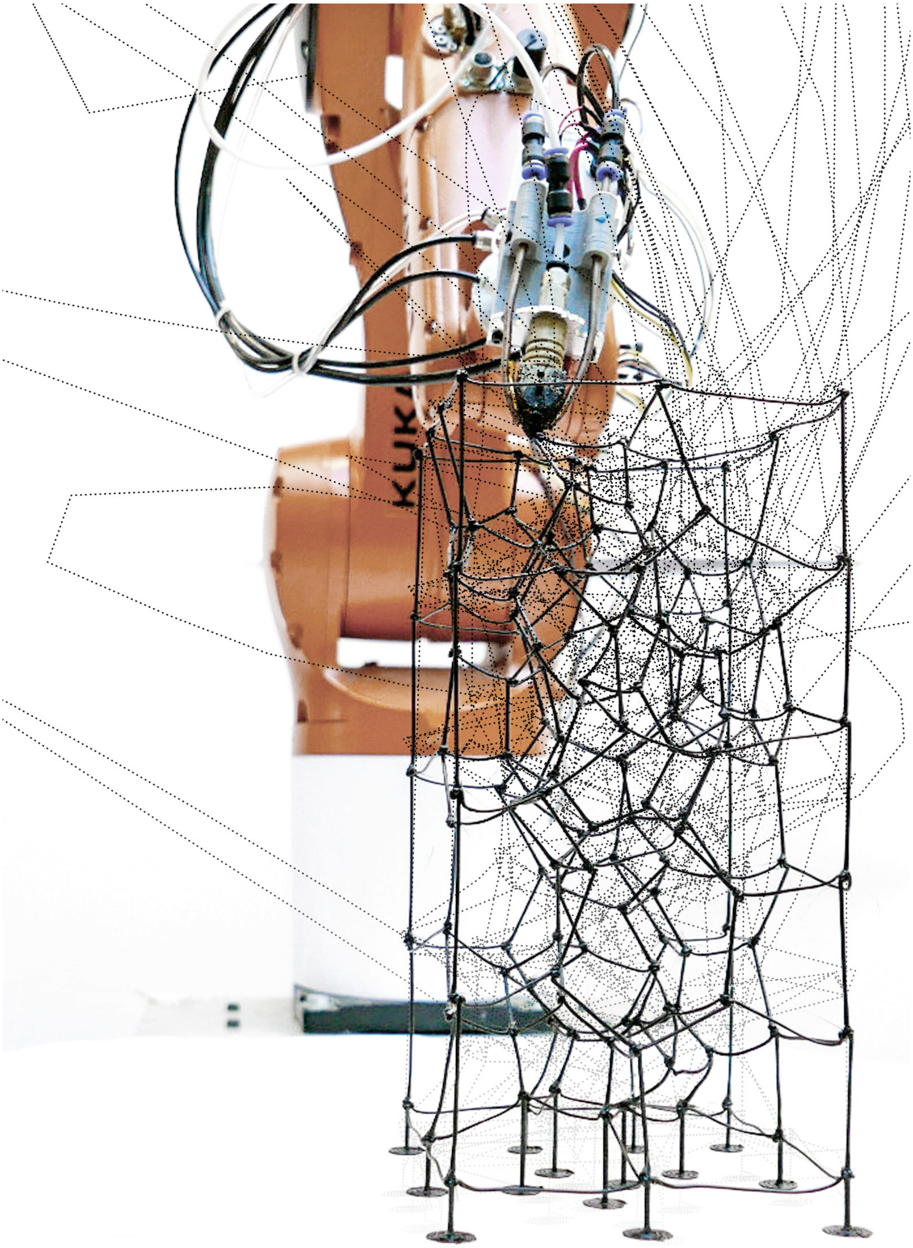

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Robotic Extrusion of Architectural Structures with Nonstandard Topology

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Abstract. This paper presents a fast and flexible method for robotic extrusion (or spatial 3D printing) of designs made of linear elements that are connected in nonstandard, irregular, and complex topologies. Nonstandard topology has considerable potential in design, both for visual effect and material efficiency, but usually presents serious challenges for robotic assembly since repeating motions cannot be used. Powered by a new automatic motion planning framework called *Choreo*, this paper's robotic extrusion process avoids human intervention for steps that are typically arduous and tedious in architectural robotics projects. Specifically, the assembly sequence, end-effector pose, joint configuration, and transition trajectory are all generated automatically using state-of-the-art, open-source planning algorithms developed in the broader robotics community. Three case studies with topologies produced by structural optimization and generative design techniques are presented to demonstrate the potential of this approach.

