Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Interactive Mixed Reality Workflow for Ad-Hoc Gridshell Assembly

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Abstract

This paper describes an interactive mixed-reality workflow for the ad-hoc assembly and form-finding of a wooden gridshell enclosure. Often, mixed-reality fabrication uses static holograms that visualize the outcome or part without much intended allowable variance. The criteria for calibration may still rely on the achievement of tight tolerances in that scenario. This project seeks to facilitate a more instinctive and conversational workflow between manual assembly and design intention, as the digital and physical outputs are created simultaneously and to the liking of the user(s). Discussed are a series of iterative prototypes of both the MR workflow and the built products, culminating in a small but inhabitable geodesic gridshell with a non-standard topology.

Keywords: Mixed Reality, Fabrication, Gridshell Topology, Material Driven Workflow, Computational Design

1. Introduction

The mixed reality (MR) workflow discussed relies on gestural user input to guide intuitive design decisions throughout the process of assembly, not prior. Through iteration, further understanding of how actively bent wooden members map over an arbitrary geometry was gained, and a custom MR experience was created such that the outcome of the enclosure was completely determined in real-time by the user. The discussed workflow collapses design and construction phases into a single process and welcomes user intuition and real time adjustment of the structural laths as the target form of the enclosure is realized.

The workflow can accommodate the assembly of gridshells with either a diagonal or rectilinear topology but is best suited for sequential assembly where each lath is bent and fixed in place individually. Since lath placement and connections are not predetermined, the gridshell topology consists of a series of semi-hierarchical laths with user-selected trajectories. The workflow embeds rules for the user-generated laths to prevent extreme overlap and torsion, and user-selected lath trajectories that fail to conform are automatically removed from the holographic guidelines. Redundancy within the lath density is acceptable in the ad-hoc assembly, linking structural capacity to subjective visual criteria. This simplifies the construction of complex structures by guiding users of various skill levels to create a stable and spatial gridshell enclosure. Both expert and novice builders could work within the same MR environment within their respective groupings or in collaboration with one another, as the 1:1 holographic projection is more visually didactic for complex assemblies than scaled drawing sets that require some prior expertise to interpret.

Digital models viewed in augmented reality can serve as guides to form and assemble parts during construction and reduce the need to build temporary formwork or sub structures (Jahn et al. [1]). The environmental impacts of the construction sector underscore continued investments in the development of digital fabrication and MR technologies toward innovative and efficient construction processes (Mitterberger et al. [2]). Modern applications of MR fabrication in architecture use predetermined digital models as anchored holographic guides. This can assist in fabricating complex structures within a certain tolerance in comparison to a digital model. Our ad-hoc workflow considers this existing framework while creating new insights to synchronized design and fabrication processes. Real time design and fabrication coordinated simultaneously, can allow for real-time design alterations resulting in collaborative outcomes with equal input from both designers and fabricators.

