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Computational Design and AR-assisted Assembly of Infinitely Reusable Temporary Structures

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Abstract

Bespoke components are typically required for building free-form spatial frame structures. These bespoke parts, tailored for specific functions and scenarios, necessitate considerable time for sorting and labeling, and their fabrication consumes substantial energy and materials and lacks potential for reuse. In contrast, standardized joints, while facilitating quicker assembly and offering reusability, are generally limited to certain regular topologies. This paper addresses the assembly-aware design and construction of free-form spatial frames with a standardized kit of parts (i.e., uniform-length wooden sticks and swivel couplers) with the aid of Augmented Reality (AR). Building upon a previous computational work that converts an arbitrary line graph to its multi-tangent realization [1], this paper focuses on exploring design and AR-assisted assembly strategies. Two design methods are proposed, one using an assembly-aware approach by combining rigid modules, and the other stability-aware, by discretizing a funicular structure. The construction of two full-scale pavilions using this design-to-fabrication workflow demonstrates the feasibility of the design-and-assembly approach. A reconfiguration experiment further showcases the flexibility of the proposed system to build multi-purpose, temporary structures.

Keywords: Infinitely Reusable Kit of parts, Reconfiguration for multipurpose designs, Assembly-aware Design)

1. Introduction

In contemporary architecture, spatial frames stand out as an important, lightweight structural system designed to withstand external loads. Their geometric flexibility enables their usage in a wide range of applications. However, the construction of these bespoke spatial frames involves connecting rods using customized joints, resulting in high manufacturing costs and challenges in reuse.

Inspired by the scaffolding system, we propose constructing spatial frame structures using standard scaffold couplers. In our approach, rods of the same length are tangentially connected using these reusable couplers, enabling the creation of frames with free-form geometries. Our system is designed to be infinitely reusable, avoiding the need for cutting, labeling, or specialized components.

This work evolved from the existing software "FrameX," [1]. The software facilitates the creation of scaffold structures with complex geometries from a given 3D line graph. However, the optimization-based software offers no guidance on designing a high-quality line graph. Infeasible inputs can result in solutions that do not converge or are structurally unsound. In addition, materializing digital models into physical constructions remains a challenge.

Our contribution includes:

- We propose two design logic for creating the input line graphs for generating free-form scaffolding structures.
- We utilize augmented reality to assemble two full-scale pavilions that share the same kit of parts.
- We demonstrate that our system can be used for reconfigurable design.

2. Related work

Design and fabrication of non-standard spatial frame structures is an active area of research in both structural design and contemporary architectural studies, because of their potential for realizing lightweight, efficient spanning solutions as well as formal and aesthetic freedom. However, these non-standard structures often require bespoke components, such as 3D printed joints and uniquely cut bars (see, e.g., [2, 3, 4]). These kits of parts are tailored for specific designs, and are hard to reuse in other structures. Recent research in reuse-driven design has explored how to design structures with a given set of reclaimed objects. The integrated method, in which structural analysis and material matching are directly formulated as a mixed-integer optimization problem, has been proposed in [5, 6, 7], and has been developed into a design tool [8]. In decoupled approaches that separate the analysis and matching, alternative methods have been considered to solve the linear assignment problem, including genetic algorithms [9], a greedy search [10, 11], statistical pattern search [12], and the Hungarian algorithm [13, 14, 15]. Interactive design tools are also developed to support flexible design exploration using the decoupled approach [16]. The uniqueness of the parts can also be considered in forward design processes, where the kit of parts are rationalized into a small set of equivalence classes. Algorithms have been proposed to reduce the number of distinct nodes [17, 18, 19, 20] and/or distinct bars [21, 22].

While most of these approaches still require bespoke joints to connect elements spatially, this work explores the use of standard, reusable swivel couplers to connect uniform-length wooden sticks. We propose new computational framework to enlarge the design space of these multi-tangent structures, where bars are offset in tangent contact with each other and joined through adhesive or reusable connectors. Such systems have been widely used in construction scaffolding, traditional rope-tied bamboo structures, and wire-tied rebar cages. Specific sub-classes of multi-tangent systems have been studied in the context of reciprocal frames [23] and multi-robot assembly [24, 25, 26]. However, reusability is not the focus of these studies. Our work proposes a design-to-fabrication workflow that enables the assembly of large-scale multi-tangent structures with unconstrained topologies, using an infinitely reusable kit of parts.