Keywords: Robotic extrusion · Motion planning · Topology optimization

1 Introduction

Architectural robotics has proven a promising technique for assembling nonstandard configurations of building components at the scale of the built environment, complementing the earlier revolution in generative digital design. However, despite the advantages of dexterity and precision, the time investment in solving the construction sequence and associated robotic motion grows increasingly with the topological complexity of the target design. This gap between parametric design and robotic fabrication congests the overall digital design/production process and often confines designers to geometries with standard topology. In order to close this gap and enable more possibilities for discrete architectural robotic assembly, a more systematic and explicit computational exploration of constraints and robotic motion planning is needed.

This paper presents a new way to apply automated robotic assembly sequence and motion planning to robotic extrusion of geometries with nonstandard topologies. The case studies presented serve to demonstrate the computational planning system's power

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to generate feasible robotic instructions and how its integration into existing digital design workflows can resurrect topology as a fundamental design variable on designers' palette for robotic assembly.

1.1 Complexity and Topology

Assemblies of discrete elements, such as trusses, space frames, masonry vaults, and stacked blocks, have been explored repeatedly in the architectural robotics domain. All discrete structures of this type can be represented by three design characteristics: size, shape (or geometry), and topology. This terminology originates from structural optimization of trusses in the 1960s–1980s (Spillers and MacBain 2009), but can be used generally to describe any discrete structure.

Within this framework, size refers to a cross sectional property of an individual element in the structure (e.g. cross sectional area of a linear truss element, or width of a brick in a stacked wall). Shape refers to the locations of internal and external points, lines, curves, and surfaces in a design. Finally, topology refers to the connectivity relationships between elements in the structure, and is the most fundamental; there is no easy way to morph a design from one topology to another (unlike with size and shape). Topology therefore offers both design opportunities and fabrication challenges: the largest impacts in visual effect and efficiency are possible (some examples are given in Fig. 1), but complex topologies can be nontrivial to assemble.

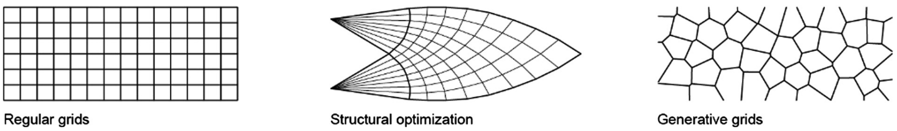

Fig. 1. Examples of different topologies resulting from different design techniques

Research in architectural robotics has included explorations in materializing design-driven complexity at all three of these levels (Gramazio et al. 2014). Most of this existing work involves generating a tool center point pose on the geometry to be assembled, and using the industrial robot's built-in interpolation method to compute transition trajectories with a certain safety factor. Recently, Søndergaard et al. propose an incremental search algorithm to find a construction sequence for a large-scale topology optimized space frame, while guaranteeing the existence of node-specific, collision-free assembly motion (Søndergaard et al. 2016). However, robotic configuration's feasibility is not considered during construction sequence searching, and robot's trajectories are resolved by inserting custom unwinding positions. While this geometry and machine-specific approach is feasible for designs with simple and sparse topologies, the construction sequence and robotic motion planning is much more nuanced for designs with denser material distribution and non-standard topologies. The computational complexity of "custom iterative path planning" in a densely populated environment has proved to be a major technical challenge that confines designers in the design domain of regular topologies (Eversmann et al. 2017).

In recent years, there has been some success in tackling this problem using automated motion planning by using a single-query robotic motion planning algorithm (Parascho et al. 2017) or an online control strategy (Giftthaler et al. 2017) to compute transition trajectory between pre-programmed assembly primitives. However, the construction sequence in the existing work was still assigned manually, taking advantage of either the sparse or the repetitive topology of the target geometry.