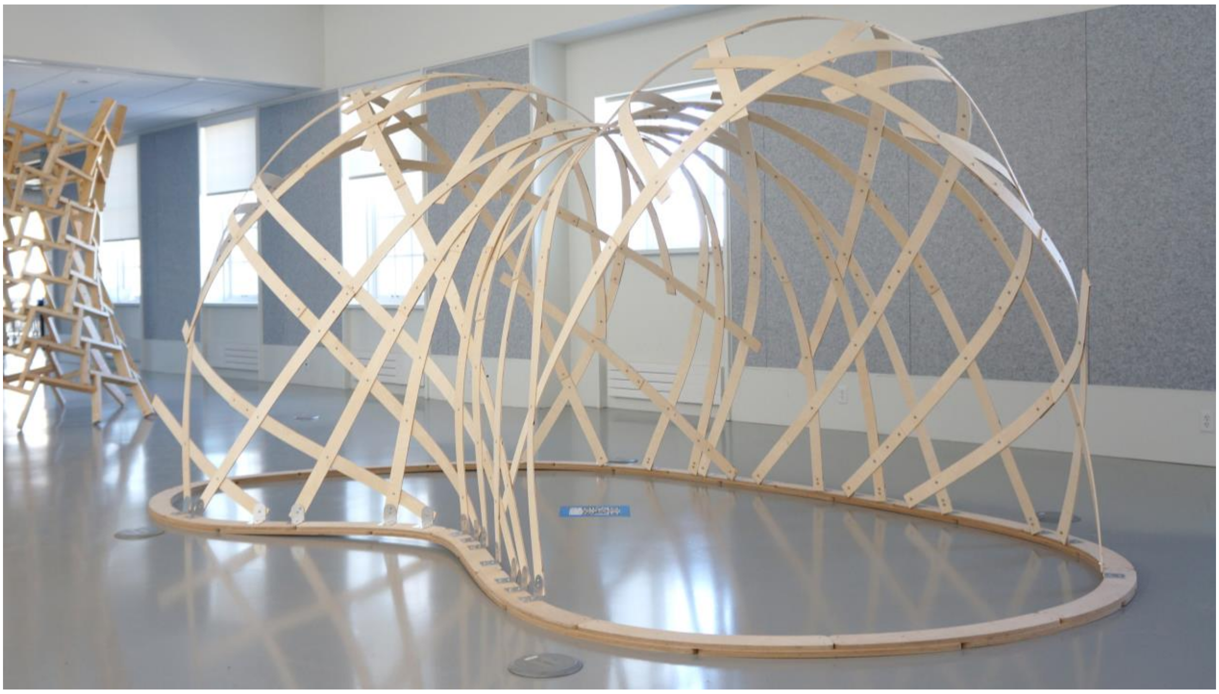

Figure 1: Ad-hoc geodesic gridshell prototype built in mixed reality.

2. Interactive MR Workflows

The accommodation for spontaneous decision-making during simultaneous fabrication and design workflows is gaining traction as a worthwhile scope of investigation by researchers engaging with MR fabrication. The ability to make intuitive and real-time adjustments is one example of how MR fabrication is agile and reverent to human ability, that in some cases is complex and difficult (if not, futile) to recreate using CNC or robotic equipment. Architectural research projects focused on or incorporating MR fabrication have increased in recent years thanks to the accessibility of robust software applications that enhance the capacity of well-known 3D modeling software and visual scripting platforms. Specifically, this research and all referenced examples in this section have used Fologram, a third-party plug-in for Rhino3D and Grasshopper that provides a general-purpose software toolkit for developing AR applications for the Microsoft HoloLens and mobile devices (Jahn et al. [3]). Since its inception in 2018, Fologram has become an established tool for the architectural design community, helping to realize MR fabrication and visualization projects that have engaged a wide variety of materials, contexts, and techniques.

Fologram brings gesture recognition data captured by the HoloLens2 to GH, enabling designers to quickly create custom user interfaces (UI) and collaborative MR experiences. This research is primarily focused on the latter, in an attempt to blend the design and fabrication processes into a single workflow. Preceding research that has demonstrated impressive progress on integrated MR design to fabrication workflows through a custom UI includes several projects by Lok et.al such as Timber De-standardized [4] and HoloWall [5], and by Kyaw et.al., in their work on the Unlog Tower [6]. These projects utilize their MR interfaces to effectively process irregular and non-standard materials into refined architectural structures and components. By contrast, our Ad-Hoc Gridshell uses standard plywood sheets cut into narrow planks. However, by comparison, the planks are bent into position in real-time, requiring an MR model that depicts plank geometry that falls within the limitations of the material. Some first-hand knowledge of material properties and bending behavior is also important, and we have noted an increase in this knowledge within the team throughout the process of completing the various prototypes. It is well documented how MR workflow can guide the fabrication process, but it is an equally capable gateway for didactic learning.

As noted by Jahn et.al., building from flexible materials often requires temporary formwork that adds cost and complication [1]. Instead, MR models define the location and shape of parts rendering the formwork unnecessary in some applications, but manually controlling flexible materials at a large scale remains a challenge especially when static digital models are used to guide the assembly [1]. Their collaborative work on the Steampunk Pavilion demonstrates how physics-based simulation with the goal-based solver Kangaroo2, when paired with MR, enables "wide tolerance" construction by hand and eye and avoids part breakages and accumulative error [1]. Our Ad-Hoc Gridshell workflow acknowledges this by first projecting only geodesic lines over a target form which guarantees the wooden laths that follow will lay flat along the surface and flush to one another at their crossings, while remaining flat and straight when at rest. Additionally, a bending simulation of the installed laths helps determine whether the lath will be able to conform to the geodesic guide, or if there is a likelihood for difficulty in part positioning or part failure due to extreme bending.

