work, an extremely elastic 35A durometer thermoplastic elastomer (TPE) was used for the concentric catenoidal forms, with a reinforcing saddle made of a 68A TPE between the concentric zones to provide additional tension in the surface to resist self-deflection.

The topological design research was undertaken towards two distinct goals: the tuning of the cable-net topology to guide the active form of the piece towards catenoid, or infundibulum, forms; and the material programming of curving mesh members to embed uniquely tailored three-dimensional forms that diverge from mathematically minimal surfaces in the two-dimensional mesh prints.

2.1.1. Infundibulum Forming

In order to explore the effect topology has on the final form, the research leverages particle-spring physics simulators to predict the form of the installation at any given time by solving the interactions between the cable-robot positioning system, the material characteristics of the elastomer, and topological structure of the mesh itself. In particular, the aesthetic or formal goal of the design team was to produce dramatically shaped catenoidal forms at the connection to the cable-robot control rings.

When working with a radial or concentric regular quadrilateral topology, the loaded forms are distinctly conical due to the direct load path from inner ring to outer frame. In order to achieve the anticlastic form through topology, a diagonal grid is introduced by replacing each edge of the original quad grid with a mesh face centered on its midpoint. The diagonal grid exhibits many advantages over the base quad grid, including the desired acutely-shaped anticlastic form due to the spiraling nature of the load paths. The diagonal grid also results in a more uniform structural utilization of the material since both directions of the grid span from inner ring to outer frame, in contrast to the base quad mesh whose radial members take on the majority of the load in the surface. Lastly, the diagonal grid does not result in odd-valence joints at the edges like a quad mesh, where an odd number of edges meet at a vertex and produce a dead-end for the additive manufacturing toolpath. While stop-and-go extrusion procedures are possible, the authors found that the additive manufacturing process is far more robust when the robot doesn't have to make unnecessary starts and stops, and therefore favored a continuous toolpath approach.

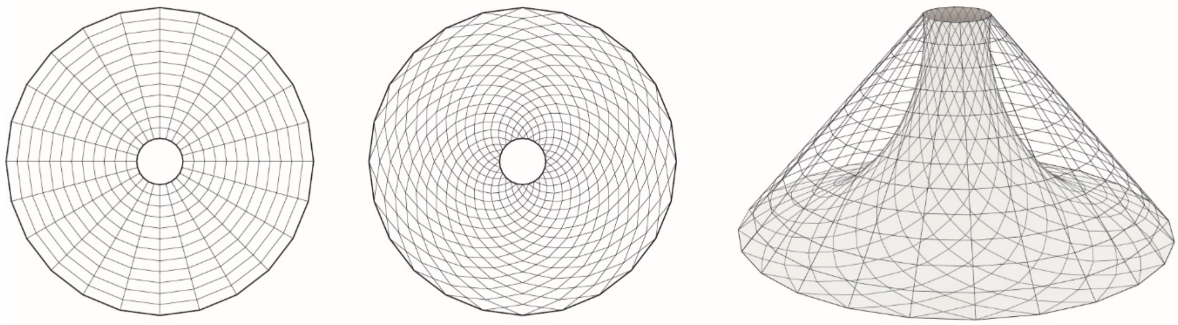

Figure 2: Form-active shapes (R) of regular quad grid (L) and diagonal grid (M) with identical properties as simulated by a particle-spring system

Additionally, a diagonal topology allows the degree of curvature of the catenoid to be tuned across the surface by controlling the UV subdivisions of the base quad mesh. By increasing the number of concentric subdivisions relative to their radial counterparts, the resultant form-active structure could be more dramatically anticlastic. The final topology of the three funnel-shaped forms utilize this method to increase the curvature of the loaded forms, while also relying on two additional subdivisions in the diagonal grid topology to maintain an appropriate density at the exterior edges and flexibility near the interior ring. As such, the overall form of the prototype installation was largely designed through precise manipulations in the meso-scale topological structure of the tensile mesh.