1.2 Topology in Robotic Extrusion

This paper focuses on one particular method for robotic assembly of discrete structures for the sake of specificity. Robotic extrusion (sometimes called spatial 3D printing) involves extruding a thermoplastic along linear paths, typically to form a mesh or grid structure, using robotic motion. This fabrication technique has been presented as an alternative to layer-based additive manufacturing, with advantages both in terms of mechanical properties and speed of construction (Gramazio et al. 2014; Yuan et al. 2014). The flexibility of industrial robotics has mostly been deployed to facilitate complexity in shape (as opposed to size or topology); morphed grids with standard topologies have been shown to be useful both for formal variation (Branch Technology 2018; Soler et al. 2017) and structural efficiency (Tam et al. 2018).

There has been some research in robotic extrusion for nonstandard topology, but all has required a time-consuming, non-automated robotic motion planning process. In the architectural robotics domain, (Tam et al. 2016) present robotic extrusion along lines of principal stress to achieve desired structural behaviors, but this work does not offer an automated planning solution and relies on milled formwork to support the structure during the printing process. In computer graphics, (Huang et al. 2016; Wu et al. 2016) have printed irregular topologies in which only the outer surface of a shape is materialized. However, none of the existing work considers the planning of entire robotic trajectories. Nor does any existing process explicitly demonstrate its ability to efficiently handle the construction sequencing and motion planning problem for designs with intricate volumetric topology patterns that are of interest in architecture.

1.3 Research Aim

In response to this need for easier robotic programming for complex, dense topologies in the architectural domain, this paper introduces a new automatic motion planning system called *Choreo*, which removes the need for human intervention in the tedious and nontrivial tasks of assembly sequence definition, collision detection, and trajectory planning.

2 Automatic Motion Planning System

This section lays out the general framework for robotic extrusion of nonstandard topologies. As shown in Fig. 2, there are four broad steps used in this workflow. First, a designer generates an overall concept using discretized linear elements; the design is defined in terms of topology and shape (or geometry). The second and third steps are carried out by Choreo without the need for human intervention: a feasible assembly sequence is automatically generated, and then the robot's path and instructions are automatically planned. In this third path planning step, the robot's trajectory is generated for both joint configurations and associated end-effector poses for each element's extrusion, and for transition between adjacent extrusions. The planning output is tagged with metadata so that users can easily weave hardware IO commands and micro path modifications using any programming platform, including Grasshopper. Taking advantage of existing robot brand-specific post processors (such as KUKA|prc 2018), an executable robot instruction file can be harvested and uploaded to a robot controller for execution. These four steps are explained in more detail in the following subsections.

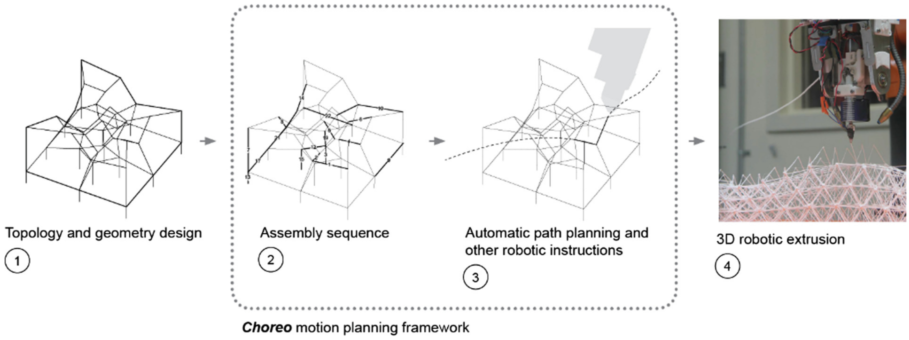

Fig. 2. Overview of the robotic extrusion workflow including the automated planning system

2.1 Step 1: Ground Structure Topology Optimization

One option for generating the initial design to be robotically extruded is topology optimization, which is especially attractive when structural efficiency is important. Topology optimization is a design approach that finds the best material distribution within a discretized design domain according to structural criteria (Bendsøe and Kikuchi 1988). The majority of approaches that use truss elements for the discretization are based on the so called *ground structure* method where nodes are distributed throughout the design domain and potential bars are defined between them (Dorn et al. 1964). Using a mathematical programme, the bars in the domain are sized to obtain the least weight design with a user-specified stiffness. By letting the smallest allowable bar area approach zero, the structural topology is obtained.