3. Methodology

Our workflow consists of three steps as illustrated in Figure. 1. Firstly, we propose two design logics for creating the abstract shape of our frame structures represented by a line graph (Section 3.1.). Secondly, we apply the “FrameX” algorithm to convert the line graph into a fabricable scaffold model containing the positions and orientations of both rods and couplers (Section 3.2.). Lastly, the digital design is assembled physically through augmented reality (Section 3.3.).

3.1. Design Logics

In this study, we utilize a line graph, illustrated in Figure 2, to encode our design intention. Every edge within this graph represents a rod in the physical construction, with the connectivity of these edges

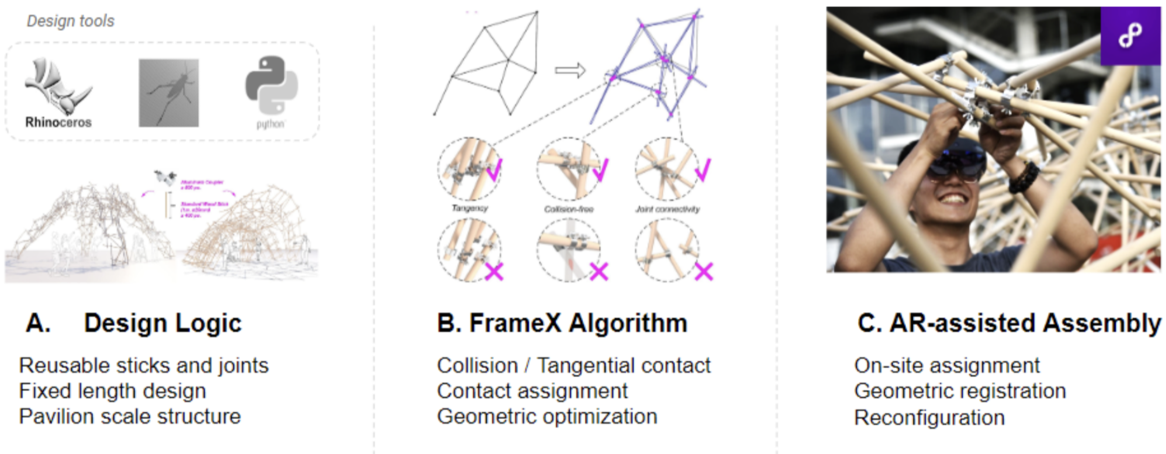

Figure 1: The overview of our workflow

indicating how the rods are joined using couplers. Note that the line graph itself is not directly used for fabrication. Instead, a fabricatable design is obtained by inputting the line graph through the ”FrameX” algorithm [1]. This algorithm requires a high-quality line graph as a prerequisite to ensure the successful fabrication of the design it generates. Therefore, in the following, we propose two design strategies for generating effective line graphs.

3.1.1. Assembly-aware design

Our target frame structures often contain hundreds of rods. Assembling these rods sequentially introduces assembly errors that can accumulate, leading to significant discrepancies between the digital design and its physical constraints. A more effective strategy is to divide the whole structure into individual modules that can be pre-assembled. Later, these modules can be combined onsite. This decompositional approach inspires us to consider a modular design strategy for the input line graph. In this work, we focus on using a cube as our building block (Figure 2-A). An important requirement for each module is that, when assembled, these modules should be strong enough to maintain their shape during transportation and installation. The original cube fabricated using our scaffold system can still be deformed by shearing forces (Figure 2-A). We add a diagonal rod to reinforce its structural strength. For two adjacent cubes, we propose four ways to reinforce their strength and discover that the last design has the most balanced performance between strength and number of used rods (Figure 2-B). Applying the same logic, we can aggregate these cubes to form a stable arch illustrated in (Figure 2-C).

3.1.2. Stability-aware design

The second design strategy utilizes graphic statics [28, 29] to generate a structurally sound line graph. Our method incrementally integrates design details using subsequent subdivisions while maintaining the stability of the design.

We employ the Grasshopper plugin “3D Graphic Statics” [27] to generate structural outlines by inputting essential vertices to define structural dimensions. These outlines are then divided into tetrahedrons to maintain structural integrity and prevent the use of overly long rods (i.e., ensuring that all subdivided lines remain under one meter in length). Similarly to the assembly-aware design strategy, our tool groups rods into various pre-assembled modules to reduce assembly error.