2.1.2. Material Programming

The research also addresses the additional challenge of fabricating cable-nets on a two-dimensional surface, so that its formation could only be a result of the combination of topology and material properties. While the thermoplastic material is very elastic and capable of substantial elongations before breaking, the range of the cable-robotic system would have greatly exceeded the elastic capacity of a completely two-dimensional cable-net topology. Therefore, the team set out to find a way to produce the doubly-curved, three-dimensional (3D) cable net structure on the two-dimensional (2D) plane of the aluminum surface.

The typical approach to this issue would be to discretize the 3D global surface, reorienting and flattening the parts onto a 2D plane, accepting a minimal displacement in the process. However, this couture-influenced approach deals poorly with the changes in surface area that occur while the piece is in motion, leading to an excess of material in the flat state and unsightly self-deflection. As an alternative to this approach, a method of programming the 3D forms into the 2D meshes was developed through the concept that the additional edge lengths lost in projection from 3D to 2D could be reintroduced as curves between the same two endpoints. This method leverages the elastic qualities of the particular TPE material in use, for which printed curves easily deform into lines when loaded and return back to their curved state when the load is removed.

This method begins by simply projecting the 3D form onto the 2D plane representing its plan figure. The mesh edges are then subdivided and their lengths iteratively grown through the use of a particle-spring physics simulator, slowly increasing the length of each mesh edge until it precisely matches the original 3D edge length. The particle-spring physics simulator also incorporates a collision avoidance system to prevent any unintended intersections and maintain a minimum distance between edges, which is calibrated to the bead width of the extrusion system. The intersection angle at each joint in the 3D mesh is also transferred to the 2D mesh due to the fixed nature of the fused joints.

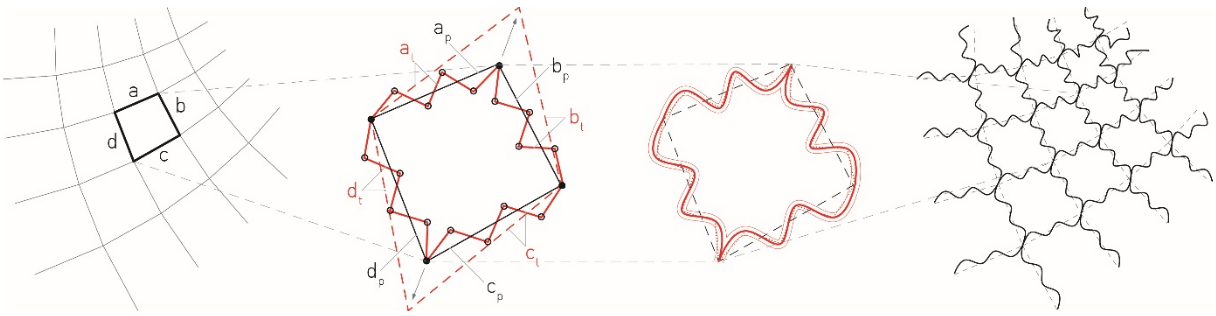

Figure 3: Process of geometric development for programmable geometry of the curving mesh edges.

Since each individual mesh edge is given a custom growth length, this method also avails the opportunity to embed tailored 3D forms that deviate from mathematical minimal surfaces in the 2D meshes. One base 2D pattern could host different 3D forms by embedding curves of different lengths into the original base geometry. Importantly for the Infundibuliforms installation, this method introduces an allowable geometric deformation in addition to the elastic material deformation, which affects the behavior of the cable-net similar to a metamaterial construct. This results in a taut surface in any state of the kinetic installation and extends the deformation capacity of the material system as a whole.

2.2. Cesca Chair Studies

In contrast to the use of topological design as a method to influence the final form-active shape, the aim of the Cesca chair case study is to tune the properties and performance of the additively manufactured cable-net itself through the topological meso-scale. Using Marcel Breuer's iconic Cesca Chair as the site for the explorations, these studies reinvent Breuer's woven cane surfaces into continuous, functionally graded cable-net surface. The goal of such explorations is to differentiate the material system in response to the stresses in the surface to efficiently deposit material only where it is needed most, an aim shared by structural topological optimization procedures which the studies incorporate.