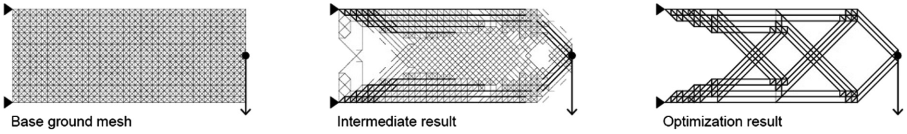

Fig. 3. Topology optimization process

Figure 3 shows an illustration of this process applied to a simple 2D cantilever problem. In the figure, a bar element's line width denotes cross section that is between 0 and 1 times of the desired constant cross section A_0. Elements with a thick line width have area A_0 and elements with areas approaching 0 are removed. This same topology optimization method is applied to a more complex 3D case in Sect. 3.1.

2.2 Step 1: Other Topology-Generating Methods

There are many other design-driven methods for generating complex topologies algorithmically of interest in architecture. For example, Stiny and collaborators have shown how to generate designs using shape grammars, including frames inspired by Chinese ice ray lattices (Stiny 1977). More recently, grammars have been used with embedded structural logic to produce unexpected equilibrium designs (Lee et al. 2016). Islamic patterns and generative tools to create them can produce culturally meaningful topologies (Khouri 2017). Voronoi diagrams, and their dual Delaunay triangular meshes, can each be used to generate meshes that seem biomimetic or that address other aesthetic agendas (Okabe 1992). In general, topology can be a key variable in creative design that leads to diversity and variations in visual expression, as illustrated in Fig. 4.

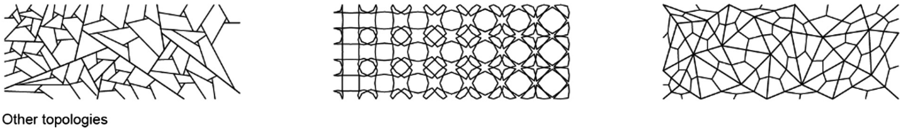

Fig. 4. Visually diverse topologies produced through generative design.

2.3 Steps 2 and 3: Assembly Sequence and Motion Planning with Choreo

The complexity of topology introduces significant challenges for finding a collision-free extrusion sequence and robot trajectory. The robotic extrusion planning problem requires finding a chronological construction sequence of motions to extrude each element, as well as moving through free space to connect adjacent extrusion processes.

To solve this combined task and motion planning problem, a three-layer computational hierarchy is proposed and implemented in Choreo to gradually narrow down the computational complexity along the search tree. First, a constraint-based sequence planner is introduced to search the construction sequence, while guaranteeing the intermediate construction's stability and stiffness, and the existence of collision-free robot kinematics solution at each extrusion step. Then, a sampling-based semi-constrained Cartesian planner is used to compute the robot's joint configuration during each extrusion process. Finally, an off-the-shelf motion planner is called to compute the robot's trajectory to navigate through free space to connect adjacent extrusions. Taking advantage of existing single-query motion planning packages, users can interact with multiple state-of-the-art motion planners and choose the one to balance their needs between the optimality, smoothness, and speed. Figure 5 highlights the three different

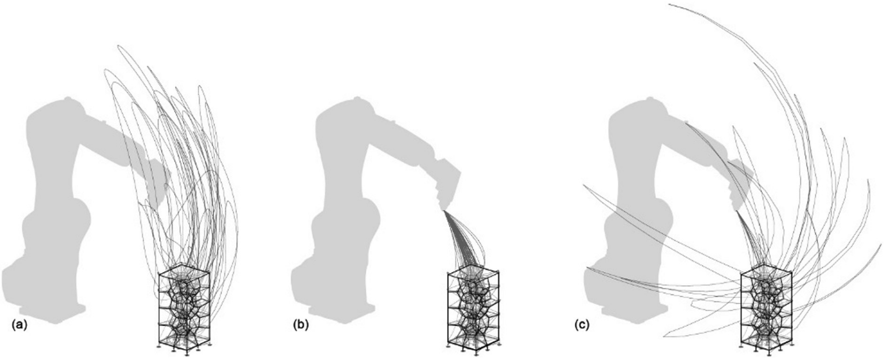

Fig. 5. Transition trajectory computed by state-of-the-art motion planners: (a) STOMP (Kalakrishnan et al. 2011) (b) CHOMP (Note that a resetting home pose is inserted in the transition trajectory if initial direct transition planning fails. Thus, the results shown here indicate that the CHOMP planner is not as good in finding a feasible trajectory as the other two planners presented here.) (Ratliff et al. 2009) (c) RRT* (Karaman et al. 2011)

planning results for a 3D Voronoi (Sec. 3.2), using three different state-of-the-art open-source motion planners developed in the robotics community. An in-progress paper (Huang et al. 2018) gives a more detailed description of the assembly planning algorithms used in Choreo.

