Statement of Research

My primary research interest is the processing and handling of geometric content. The existence of such content is ubiquitous and self-evident across disciplines. Still, its interpretation varies according to the information it encloses (e.g., incidence, connectivity, metric). From a Computer Scientist approach, I am curious about the type of inquiries and methods we can execute over a piece of geometric information. I have formulated such kinds of procedures solidly founded in Computational Geometry and Polygon Geometry Processing scopes. Hence, the main goal of my work is to formulate robust and generalized computational frameworks aimed to solve real-world problems and enhance existing solutions to new grounds.

My research approach merges classical concepts along with modern tools to formulate generalized frameworks. As an example, I find inspiration on traditional design techniques that have survived across time and are still useful up to this day. My mindset while working on the generation of Topological Interlocking Configurations was to approach those assemblies as a generalization of well-known compression-only structures such as the Roman arch. The result is a general theory that describes each block in the assembly as the process of discrete evolution steps starting on a planar polygon. Maintaining such a mindset allowed me to explain my research results to architects and engineers on their terms, which granted insightful discussions and potential for collaboration. I believe this research approach opens exciting venues in two directions: 1) Considering classical concepts worth revisiting under a modern lens, and 2) Proposing generalized frameworks that explain new solutions while expanding the formulation of known proposals.

Dissertation Research: Generation of Topological Interlocking Configurations

Topological Interlocking (TI) is a design technique for single-layered non-monolithic structures. The shape and alignment of the blocks in a structure impose the required kinematic constraints to reach a static equilibrium state. Traditionally, the shape of each block is a convex solid. Additionally, the technique disregards the use of joinery, adhesive materials, or any other bonding mechanism between the blocks. Consequently, the structure requires a peripheral support frame to prevent lateral strain. The overall shape of a TI configuration comes from a geometric domain described by a surface tessellation. A TI generation method then returns an interlocking block per tile in the tessellation.

Over the last twenty years, there has been an increased interest in TI configurations from the architecture and engineering fields. From an architectural point of view, TI provides an alternative to design and assemble reliable vault-like masonry structures. Engineers, on the other hand, regard TI as an approach to generate composite materials resistant to random failure and crack propagation under loads. Both disciplines have found remarkable properties on TI assemblies, which continue to attract the attention of researchers across disciplines.
Concrete applications of TI configurations are found in prosthesis designs, military industry, and space colonies proposals.

Despite the growing interest in TI configurations, their generation process has been mostly the same for convex interlocking blocks. The edges of each tile in a tessellation are assigned with direction and angle values. The direction values toggle between inside and outside of the tile along its edges. The angle value is the inclination of an incident plane that passes through its incident edge. The intersection of such planes in a tile defines the vertices of the block. It is known that the angle values can be all the same when the tessellation is planar and regular. Otherwise, the angle values need to be adjusted such that the resultant blocks have both alignment and no overlapping to each other. In some cases, there may not exist a set of angles that result in blocks with such requirements. Therefore, clipping the blocks to remove overlapping becomes a viable solution to make a TI configuration valid.

My thesis focuses on TI generation methods that return valid TI configurations (i.e., aligned and non-overlapping blocks) using non-planar surface tessellations [1] [2]. The fundamental idea is to consider the distance from each tile towards the top and bottom sections of the resultant block. Such distances become the respective generation parameters for the block. Therefore, the distance values are scalar parameters that determine the location of the top and bottom section points concerning the centroid and normalized normal vector of a tile. These points, along with the edges of the tile, define the required inclined planes to generate the respective block. In the case of two adjacent tiles with a dihedral angle greater than zero, the bisector plane between the incident planes that pass through the common edge determines the required plane that guarantees alignment between the two adjacent blocks. If overlapping occurs, the offset of the planes that contain the tiles of the tessellation work for clipping the blocks. Such offset can be parameterized similarly to the height parameters. All these new parameters allow the definition of a generation pipeline that returns TI configurations with maximal block volume as possible.