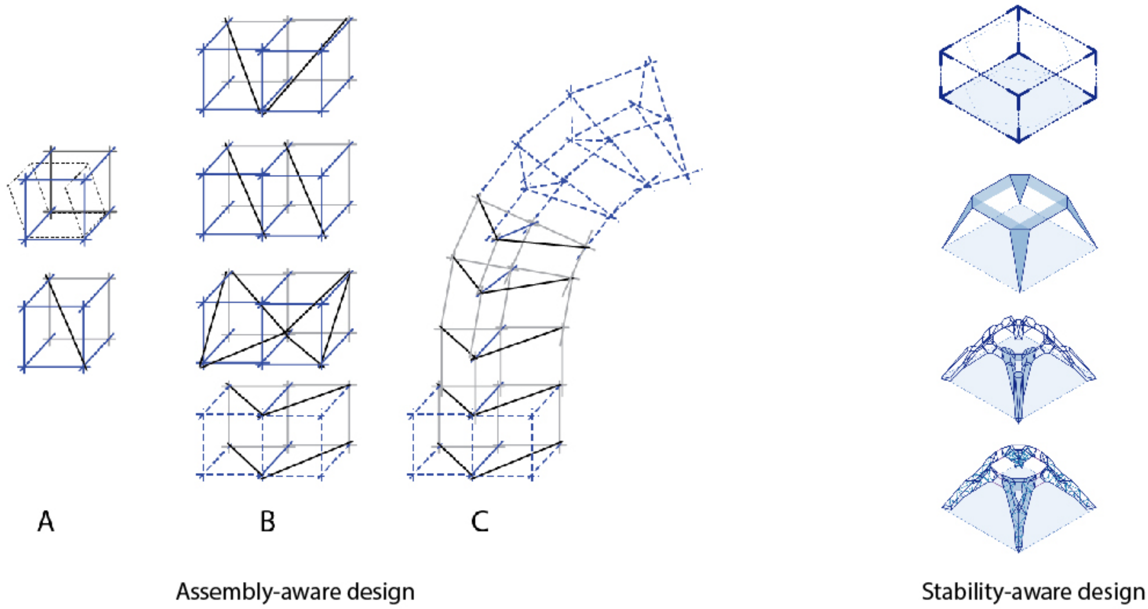

Figure 2: Two design strategies. Left: our "Assembly-aware design" strategy starts with the most basic and boxy module. A diagonal bar is added to a cube to efficiently help stiffen the module (A). Multiple attempts to add diagonal bars are experimented, with consideration of aggregation method, stability, number of rods, and overall aesthetic pattern (B). Then, the modules are assembled as functional structures by adapting their geometry to the target reference shape (C). Right: our "Stability-aware design" strategy. A funicular shape is generated procedurally using the Grasshopper plugin "3D Graphic Statics" [27]. The tool takes the bounding volume, location of support, and load conditions as input and generates structurally stable line graphs accordingly. With this design strategy, the result is considered both form and force with the number of parts(rods and couplers) used.

3.2. The FrameX Algorithm

The algorithm "FrameX" can automatically convert a line graph into a multi-tangent bar structure that can be built using our kits of parts; see Figure 3. The algorithm optimizes the bar geometry and the contact assignment with constraints such as tangency, collision-free and joint connectivity. By this way, the overall structure achieves stable structure with a reasonable number of couplers, which benefits both assembly time and construction budget.

3.3. AR-Assisted Assembly

We use augmented reality to assist the assembly of the digital scaffold models. Before fabrication, users can preview their digital models directly at the intended installation site through the AR glasses, offering an immersive experience that facilitates design iteration (fig.4-A). Augmented reality also benefits fabrication. Individual modules are pre-assembled indoors. Using AR, users can locate rods and couplers in space to build modules. Each module is positioned on the ground in the most ergonomic way for human assembly. For example, the upper modules of our arch column are put upside down, as shown in Figure 4-(B). Extra rods (white bars in Figure 4-(B-C)) and anchors (Figure 4-(D)) are used to temporarily secure our modules to the ground, preventing any unintended shifts that could cause misalignment when employing AR. Later, these pre-assembled modules are transported to the final construction site for combination, where AR can provide guidance on the assembly sequence of the modules.