Choreo is implemented in C++ on Robot Operating System (ROS) (Quigley et al. 2009), integrating functionalities from ROS-Industrial (ROS-Industrial 2018) and Moveit! framework (Sucan et al. 2018). Choreo's system architecture is designed to be modularized and adaptable. This modularized system feature offers users and researchers the flexibility to plug in and experiment their customized sequence or motion planner without changing the entire system's codebase. Finally, Choreo can be configured to support 6 or 7-axis industrial robots of any brand with any user-defined end-effector[1].

2.4 Step 4: Post-processing and Robotic Extrusion

The generated robotic trajectory from Choreo is geometrical and without timestamp information. In order to generate instructions for the robot to interact with the physical world, the user needs to weave IO commands to synthesize the robot's motion and its end effector's behavior. In addition to this, the variation of extruder design and extrusion material properties requires the incorporation of ad hoc fabrication logic to achieve the desired visual results (Hack and Lauer 2014) or increase the product's structural performance (Tam et al. 2018). These fabrication logics derived from physical extrusion experiments usually involve local modification of an end effector's pose, such as pressing or extruding following small circular movements at structural

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[1] The mechanical parts of the extrusion system used in this work's case studies are developed by Archi-Solution Workshop (http://www.asworkshop.cn/).

joints. The correct weaving of these modifications and IO commands requires the computed trajectory to be tagged with extrusion process metadata, so users can easily separate trajectories for different processes and insert commands accordingly.

To increase the computed trajectory's compatibility to programming platforms, Choreo's trajectory is formatted in a customized JSON format, where each element extrusion process's joint trajectory and associated TCP poses are packed with the element's ID. Then the formatted trajectories are imported into any programming environment, such as Grasshopper, with a simple customized parser, to decode the JSON file and allow a direct and visually friendly IO commands insertion and path micro-modification. Then, existing robot simulation packages can be used to visualize and simulate robot's trajectory and export executable robot instruction code. The fabrication parameter calibration process can go back and forth between Grasshopper and physical tests, keeping the overall robot trajectory unchanged.

3 Case Studies

This section presents three robotic extrusion case studies of different topologies. Computation time on assembly planning and fabrication results are presented in Table 1, and overall shape and topology properties are given in Fig. 6. These case studies demonstrate Choreo's power in automatically generating executable robotic extrusion trajectory in a reasonable amount of time.

Table 1. Computation statistics of the case studies. All computational experiments were performed on a Linux virtual machine with 4 processors and 16 GB setup on desktop PC with a quad-core Intel Xeon CPU. $^+$Extrusion planning time is specified by users.

Model	Node count	Element count	Sequence planning time [s]	Extrusion planning time [s]$^+$	Transition planning time [s]	Fabrication time [hr]	Size [mm]
Topopt vault (Sec 3.1)	114	205	1346	1200	843 (STOMP) 1211 (RRT*) 1511 (CHOMP, 9 fails)	3	200 × 200 × 200
Voronoi (Sec 3.2)	148	292	2299	1200	846 (STOMP) 1286 (RRT*) 945 (CHOMP)	3.2	150 × 150 × 320
Mars habitat (Sec 3.3)	86	214	1498	1200	800 (STOMP) 918 (RRT*) 1054 (CHOMP, 4 fails)	3	180 × 180 × 155

3.1 Topology Optimized Vault

Using the ground structure topology optimization method described in Sect. 2.1, a 3D-trussed vault was generated. With this approach, it was possible to remove 91% of the material initially included in the ground structure.

