archi|DOCT

The e-journal for the dissemination of doctoral research in architecture.

11

July**2018**

INTELLIGENCE

Automated robotic toolpath generation of elastic mesh structure
An additive waving techniques for form-finding, MOGA optimisation, and robotic fabrication

George Tryfonos

Abstract

This research focuses on the development of an automated robotically-driven algorithm that can be used for the design, simulate and robotic fabrication of elastic tensile mesh structures. This approach aims to automate the process between the design development and additive fabrication phases through the development of a custom-made end-effector tool for physical execution. Specifically, the suggested procedure explores a weaving elastic mesh technique, followed by an automated form-finding and static analysis investigation as well as a direct tool-path generation implemented by an industrial robotic fabrication process. Within this frame-work, a feedback loop between the form-finding and optimisation algorithm is investigated, which is responsible for controlling the pretension of the elastic threads, aiming to suggest optimum additives robotic tool-paths. In parallel, robot's and end-effector tool's parameters and limitations are taken into account during digital form-finding and optimisation processes. The suggested procedure aims to extend the automated robotically-driven algorithm in order to achieve accurate repeatability control of the elastic material and in turn the effective physical fabrication of complex tensile shapes.

Keywords

Tensile structure, elastic material, optimisation, automated tool-path generation, industrial robotic fabrication

Automated robotic toolpath generation of elastic mesh structure
An additive waving techniques for form-finding, MOGA optimisation, and robotic fabrication

George Tryfonos

Introduction

The drift towards the digital development of complex, lightweight structures based on form-finding and their structural simulation, as well as the ability to incorporate optimisation procedures such as Multi-objective generic algorithms (MOGA) and the use of new elastic materials allow innovative robotically driven fabrication processes to come to the fore. Nevertheless, the knowledge regarding the design and fabrication of elastic tensile mesh systems requires an in-depth step by step simulation of their geometric, material characteristics and construction method (Bletzinger and Ramm, 2001). The study of such elastic material through physical experimentation and digital simulation enables a deeper understanding of their structural performance. However, full integration of these results within a design and fabrication method requires the development of innovative design algorithms and digital fabrication mechanisms (Duro-Royo, Mogas-Soldevila and Oxman, 2015). In order to achieve design complexity as well as accuracy and precision in the fabrication process a more advanced communication between design and fabrication is required.

The application of form-finding and material behaviour experiments in design traces back to the work of Frei Otto in the Stuttgart Institute of Lightweight Structures, where soap lms or other materials were used for physical form- nding (Otto, Rasch and Schanz, 2006). Moreover, the innovation of digital tools for form- nding and, in parallel, the ability to simulate the behaviour of any material (Gramazio and Kohler, 2008) allow precise integration in complex construction shapes. For example, a large-scale tensile structure might be divided into smaller units and patterns, then analysed and finally fabricated. Conventional procedures might include the subdivision of meshes or membranes into smaller units, the flattening of each 3D geometry unit into 2D, the application of a stress reduction algorithm to reduce stresses from flattening and finally the shrinkage of the flattened units and their preparation for fabrication (Gale and Lewis, 2016). Such procedures depend on the accuracy of material simulation under tension and the assemblage strategy.

An essential factor towards automated design and fabrication method is the application of digital design and static analysis principles. By combining form- nding spring-based techniques with Multi-Objective Genetic Algorithms (MOGA), the accurate static simulation and optimisation of tensile mesh structures can be achieved. In the work (Ahlquist, Erb and Menges, 2015) the form-finding process is combined with the results of finite element analysis (FEA) using multi-objective optimisation strategies for the creation of digital meshes of elastic threads, which are then reproduced into physical tensile structures using conventional cutting and assembly strategy.

In parallel, the continued development of automated construction tools opens new directions that achieves better material control during the construction process. The design and simulation of custom-made end effector tools for material control move investigation beyond conventional fabrication methods (Iwamoto, 2009), allowing automated procedures that combines fabrication strategies and construction experimentation (Keating and Oxman, 2013). For example, in (Knippers et al., 2015) a custom-made tool mounted on a robotic arm is developed and used for controlling and feeding with thread material. By integrating robotic simulation, form- nding and structural performance analysis the construction of the overall structure can be achieved. In addition, the use of industrial robots, aerial robots or gantries improve the control of the process, allowing the construction of free-form structural systems. Moreover, the integration of simulation mechanisms for form-finding with the end effector tool for tensile mesh structure execution, leads to several advantages as compared to conventional construction techniques, such as the overall control accuracy of materials resulting the accurate repeatability during the fabrication process.