The chair surface is produced with a mono-material extrusion process, and thus must produce variable stiffnesses through differentiations in the topology to functionally grade the surface as a whole. The process developed to optimize the chair surface is similar to the SIMP method in that it attempts to determine a required density for each local area of the surface. However, in contrast to the SIMP method which requires a penalization routine to guide the densities towards binary solid or void distinctions, our employed method uses an evolutionary solver to search for optimal differential density configurations. Therefore, our method is enabled by and responds to the unique capacities of the robotic additive manufacturing process, leveraging the ability to design and print custom single bead topologies to produce the differential densities. Such a process engages the meso-scale of the material system in order to calibrate the structural performance of each area of the surface.

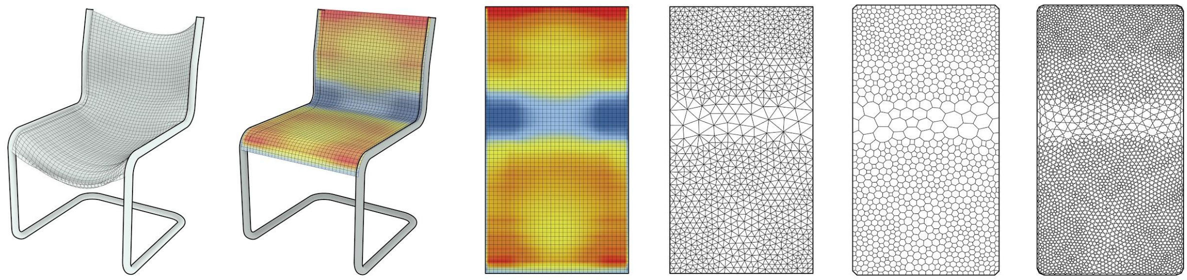

Figure 4: Process diagram for the topological optimization method, from simulated mesh to final toolpath.

A particle-spring physics simulator produces a high resolution data set of the strains in a regular quad mesh surface caused by an average person's seated weight and form. The chair surface is divided into 40x40mm subsection areas and the strain data for the edges within each local subsection are averaged in both the transverse and longitudinal directions. The average strain figures are then translated to a corresponding material density by remapping each strain value into a new domain bracketed by the minimum and maximum densities defined by the optimization sequence. The material densities are used to create corresponding mesh topologies for each subsections of the surface. The mesh topologies can be generated either through the random uniform distribution of a number of points determined by the density specification and a subsequent Delaunay triangulation, or through the specification of subdivisions in the parameter space of the subsection surface in order to create greater densities in one direction or another. The subsection meshes are then stitched back together into a continuous surface that blends the densities from one area to another.