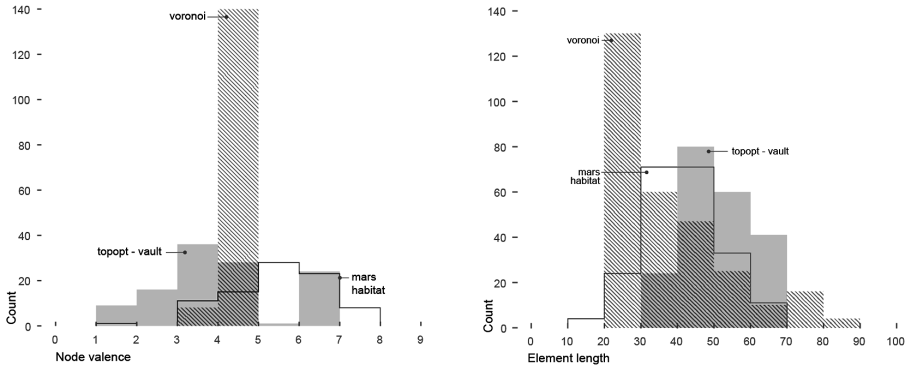

Fig. 6. Node valence and element length histograms of the case studies.

The average element length is long, and element length variation is low because the design is generated from a regular base mesh. However, the geometric configuration generated from these elements is not trivial. 12% of the nodes have valence of six, tending to create narrow pathways for robot in transition planning. The trajectory highlighted in Fig. 7 shows the corresponding tool center point traveling trajectory from the transition planning result, indicating that the robot's configuration changes significantly between many pairs of adjacent extrusions, requiring the planner to output a long and unintuitive trajectory to stay within joint limitations and stay clear from collisions.

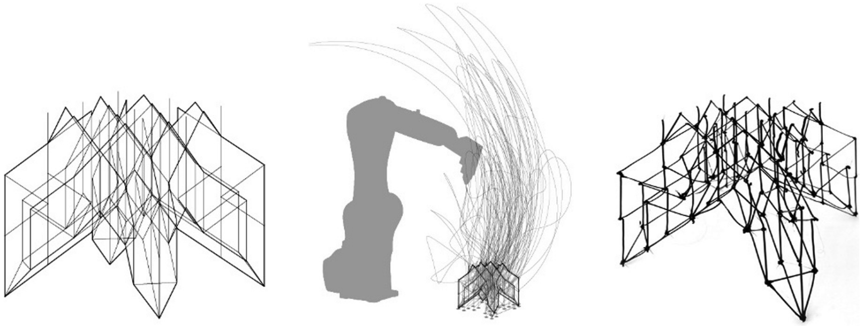

Fig. 7. Topology optimized vault, robotic trajectories with STOMP, and final extruded result.

3.2 3D Voronoi

The 3D Voronoi design was generated by randomly sampling points within a rectangular solid, and then using the 3D Voronoi component in Grasshopper together with Kangaroo 2. A sphere collision algorithm was used to force the elements lengths to have a distribution with lower variance. Figure 8 shows the design and fabrication of this case.

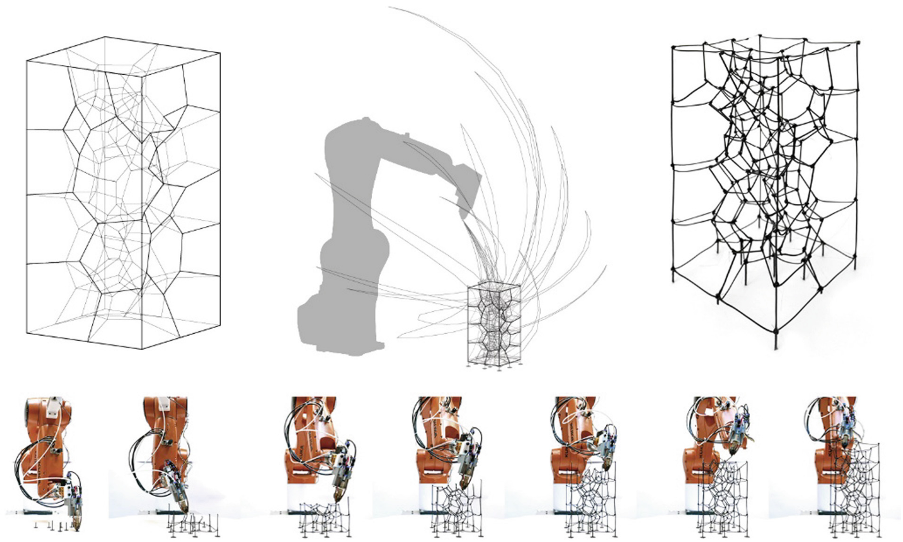

Fig. 8. 3D Voronoi design, robotic trajectories with RRT*, and final extruded result.