In conclusion, the development of interactive digital design and fabrication techniques that combine real-time form- nding methods, structural optimisation control and fabrication strategies allows a more effective aproach in automated tool-path generation (Braumann and Brell-Cokcan, 2012). This, in combination with the integration of custom-made end-effector tool development for material control and the form-finding process, can achieve an accurate repeatability process for the construction of complex tensile mesh structures. Similar works in this direction can be found, for instance in the experimental investigation undertaken in (Wendy and Antoine, 2016), where semi-autonomous wall-based robots are developed for the weaving of a small installation with carbon threads. The direct control between the automated toolpath generation and the material techniques allows the development of innovative fabrication strategies with new materials and complex shapes.

Suggested Methodology

The current research study focuses on the feedback loop communication of form-finding, structural optimisation and tensile analysis with the combination of robotic fabrication principles, which aims towards an automated process. This achieves the development and static behaviour analysis of innovative shapes, as well as their fabrication through precise robotic control. Specifically, a parametrically controlled algorithm is developed that can be used for both, the optimisation and the fabrication of complex elastic tensile structures. In this way, an automated method to control the form-finding process of the elastic tensile shapes and to generate the robotic tool-path through a custom-made end-effector can be achieved. Thus, the automation might respond to the fabrication of any complex system with high accuracy. Important parameters and criteria of optimization control include specific material characteristics, in this case elasticity and diameter, additive weaving technique applied as well as robotic setup and end-effector limitations.

The parametric design environment of Grasshopper, a plug-in for 3D modelling software Rhino, is used for algorithmic development. In this environment, the formulation of 3D input surface and the application of the initial weaving pattern, which in uence the final robotic tool-path, is conducted. The physics-based software Kangaroo (Piker, 2013), a plug-in for Grasshopper is applied for the process of form-finding. Within this framework, the thread tensile equilibrium of elastic mesh system, which occurs between the material pretension and tensile strength is taken into account in order to prevent the formation of high sag threads geometry. By using spring behaviour (Kilian and Ochsendorf, 2005) the relaxation of treads is initially simulated, based on the mathematical equation $K = (A*E)/L$, where K is the spring stiffness, A is the cross-sectional area, E is the (tensile) elastic modulus of the rubber (Polyurethane Elastomer) thread (0.02 GPa), and L is the length of the thread. The static equation is used for non-linear mesh behaviour simulation, in which pretension forces are applied on threads leading to grid structure overall deformation and hence its stabilisation (Figure 1). In parallel, results of form-finding are evaluated and correlated with the results obtained by using the general-purpose civil-engineering software CSI SAP2000.

In order to overcome problems due to the complexity of the process, which includes form-finding and specific weaving technique based on the end-effector tool as well as material limitations, a MOGA analysis process (Deb, 2002) is introduced and developed as a feedback loop workflow. The analysis process controls the material section and the prestress behaviour (L/D factor) and considers the robotic setup and the end-effector parameters such as the dimension of nodes, pretension accuracy and positioning. This leads to results influenced by material tensile strength (5MPa) and end-e ector tool limitations. The overall process achieves a large number of best solutions to be

Automated robotic toolpath generation of elastic mesh structure
An additive waving techniques for form-finding, MOGA optimisation, and robotic fabrication

George Tryfonos

generated that are projected on the Pareto front graph. This allows the selection of desirable ones based on their static behaviour by prioritising structural performance and on their geometry by prioritising shape deformation.

In addition to the automated fabrication algorithm (Figure 2) and in order to evaluate the results of digital form-finding and structural optimization with robotic fabrication, a custom-made end effector tool for a small-scale physical prototype is developed. As a consequence, fabrication constraints, which allows an automated mesh weaving process through the working area of an industrial robotic arm ABB IRB2600 with an IRC5 controller, are also used to evaluate the method introduced in this paper. This allows digital to physical experimentation of the initial weaving pattern of the nodes and threads (Kontovourkis and Tryfonos, 2015) in a feedback loop communication.

Initial Pattern Configuration

In previous investigations, the research has explored possible weaving patterns that would achieve an automated robotic control (Kontovourkis and Tryfonos, 2015). This has been focused on the capability of the algorithm to control automatically the form-finding and fabrication through tool-path generation. Towards this direction, the research has developed a weaving algorithm to explore eight different input categories with different Gaussian curvatures. Two input lines A and B at a distance (y) are used for the geometrical development and the determination of each elastic mesh. In parallel, eight surface variations for each category of results are achieved by using the two combined curves on which tree control points (start, middle and end) in z-axis are modified. in. The categories are developed base on 1x1 YZ coordinate polygon system, allowing the adaptability in any shape. The correlation of the initial Gaussian curvature (Ks) (Table 1) with the nal mesh Gaussian curvature (Kf) values allows the behaviour investigation of the suggested elastic mesh weaving algorithm. The nine interior points for the measurement of the initial and nal Gaussian curvature are shown in Figure 3.