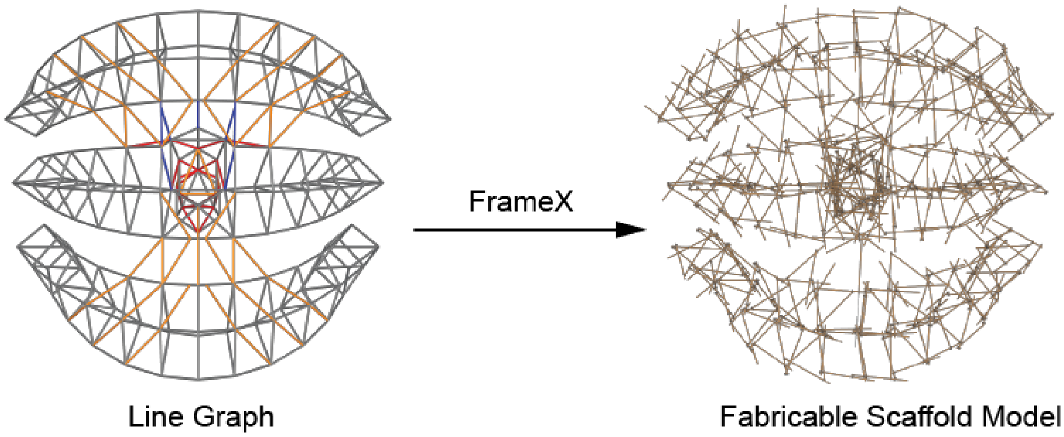

Figure 3: The conversion from line graph to fabricatable scaffold model

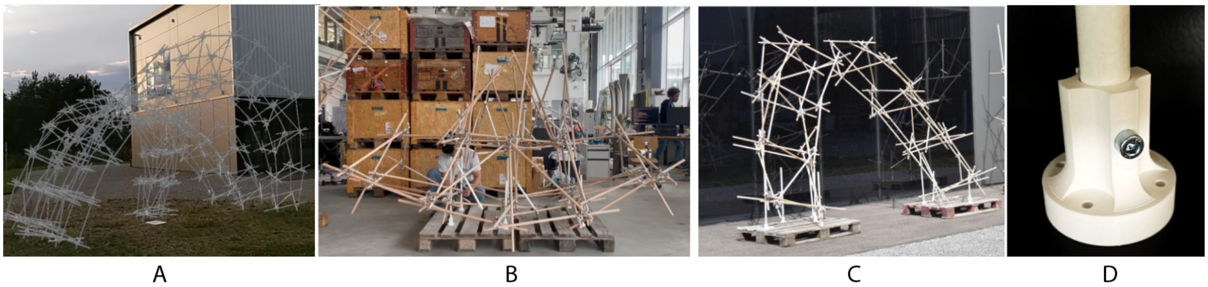

Figure 4: AR-assisted design preview and modularized assembly. (A) on-site design preview; (B-C) AR-assisted assembly of modules; (D) the 3D printed ground anchor detail.

4. Result

4.1. Archcolumn

Our first demonstrator is called ”Archolumn,” which consists of three arches with a central column (Figure 5-B). The whole structure was assembled by two people using 430 rods and 750 couplers. The pavilion is composed of 10 modules with a pre-assembled time of 24 hours. Then, these modules were combined into a large pavilion with dimensions of 5.45 meters in width, 6.25 meters in length, and 3.4 meters in height. The final combination time is within 6 hours without using any power tools.

Point-cloud scan (fig. 6-A) and augmented reality (fig. 6-B) are used to compare the total deviation with the digital model. The overall structure achieved expected stability and was within a 9% deviation of the overall designed height. The bar with the longest overhang (2.6m) has a deviation of 32 cm.

4.2. Reconfiguration extension

As an extension, our system can change its appearance by rearranging rods. For instance, the central column module group of the pavilion ”Archolumn” is designed to be removable; see Figure 5-A. To compensate for the support forces provided by this central column, we relocated some of the components to reinforce the arch’s strength (blue bars in fig. 5-C). Removing the central column creates a large opening while the structure still remains stable, thanks to the rearrangement of the rods and couplers. During this process, 65 bars are relocated from the central to the sides, and 49 bars are recycled to stock.