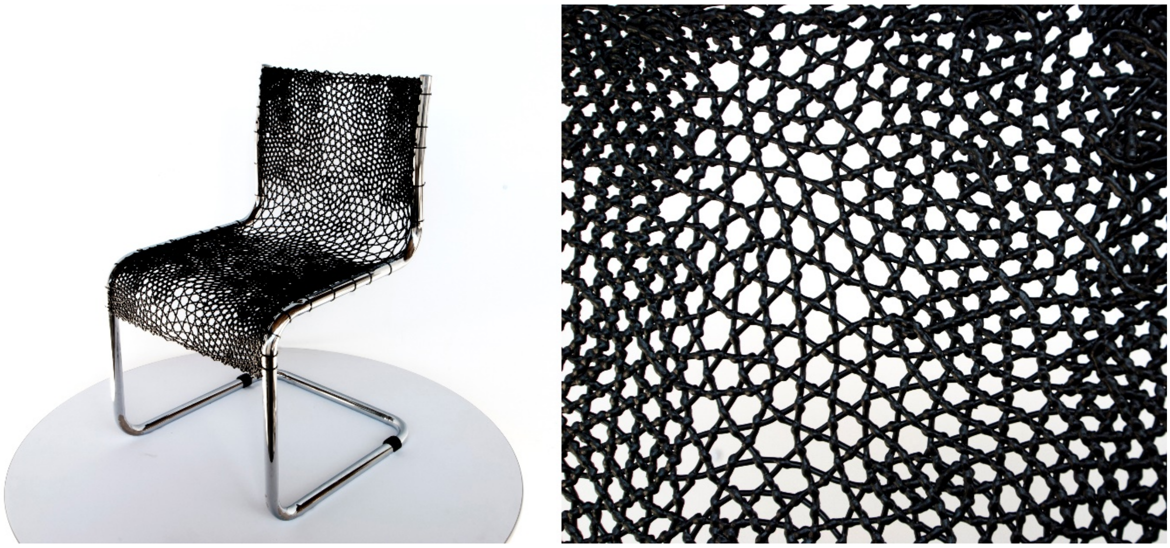

Figure 5: Final result of the random distribution topological optimization process on the Cesca chair (L), detail of the additively manufactured cable-net topology (R).

The optimization process minimizes the material usage of the cable-net surface while maintaining a baseline structural performance criteria by determining the range of densities in the graded topological structure. The fitness criteria used to evaluate the configurations within the solution space utilizes finite element analysis to simulate the deformation of each mesh topology under a typical sitting load. Each mesh topology whose maximum deformation exceeds the prespecified limit is penalized proportionally to its difference from the limit, while all those that perform under the limit are given the same numerical benefit. This deformation score is combined with the estimated total mass of the printed topology into a single objective for minimizing optimization. Using the NLOpt library [16], an evolutionary algorithm [17] is run first to search for a globally optimal solution, which is then locally refined using an implementation of the Subplex algorithm [18]. The optimization process results in substantial differences in density in the case of the Cesca chair surface, from a minimum area density of 0.815 kg/m^2 to a maximum of 2.61 kg/m^2 in the case of the random distribution method and a range of 1.09 kg/m^2 to 2.76 kg/m^2 in the surface subdivision method, where 2.84 kg/m^2 would represent a completely solid cell at the same extrusion height. The topological densities of the cable-net surface didactically expose the areas of highest stress in the surface and produce the greatest stiffness near the chair frame, especially in the back and seat areas, as compared to the underloaded areas such as transition from seat to back where the topology is sparsest.

2.3 Transient Geometries

The Transient Geometries installation at the University of Technology Sydney offered an opportunity to scale up the topological optimization methods developed through the Cesca Studies and to combine these with the programmable meshes from the Infundibuliforms research. The case-study also engaged with more complex *global* topologies in the construction of the form-active structures, specifically those with a 3D base geometry. The case-study's form-active shape creates a complex continuous surface spanning from one end of the building lobby to the other, engaging with the lobby column by wrapping down it and anchoring to the ground at its base, and features an actuated funnel form that senses and responds to the pedestrian flow entering and leaving the building. This case-study was fabricated using a custom-built filament extruder end effector and a UR10 robot with a 1200mm x 1200mm heat bed. The material in use for this installation was an 85A durometer thermoplastic polyurethane due to the necessity for a stiffer material to feed through the filament extruder.