Weaving pattern development algorithm

The physical behaviour of every mesh variation in each category and hence the behaviour of the rubber material in each case are tested through the suggested weaving algorithm, together with the sequence of nodes and evolution of robotic toolpath generation. In addition, the size of the surface, the weaving pattern density, the space (y) that is the distance between curves de ning the surface, and the value (x) that is the distance of start to end point of each curve including surface subdivision, are determined by parameters controlling the initial geometry. Moreover, the surface subdivision (div) in x and y-direction in uences the pattern density. This can be described in details, firstly, by diving the two lines in corresponding nodes that are connected in one direction based on the parameter (N), for instance in the following sequence, A3, B3, B5, A5, A7, B7, B9, A9, A11 and B11, which create springs 1-9 (Figure 4). Then, the process of weaving continues in the other directions, intersecting and dividing existing springs into two new segments, leading to the creation of spring between two nodes. Also, a movement of nodes by 25-75% of the neighbouring points can be allowed. The connecting nodes to the adjacent units or to the anchor points leading are represented by remaining points on A, B, C and D (Figure 4).
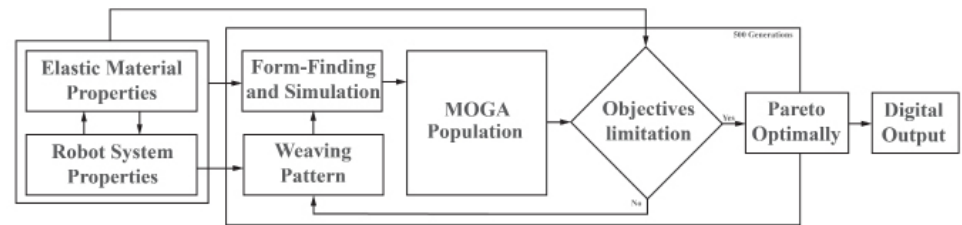
Form-Finding Simulation

Preliminary physical and digital experiments (Kontovourkis and Tryfonos, 2016) have been used to
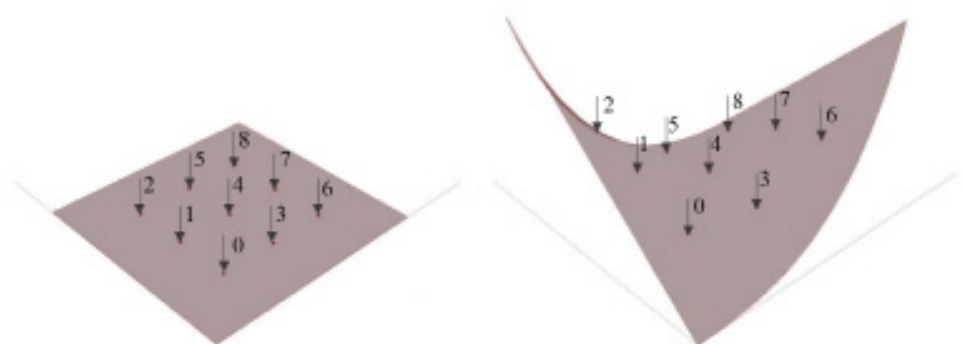
Automated robotic toolpath generation of elastic mesh structure
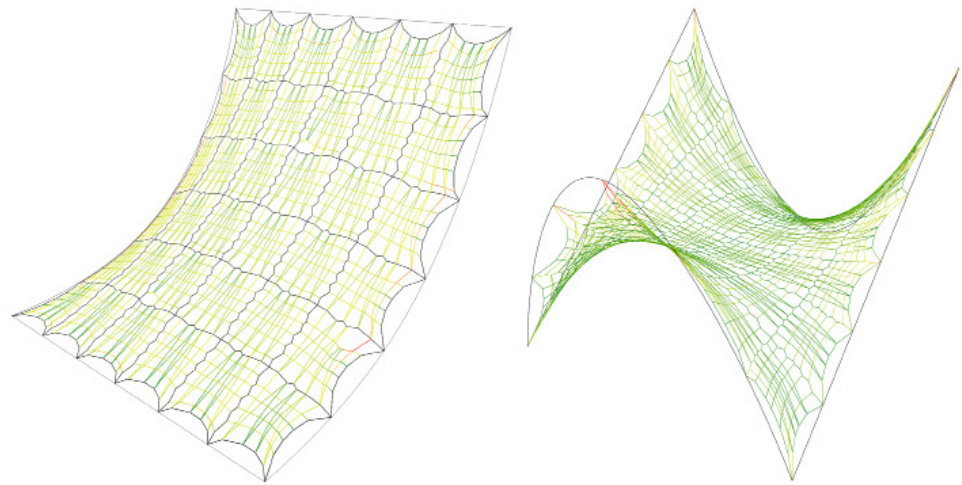
Figure 1.