Figure 5: The demonstrator “Archcolumn” is designed for 2 scenarios, which are “scenario 1” (A) with a central diamond shape opening and “scenario 2” (B) with a central diagonal column. The transformation from “scenario 1” to “scenario 2” is deployed by removing the central column (pink) and redistributing the bars (blue) to the two sides for reinforcement (C).

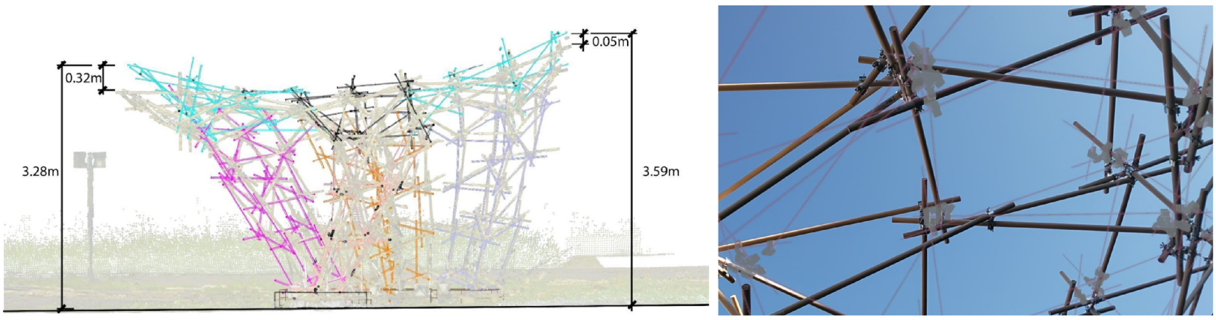

Figure 6: (A): a comparison between 3D scanned point-cloud model and designed model from side view. As we can see, the long overhang side arch is 9% lower than the designed height. (B): comparison between digital model and assembly output through AR goggles.

4.3. Bloomdome

Our second demonstrator is named ”Bloomdome,” a three-leg dome, using 210 rods and 445 couplers (fig. 7-B,C). The pavilion has a size of 6.5m x 5.6m x 2.8m (W x L x H). The structure is divided into 7 modules with a pre-assembling time of 18 hours. The final combination time of the modules took another 3 hours by two people. An analysis of the fabrication resource and time of the three prototypes is provided in Figure 7-A.

5. Conclusion and Future Work

With the developed design strategy, the ”FrameX” algorithm, and the modular AR-assisted assembly workflow, free-form scaffolding structures can be designed, assembled, reconfigured, and re-assembled without bespoke joints. This project has experimented with different logic to divide the overall geometry into modules to facilitate the assembly process, allowing the large-scale pavilions to be assembled by two persons in a short amount of time.

There are many promising future directions to broaden the impact of this work. From the ”Archolumn” experiment, we found that the deviations when assembling a low arch were much more than expected. Although we can use structural analysis tool to have an optimistic prediction on the structural behavior

Analysis of Assembly Working Time			
	Archolumn (Phase I)	*Archolumn (Phase II)*	*Bloomdome*
People / HoloLens	2 people / 2 HoloLens	2 people / 2 HoloLens	1 people / 1 HoloLens
Sticks / scaffold couplers	430 Sticks / 750 scaffold couplers	381 Sticks / 670 scaffold couplers	210 Sticks / 445 scaffold couplers
Size	5.45 * 6.25 m / H: 3.4 m	5.45 * 6.25 m / H: 3.4 m	6.5 * 5.6 m / H: 2.8 m
Module assembly time	10 modules / 24hr	-	7 modules / 18 hr
Combination assembly time	2 people / 5 hr + 3 people / 1 hr	Transformation - 3 hr Disassembly - 2 hr	2 people / 3 hr

A

B C

Figure 7: (A): a comparison on fabrication resource and time for the Archcolumn, reconfigured Archcolumn, and Bloomdome. (B-C): Bloomdome assembled indoors and reassembled outdoors.

by assuming all joints are fixed, a more tailored structural analysis method is needed to have a more precise prediction of the free-form scaffolding system's deformation.

Although this work uses only wooden bars as the elements, we would like to experiment with other natural materials, e.g., bamboo, and utilize their natural curvature to build active bending structural systems.

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