An immediate limitation of both angle-based and height-based generation methods is the family of solids they can generate. Overall, the shape of such solids would be an antiprism. The work of Dyskin et al. [3] describe that all Platonic solids have TI properties. My next contribution [4] generalizes the concept of Mid-Section Evolution from Kanel-Belov et al. [5] to generate infinitely many TI shapes by defining sequences of evolution steps to generate a solid. In hindsight, an evolution step is a procedure that translates and reshapes a polygon into an n-polytope, where n could be 0, 1, or 2. An evolved 2-polytope can be evolved again to define a new section of the respective block. Each evolution step is a parametrized procedure in terms of angles and evolution distances. The generalized approach generates all Platonic solids, along with their respective truncated versions.

Finally, my concern focused on how to generate TICs that can maintain static equilibrium regardless of the shape of the geometric domain [6]. I kept my approach geometric as much as possible. The work of Whiting et al. [7] on structure feasibility was adequate for my
proposed generation pipeline. Given some fundamental physical information (block density, static friction between blocks, and gravity load), we can calculate the minimum force components (compression, tension, and tangential) required to maintain static equilibrium. Embedding such an analysis to the TIC generation pipeline resulted in an end-to-end pipeline.

**Future Research Directions**

Working on TI granted me skillsets I am thrilled to continue using in my research area. The generalized TI generation problem is the first step on a sequence of diverse open problems that I am interested to work on as a researcher. Such problems lie at the intersection between Computer Science, Computer Graphics, Computational Geometry, Polygon Geometry Processing, and Engineering.

**TI configurations based on concave shapes:** It is possible to design TI configurations using concave blocks. However, there is no framework to generate such type of blocks. Examples of such TI blocks are the Osteomorphic Block [8] and Mecke’s tetrahedron design [9]. To expand my proposed TI generation framework to support concave blocks requires the embedding of a continuous, symmetric, and periodic function at each face of the blocks. Therefore, two neighboring blocks must share the same embedded function to fit with each other. Additionally, including phase parameters per block’s face may provide unique interfaces between adjacent blocks.

**Computational organic design:** Designers, engineers, and researchers often find inspiration from shapes and functionalities in nature. I am interested in the geometries formed by differential growth methods. Examples of such geometries are wrinkle-like shapes (e.g., lily petals), cellular forms (e.g., nervous systems and tissue), catenary design (e.g., Sagrada Familia Cathedral in Barcelona, Spain), and specimen shapes (e.g., Ernst Haeckel’s illustrations). The resultant geometries are often regarded as biomimetic, laminar, shell-like structures. I plan to explore parametric differential growth mechanisms to describe different types of organic shapes. I am mostly interested in structures suitable for 3D Printing and Scientific Visualization applied to engineering and medical purposes.

**A comprehensive theory on geometric interlocking mechanisms:** Interlocking assemblies and mechanisms are common across disciplines (e.g., from joint techniques in woodworking to virus capsid studies in epidemiology). Despite their importance, there is no unified interlocking theory that explains the taxonomy of possible interlocking structures. Still, there are recent approaches that aim to such a goal during the assembly generation process. As an example, DESIA (a framework proposed by Wang et al. [10]) generalizes on the generation of assemblies based on key blocks and recursive interlocking. Still, TI configurations do not fit in the DESIA model since they do not fulfill such characteristics. Furthermore, DESIA assumes the blocks have flat faces, which implies that the generation of specific concave blocks (such as the Osteomorphic Block) cannot be generalized using such a model either.
Immersive experiences using Mixed Reality: I am interested in recent advances and applications of Augmented and Virtual Reality concepts. The technological capabilities from AR/VR devices open the door to unexplored Human-Computer interactions that cannot be addressed by traditional User Interface elements. Tracking user actions and poses is just one of the tasks required to design successful immersive and responsive mixed environment. The current trends for using AR/VR technologies in educational, medical, and industry show there is room for improvements. Having proper and intuitive UI elements in AR/VR may increase the effectiveness of such immersive technologies.

References