Weaving pattern of real scale case-studies after form-finding. Left B.8 and Right F.8

Figure 2.

The automated robotically driven optimisation workflow in the form of a diagram

Figure 3.

Measuring points of the Gaussian curvature

Table 1.

The eight categories and their initial surface Gaussian curvature

Categories	A		B		C		D	
Curves	A	B	A	B	A	B	A	B
C (m) Start	0	0	0	0	0	0	0	0
C (m) Mid.	0-0.7	0-0.7	0-0.1	0-0.1	0	0-0.1	0	0-0.7
C (m) End	0	0	0-0.8	0-0.8	0	0-0.8	0	0
Black = A curve Red = B curve								
(-)Ks	0	0	0	0	0	0.15	0.85	1.24	1.77	0	1.77
	0	0	0	0	0	0.09	0.6	1.09	0.75	0	0.75
	0	0	0	0	0	0.05	0.33	0.66	0.30	0	0.30
Categories	E		F		G		H	
Curves	Curves	B	A	B	A	B	A	B
C (m) C (m)	0	0	0-0.8	0	0	0-0.8	0	0.8
C (m) Μέσο	0	0-0.7	0	0-0.8	0-0.1	0-0.1	0.1	0.1-0.8
C (m) Τέλος	0	0-0.8	0-0.8	0	0-0.8		0.8	0
Black = A curve Red = B curve								
(-)Ks	1.46	0.44	0.05	2.79	0	2.79	1.46	1.92	1.32	7.92	1.18	0.07
	0.81	0.24	0.03	12.68	0	12.68	2.01	3.02	2.01	6.38	1.18	0.07
	0.44	0.14	0.02	2.79	0	2.79	1.32	1.92	1.46	1.56	0.82	0.07

Automated robotic toolpath generation of elastic mesh structure
An additive waving techniques for form-finding, MOGA optimisation, and robotic fabrication

George Tryfonos

determine the material deformation and the tensile forces behaviour applied in the elastic thread. . The prestress is described by the thread length and the initial point distance (L/D) and is set at the lower value of 70% for maximum deformation and a maximum value of 100% without deformation. The robotic end-e ector capability to apply accurately holding force is used to calculate thread values that occur during prestress and node creation. In order to avoid thread sags in the whole structure, the (L/D) factor is introduced and changed to set the prestress values. Thus, to additional investigate the node connectivity of the tensile stress behaviour, the anchorages-nodes can be moved from 25-75% a ecting the mesh typology and curvature.

As it has been mentioned, the Kangaroo plug-in for Grasshopper is used for simulation and specifically through the particle-spring behaviour modelling approach. At the same time, verification of the results is achieved through the use of SAP2000 software. In order to achieve this, properties of applied material include high tensile strength (Fst = 5Mpa) and yield stress (Fy = 3MPa) compared to the elastic module (E= 2Mpa) as well as Poisson's ratio of 0.5. In addition, all material characteristics are used as tendons inputs and the threads are modelled as cables with diameter 0.8mm with deformation prestress and self-weight of = 0.93 Mg/m3 (Ashby, 2011). Also, the node mass, which is generated by the end-effector tool is calculated as point load with value 0.012985N. The results of SAP2000 nonlinear analysis and the results derived from Kangaroo form nding process are almost similar with minimum deviations, proving the effectiveness of the process. In addition, the algorithm allows changes in regard to the input thread diameter range from 0.8mm to 20mm as well as adjustment based on external loads, showing future potential for alternative selection of elastic thread diameter that in turn will lead to end-effector modifications for new material control.

Optimisation and Static Analysis

Results of multi-objective optimisation process using the Octopus optimisation engine (Vierlinger and Bollinger, 2014) show a range of acceptable fabrication solutions. Alternation of results are obtained based on changes of anchorage range from 25%-75% and length factor range from L/D 70 - 100%, associated with the tensile stress, the amount of material used and the total deformation material. In addition, material tensile strength limitation of the end-effector tool $F_a=(F_{st}*A)/(F.S)$ (A=section area, S.F = safety factor = 1.35) (Stranghöner and Uhlemann, 2016) is taken into account during evaluation and selection of optimum solutions using the Pareto front (Pareto optimality). This shows that threads of 0.8Ø can be controlled by the suggested end-effector tool. Also, experimentation with YZ scale at 0.7x0.7m due to the limits of the working area of an industrial robotic arm ABB IRB2600 can be conducted.