Because of the Voronoi-generating algorithm, there is low variation in node valence, with most nodes having four elements, a relatively low number, connecting. In this design, elements are well supported during each construction step, and there are few very long elements. However, the long elements at the boundary have smaller node valences, and the resulting material warping and sagging can sometimes prevent the robot from locating and connecting to these elements even though the computed trajectory is feasible. In terms of motion planning, the internal topology does not have a trivial layer-based pattern. Thus, it is unintuitive for humans to find a sequence manually, and the Choreo platform proves useful.

3.3 Mars Habitat Design

The third case study is a model of a pressurized habitat designed for a human colony on Mars. An outer dome membrane, discretized into a mesh-like structure, is helped structurally by an internal tree structure that acts like a tension spoke system to anchor the membrane to the ground. Figure 9 shows the design and fabrication of this case.

The construction sequence alternates between outer and inner structure to gradually close the membrane at the top. Nodes on the stem of the internal tree structure have highest node valence. The outer layer needs to be built before the internal tree elements, but introducing more surrounding collision objects leaves narrow pathways for the robot to enter. This forces the planner to find long trajectories to allow specific joints to have sufficient rotation in open space to approach the desired joint configuration.

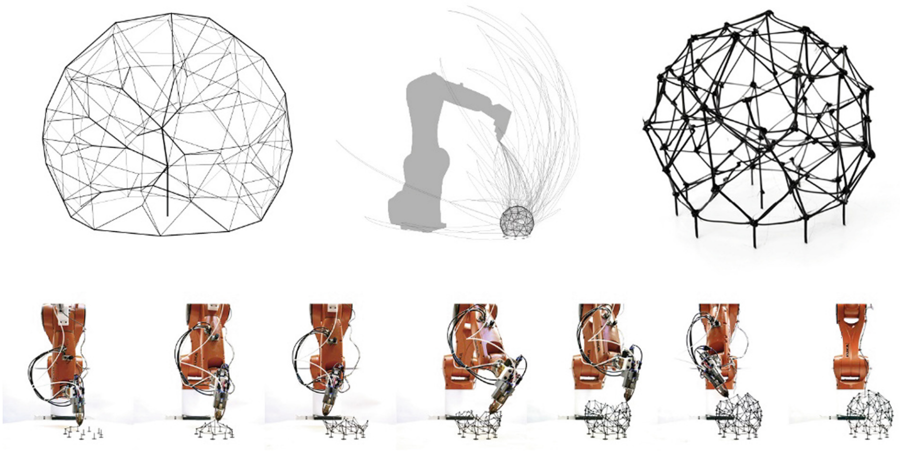

Fig. 9. Mars habitat design, robotic trajectories with RRT*, and final extruded result.

4 Conclusions

This paper has demonstrated a new path planning framework, Choreo, and used it to show how opening up topology as a design variable in robotic extrusion offers opportunity for more efficient structures and more creative flexibility. Three case studies were presented, each of which has nonstandard topology and more than 200 elements. Because of the flexibility and speed of Choreo, the trajectories in all of the case studies were computed in a little more than an hour, with three additional hours needed for the actual robotic execution. This timescale suggests an exciting future possibility: fabrication logic related to robotic constructability could be integrated as a driver in iterative conceptual design, pushing the role of technical assessment from checking a nearly finalized design to an early-stage decision-making aid.

Although the approach presented in this paper was applied to the specific method of robotic extrusion at a relatively small scale, the Choreo framework is very flexible. Because the underlying algorithms state-of-the-art, they are fast enough to generate robotic sequences to be used in production. Choreo could also be applied to other aggregations of linear elements beyond extrusion with similar benefits, or more broadly to assembly problems in general (e.g. masonry structures with nonstandard topologies). Because Choreo is independent of robot brand or even numbers or types of axes, it can work with many different robotic set ups, including those with additional external linear axes or turntables. The broad future vision for this work is a better way for designers to interact with robots, shifting the machine programming experience back to high-level tasks in the architectural language of shape and topology.

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