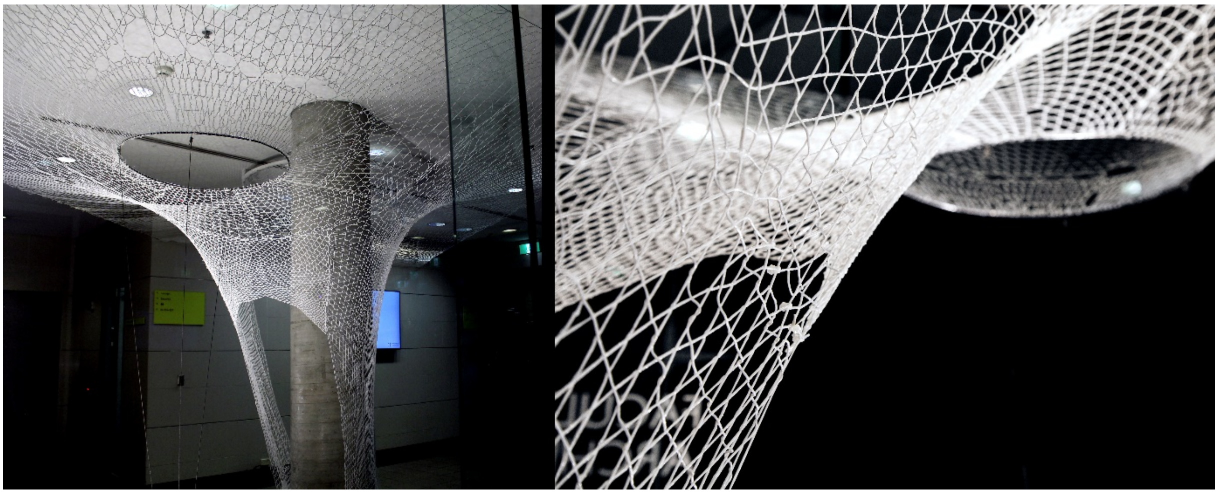

Figure 6: Transient Geometries installation at the University of Technology Sydney.

The topology of the cable-net structure is graded in response to the stresses in the surface using the methods developed by the Cesca Chair studies. The portions of the surface that surround the lobby's column and anchors to the ground carry the most tension in the system, and are therefore the densest while the outer areas of the overhead surfaces carry the least stress and are the most open. The actuated funnel form utilizes the material programming methods developed in Infundibuliforms to help adapt to its changing shape. In the process of trying to combine these two methods developed for unique purposes, however, some compatibility issues arose. Since the topological pattern of the graded surfaces is comprised mainly of a series of interconnected triangles, the material programming physics engine struggled to find space to add extra material with such an inflexible topology, as compared to one made of quadrilaterals, and only half of the additional material was able to be programmed in.

3. Discussion and Conclusion

As the presented case studies demonstrate through both topological design and topological optimization, the design of additively manufactured cable-net structures produces a dramatic reversal of the typical form-material relationship, wherein the material is subservient to the form. Rather than the normative mode in which a form is designed and a material is forced to conform to its specified shape, here the material system is designed in such a way that the desired formal qualities or performance characteristics are brought about through material agency in a bottom-up approach.

The next steps of the research will undertake structural tests to verify the expected performance and behavior of the cable-net structures. The topological optimization studies in particular should be tested to determine which method of topology generation consistently delivers the best results at a minimal weight, or which pattern types are most effective with certain load cases. Additionally, as the research so far has engaged with cable-net structures on a macro- and meso-scale, the next step would be to investigate how the micro-scale could be an arena for design through multi-material additive manufacturing. The ability to deposit materials of different strengths or durometers across the structure would alter the requirements for the topology and the behavior of the final form.

Robotic additive manufacturing techniques have the ability to change the way that designers not only fabricate, but conceive of and design cable-net structures. Custom topological organizations which would have been difficult to accurately achieve by prior manual or mechanical methods, can now be designed in standard CAD environments and fabricated easily. This ability opens up the topological structure, long known to be a key factor to the form-active shape of cable-nets, to new modes of design and optimization. This paper has presented three such novel approaches to topological design and optimization, conceiving of it as a part critical part of the metamaterial construct, and developing ways to program variations in form, behavior, and performance into the topology itself.

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References

[1] J. D. Deaton and R. V. Grandhi, "A survey of structural and multidisciplinary continuum topology optimization: post 2000," *Structural and Multidisciplinary Optimization,* vol. 49, no. 1, pp. 1-38, 2014.