The process involves 500 generations, each one with a population of 100 solutions, which are evaluated based on the decrease of the average tensile force, the reduction of material deformation under external load and the total length of the deformed elastic material. The deformation of the elastic material, the length amount of material required, the pretension and the curvature are used as objectives to evaluate the static performance and constructability of structure. Optimum results obtained are selected based on their static behaviour and on their geometrical configuration (Kontovourkis and Tryfonos, 2018), firstly by evaluating tension and thread deformation changes and secondly by evaluating curvature changes respectively.

An example of best trade-offs results for the case (F.8) for generation 0,50,100,250 and 500is shown in Figure 5. The two axes of graph describe the average of the tensile stress and the length of the deformed thread, wherein the 500th generation the best Pareto curve appears. The solu-

// **Automated robotic toolpath generation of elastic mesh structure**
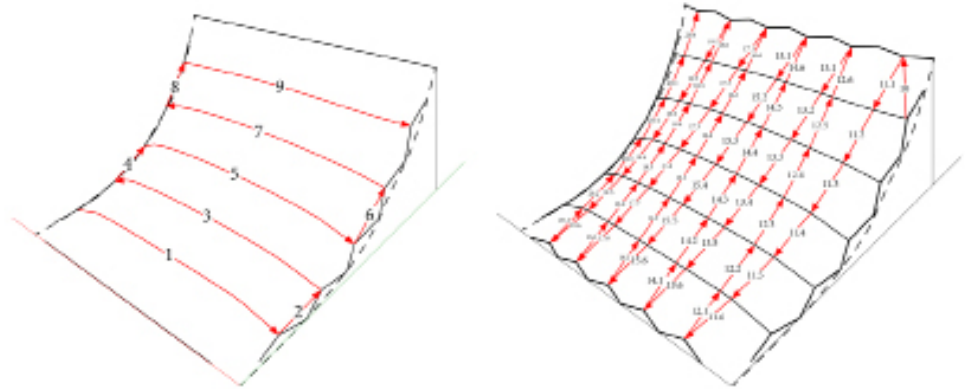
Figure 4.

Elastic threads of the structure in wave sequence
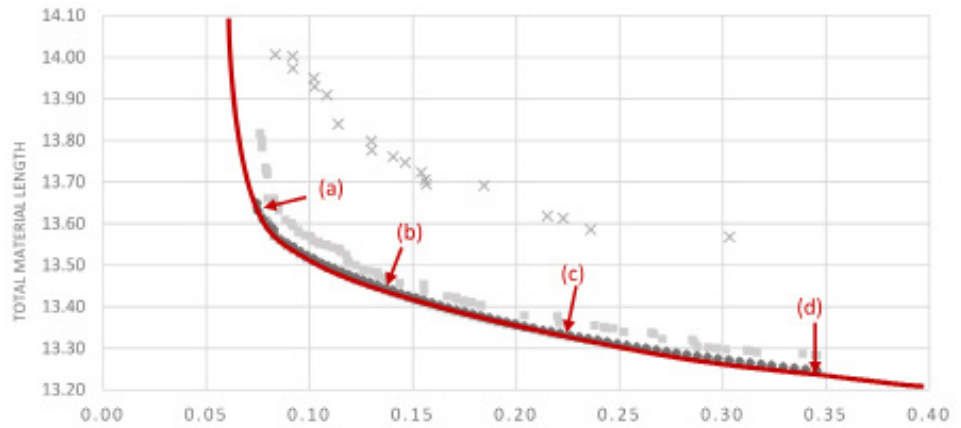
Figure 5.

Case study F.8 optimum results.

Table 2.

Results of Case Study F.8

SOLUTION	a	b	c	d
L/D (%)	89.50%	83.90%	79.30%	70.10%
Aerage Tension (N)	0.075	0.135	0.196	0.344
Total Material Used (m)	8.719	8.133	7.688	6.798
Total material deformation (m)	0.345	0.686	1.012	1.725
Average Final Curvature -(Kf)	9.491	9.858	10.087	10.348
K = (-Ks)-)-(Kf)	-2.832	-3.198	-3.428	-3.689

Automated robotic toolpath generation of elastic mesh structure
An additive waving techniques for form-finding, MOGA optimisation, and robotic fabrication

George Tryfonos

tion (a) with the minimum tensile stress average 0.075N has the higher L/D factor = 89.5% and deformation length material with value 0.345m, with material length 8.719m as well as the lowest curvature change (K)=-2.832, indicating this as geometricallypreferable solution. The solution (d) is defined with themaximum tensile stress average 0.344N and the lowest L/D factor = 70.1% as well as the higher deformation length material with value 1.725m and with material length 6.798m, indicating this as an alternative solution for robotic execution. In general, results where systems' average tensile stress is higher can be considered as optimum and preferable in terms of their static performance and at the same time they use less material length, however their maximum average final curvature (k)= -3.689 show that these are less geometrically acceptable since they require higher pretension during robotic fabrication.

For fabrication execution, solutions that are near to the centre of Pareto front are selected. These consists of less material length and hence better static behaviour since are approaching the maximum allowable (L/D) facto and their average tensile stress is the higher (Table 2, solution c). In comparison, solution (b) (Table 2) has lower average tensile stress and higher (L/D) factor, showing this as a solution geometrically acceptable but with fewer curvature changes and hence with less thread deformation.

Results from small to large-scale algorithmic experiments (Kontovourkis and Tryfonos, 2018) show that solutions with higher section diameter and higher average tension have lower material deformation under the influence of loads and hence higher curvature change, considering these as statically adequate. On the other hand, results with higher material deformation, lower average tension and section diameter have lower curvature change, considering these as geometrically appropriate.

End Effector And Tool-Path Development

After multi-objective optimisation results are obtained and selection of the appropriate solutions for fabrication execution is conducted, a step by step material addition simulation is needed for the construction of elastic threads due to the elastic material behaviour and specifically the deformation of the tensile mesh in every node addition process. The redefinition of the tool-path and the robotic manufacturing process occur automatically and is achieved through 51(Figure 6) weaving sequence (every additional thread and node in the weaving pattern) simulations per unit mesh.

The end-effector tool is responsible for the pretension of the elastic material and the node creation tasks and generally for controlling the weaving pattern development. The tool is operated through an Arduino board that controls the actuator and the other mechanical parts and it has been programmed to directly communicate with the IRC5 controller and synchronise with the tool-path developed through digital simulation. Analytically, two programming tasks are enabled; a. The pretension of the thread that is calculated from the L/D factor based on automated form-finding and optimisation process, and b. The node creation task (Figure 7) that included operations for holding the threads, supplying and moulding the node using a hot-melt adhesive technique.

Figure 8 shows a preliminary investigation on the robotic fabrication of a robotic toolpath controlled by the custom-made end effector tool. In order to achieve high precision during physical fabrication, calibration of the anchor points in the physical and digital model is required. In a future stage, the physical development of a small-scale tensile mesh system will allow verification of the results obtained during the process of automated robotic toolpath generation.
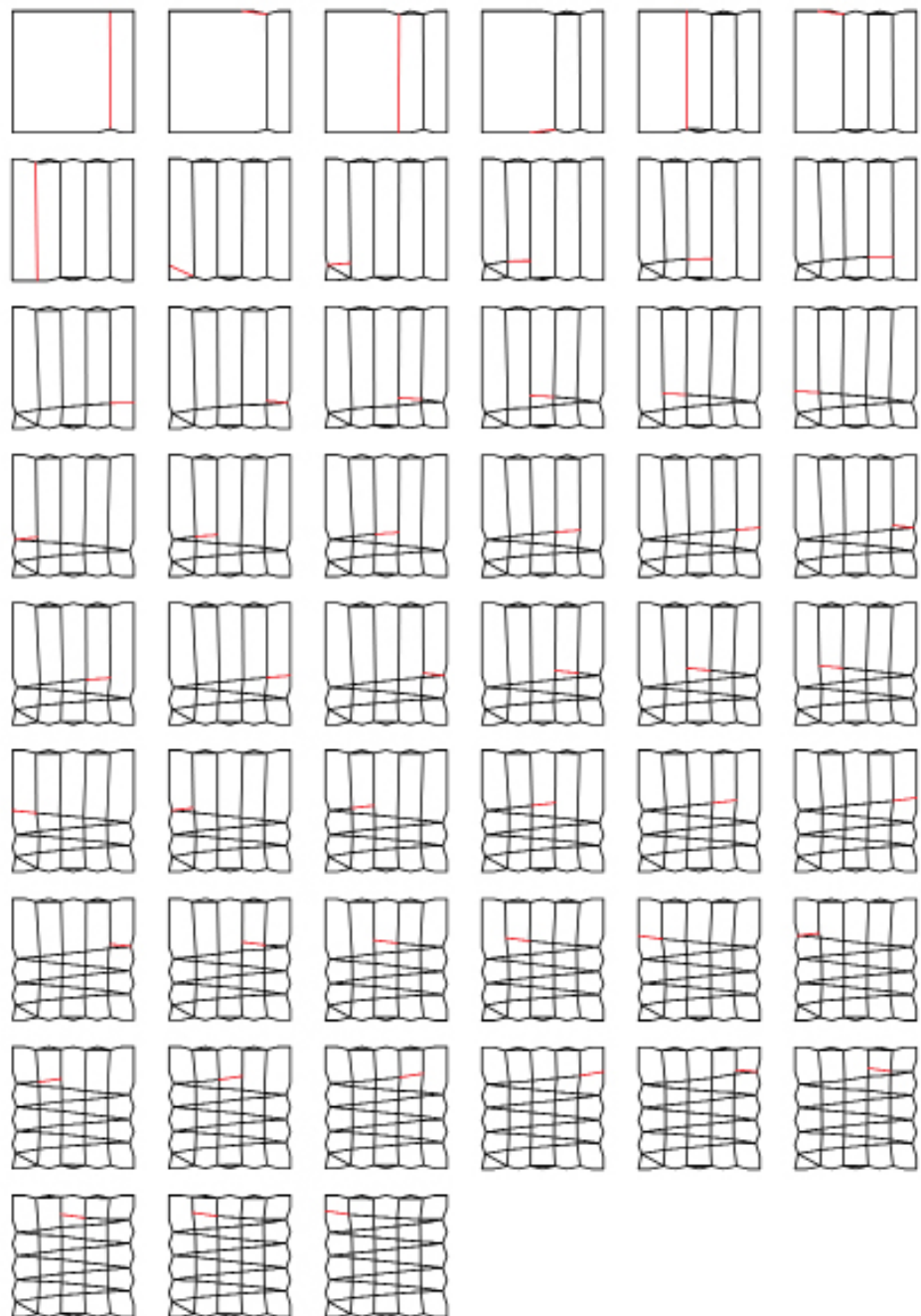
Figure 6.
Weaving sequence simulation for the automatic toolpath generation of one unit.