[2] K.-M. M. Tam and C. T. Mueller, "Additive Manufacturing Along Principal Stress Lines," *3D Printing and Additive Manufacturing,* vol. 4, no. 2, pp. 63-81, 2017.

[3] J. Gardiner, "Exploring the Emerging Design Territory of Construction 3D Printing – Project Led Architectural Research," PhD Thesis, School of Architecture and Design, RMIT, 2011.

[4] J. H. Lee, J. P. Singer, and E. L. Thomas, "Micro-/Nanostructured Mechanical Metamaterials," *Advanced Materials,* vol. 24, no. 36, pp. 4782-4810, 2012.

[5] O. M. Querin, G. P. Steven, and Y. M. Xie, "Evolutionary structural optimisation (ESO) using a bidirectional algorithm," *Engineering Computations,* vol. 15, no. 8, pp. 1031-1048, 1998.

[6] D. Brackett, I. Ashcroft, and R. Hague, "Topology optimization for additive manufacturing," in *Proceedings of the solid freeform fabrication symposium, Austin, TX*, 2011, vol. 1, pp. 348-362.

[7] M. P. Bendsøe, "Optimal shape design as a material distribution problem," *Structural optimization,* vol. 1, no. 4, pp. 193-202, 1989.

[8] M. Zhou and G. Rozvany, "The COC algorithm, Part II: topological, geometrical and generalized shape optimization," *Computer Methods in Applied Mechanics and Engineering,* vol. 89, no. 1-3, pp. 309-336, 1991.

[9] P. Michalatos and A. O. Payne, "Working with multi-scale material distributions," in *ACADIA 2013 Adaptive Architecture*, P. Beesley, M. Stacey, and O. Khan, Eds. Cambridge, Ont.: ACADIA, 2013.

[10] F. Otto, *IL-8: Nets in Nature and Technics* (Mitteilungen des Instituts für Leichte Flächentragwerke (IL)). Stuttgart: University of Stuttgart, 1975.

[11] A. Kilian and J. Ochsendorf, "Particle-spring systems for structural form finding," *Journal of the International Association for Shell and Spatial Structures,* vol. 46, no. 148, p. 77, 2005.

[12] D. Piker, "Kangaroo: form finding with computational physics," *Architectural Design*, vol. 83, no. 2, pp. 136-137, 2013.

[13] S. Ahlquist and A. Menges, "Realizing Formal and Functional Complexity for Structurally Dynamic Systems in Rapid Computational Means: Computational Methodology based on Particle Systems for Complex Tension-Active Form Generation," in *Advances in Architectural Geometry 2010*, C. Ceccato, L. Hesselgren, M. Pauly, H. Pottmann, and J. Wallner, Eds. Vienna: Springer-Verlag, 2010.

[14] K. Velikov, W. McGee, G. Thün, and D. Tish, "Prologue for a Robotic Architecture: Bridging design environments, robotic additive manufacturing, and systemic controls for kinetic in-formation," in *Towards a robotic architecture,* M. Daas and A. J. Wit, Eds. New York: ORO Editions, 2018.

[15] W. McGee, G. Thun, K. Velikov, and D. Tish, "Infundibuliforms: Kinetic Systems, Additive Manufacturing for Cable Nets, and Tensile Surface Control," in *Fabricate 2017: Rethinking design and construction*, B. Sheil, A. Menges, R. Glynn, and M. Skavara, Eds. London: UCL Press, 2017, pp. 84-91.

[16] S.G. Johnson, The NLopt nonlinear-optimization package, http://ab-initio.mit.edu/nlopt.

[17] C. H. da Silva Santos, M. S. Gonçalves, and H. E. Hernández-Figueroa, "Designing Novel Photonic Devices by Bio-Inspired Computing," *IEEE Photonics Technology Letters*, vol. 22, no. 15, p. 1177, 2010.

[18] T. H. Rowan, "Functional stability analysis of numerical algorithms," Ph.D. Thesis, Department of Computer Sciences, University of Texas at Austin, 1990.