Automated robotic toolpath generation of elastic mesh structure
An additive waving techniques for form-finding, MOGA optimisation, and robotic fabrication

George Tryfonos

Conclusion

This research aims to apply an automated robotically driven procedure for toolpath generation using form-finding, static analysis and MOGA optimization processes for the physical development of elastic tensile mesh structures. The suggested workflow and the involvement of various techniques within a common framework of investigation attempts to examine the viability of the process and hence the effectiveness of the algorithm, to be used towards an automated and integrated procedure that includes design optimization and physical construction. Through the suggested automated procedure that involves repeatability of additive construction task, the accurate control of complex elastic mesh morphologies can be achieved. At the same time, the procedure examines in which extend the users can control the process of design selection and then, the form-finding results. Also, the effectiveness of the weaving technique, which is controlled by the custom made end-effector tool, can be examined. All the above can be accomplished due to the recent developments occur in the area of parametric design and robotic control that offer tools for elastic mesh structure simulation and parallel toolpath generation as well as robotic movement planning and custom-made tool control. The simultaneous use of different tools and platforms extend the ability of users to be actively involved in all parts of the procedure in a holistic manner. Within this framework, designer-user can decide and select the desirable "ready for fabrication design" based on the results obtained during the feedback loop analysis and simulation process.
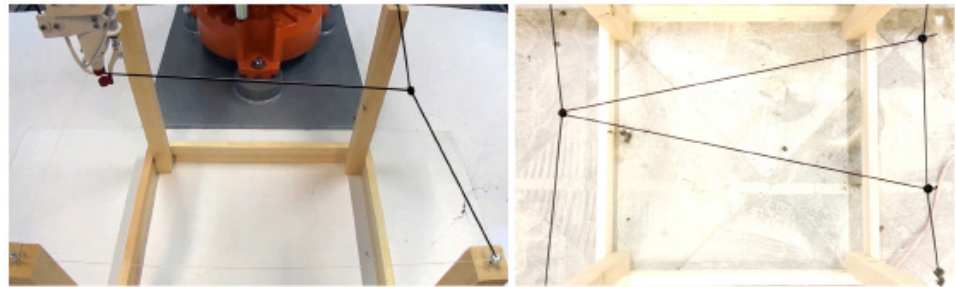
Feather research will continue towards the physical production of digital results derived from form-finding, simulation and analysis. Also, physical with digital outputs will be compared and evaluated though a series of case studies that will examine possible deviations. The suggested procedure might allow further developments towards the construction of other tensile shapes using similar material behaviour, leading to an ideal and an autonomous holistic construction process of complex, lightweight structures with minimal materials.

Acknowledgement

Figure 7.

Figure 8.

An example of elastic mesh structure using the suggested end-effector tool.

References

Ahlquist, S., Erb, D. & Menges, A. 2015, "Evolutionary structural and spatial adaptation of topologically differentiated tensile systems", Artificial Intelligence for Engineering Design, Analysis and Manufacturing, vol. 29, no. 04, pp. 393-415.

Ashby, M.F. 2011, "Appendix C - Material Indices" in Materials Selection in Mechanical Design (Fourth Edition), ed. M.F. Ashby, Butterworth-Heinemann, Oxford, pp. 559-564.

Bletzinger, K.U. & Ramm, E. 2001, Structural optimization and form finding of light weight structures.

Braumann, J. & Brell-Cokcan, S. 2012, "Digital and Physical Tools for Industrial Robots in Architecture: Robotic Interaction and Interfaces", International Journal of Architectural Computing, vol. 10, no. 4, pp. 541-554.

Deb, K. 2002, Multiobjective optimization using evolutionary algorithms, 1st edn, Wiley, Chichester U.A.

Duro-Royo, J., Mogas-Soldevila, L. & Oxman, N. 2015, "Flow-based fabrication: An integrated computational workflow for design and digital additive manufacturing of multifunctional heterogeneously

Automated robotic toolpath generation of elastic mesh structure
An additive waving techniques for form-finding, MOGA optimisation, and robotic fabrication

George Tryfonos

structured objects", Computer-Aided Design, vol. 69, pp. 143-154.

Gale, S. & Lewis, W.J. 2016, Patterning of tensile fabric structures with a discrete element model using dynamic relaxation.

Gramazio, F. & Kohler, M. 2008, Digital Materiality in Architecture, 1st edn, Lars Müller Publishers, Baden.

Iwamoto, L. 2009, Digital Fabrications: Architectural and Material Techniques, 1st edn, Princeton Architectural Press, New York.

Keating, S. & Oxman, N. 2013, "Compound fabrication: A multi-functional robotic platform for digital design and fabrication", Robotics and Computer-Integrated Manufacturing, vol. 29, no. 6, pp. 439-448.

Kilian, A. & Ochsendorf, J. 2005, "Particle-Spring Systems for Structural Form Finding", Journal of the International Association for Shell and Spatial Structures (J. IASS), vol. 46, no. 148, pp. 77-84.

Knippers, J., La Magna, R., Menges, A., Reichert, S., Schwinn, T. & Waimer, F. 2015, "ICD/ITKE Research Pavilion 2012: Coreless Filament Winding Based on the Morphological Principles of an Arthropod Exoskeleton", Architectural Design, vol. 85, no. 5, pp. 48-53.

Kontovourkis, O. & Tryfonos, G. 2018, "An integrated robotically-driven workflow for the development of elastic tensile structures in various scales", SUSTAINABLE COMPUTATIONAL WORKFLOWS: Computational Design and Fabrication towards Sustainable Products and Processes - 6th eCAADe Regional International Symposium 2018, ed. O. Kontovourkis, eCAADe, Nicosia, Cyprus, 24th-25th May 2018.

Kontovourkis, O. & Tryfonos, G. 2016, "Design optimization and robotic fabrication of tensile mesh structures: The development and simulation of a custom-made end-effector tool", International Journal of Architectural Computing, vol. 14, no. 4, pp. 333-348.

Kontovourkis, O. & Tryfonos, G. 2015, "An additive robotic fabrication methodology for tensile mesh structures development", IASS2015 Annual International Symposium on Future Visions, ed. P. Huybers, KIVI, Amsterdam, 17-20 August.

Otto, F., Rasch, B. & Schanz, S. 2006, Freí Otto, Bodo Rasch: finding form : towards an architecture of the minimal, 3rd edn, Axel Menges, Fellbach, Germany.

Piker, D. 2013, "Kangaroo: Form Finding with Computational Physics", Architectural Design, vol. 83, no. 2, pp. 136-137.

Stranghöner, N. & Uhlemann, J. 2016, Prospect for European Guidance for the Structural Design of Tensile Membrane Structures: Support to the implementation, harmonization and further development of the Eurocodes, Publications Office of the European Union, Luxembourg.

Vierlinger, R. & Bollinger, K. 2014, "Acommodating Change in Parametric Design", ACADIA 14: Design Agency [Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), eds. D. Gerber, A. Huang & J. Sanchez, ACADIA, Riverside Archi-

77 // **Automated robotic toolpath generation of elastic mesh structure**

tectural Press, Los Angeles, California, US, 23-25 October 2014, pp. 609.

Wendy, W.,F. & Antoine, P. 2016, Digital property : open-source architecture, 1st edn, John Wiley & Sons Ltd, Chichester, West Sussex, UK.