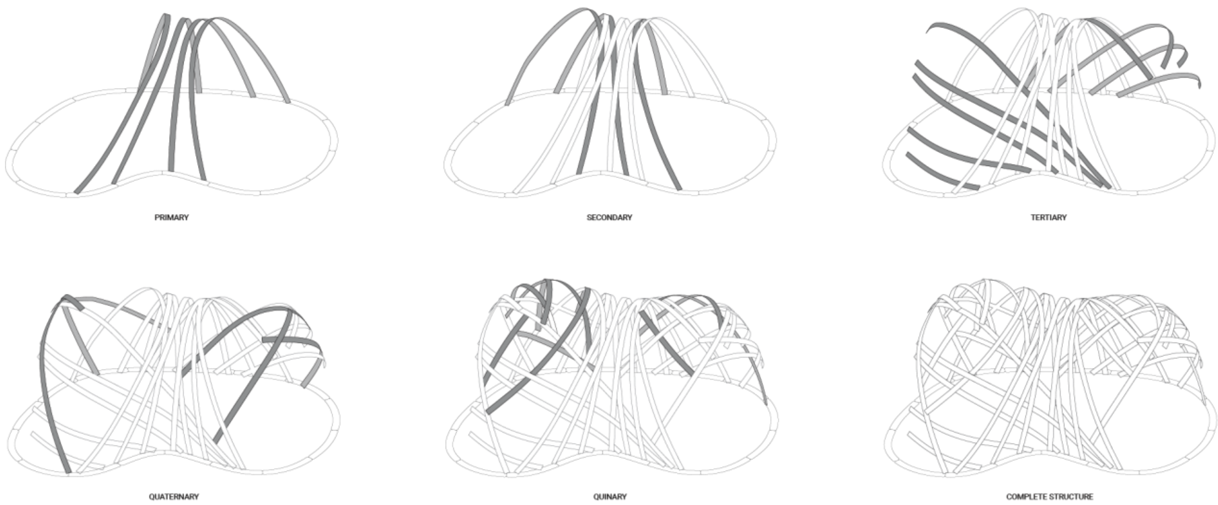

Figure 2: Sequential lath topology, each responding to previous steps. The digital model is a product of mixed reality geodesic lath placement in real time.

3. Sequential Gridshell Topology

This work to date has taken a case study-based approach that recognizes how MR environments can allow for ad-hoc decision making by aligning with two primary case studies, the Faraday Pavilion by Nicholas, Tabatabi et.al. [7] and the Ongreening Pavilion by Harding, Pearson, et.al [8].

While the Faraday Pavilion is built from GFRP rods, the approach to its construction differs from that of typical post-formed gridshells. Normally, an initially flat grid is deformed into a double-curved 3D form by exerting force and is eventually locked into position. The entire grid topology is needed to begin in the relaxed state, restricting more irregular grid topologies that may be more difficult to manage when flat. Alternatively, the authors developed an approach that allows for on-site decision making, where the placement of structural elements are determined by a desired target geometry and a form-finding process that incorporates the bending behavior of the material within the digital model [7]. The topology is not predefined. Rather, it is developed by material behavior and by design intent in a feedback loop that approximates the desired target form, but only as far as the material allows. This is made possible by a workflow that invites adjustment to the simulation and a rapid recalculation of equilibrium to validate the on-site placement of elements and how they contribute to the existing topology. Our MR workflow aligns well as an exercise in collaborative construction with integrated computation and intuition.

The Ongreening Pavilion also exhibits a non-standard gridshell topology and is sequentially constructed in a similar fashion [8]. Additionally, the grid topology is not predefined but emerges as part of a simulation. The entire pavilion is designed prior to construction by establishing first the planar curves that defined the desired free-form surface that encapsulates the spatial volume. The surface is then used to draw a series of geodesic lines that comprise the primary lath layer. Geodesic laths are then added to the primary layer from a random set of points, increasing stability and enclosure. The random aesthetic of the secondary layer of geodesic laths gives the gridshell strength in all directions, acting more like a continuous shell. Additionally, the authors describe the necessity of manual adjustment to the random seed points that locate the secondary laths to improve aesthetics, avoid unwanted material accumulation, and evenly fill out the target surface without large gaps. By incorporating structural analysis into the parametric model, each configuration and manual design change could be evaluated very quickly. We find inspiration in the real-time analysis used in combination with human intuition, as opposed to finding an optimal result that excludes qualitative judgement [8].

Other related works include the geodesic gridshell by Adiels, Bencini, et.al. [9], the UWE Research Pavilion by Harding, Hills, et.al. [10], the Almond Pavilion by Soriano [11], and the geodesic segmenting of a funicular shell by Schulitz [12]. Each demonstrate successful implementations of timber geodesic planks at an architectural scale.

Figure 3: Faraday Pavilion (Nicholas et al [7]), Ongreening Pavilion (Harding et al [8]), Geodesic Gridshell (Adiels et al [9]), UWE Pavilion (Harding et al [10]).

4. Ad-Hoc Gridshell Development

4.1. Workflow Trials

The MR workflow was assessed and improved through a series of iterative trials, increasing in scale and complexity but consisting of the same materials. To begin, a target form of a hemisphere is calibrated to a circular plywood base. First exists the “design mode” where, points, spaced equidistantly, are generated along the base, and subsequently made selectable in the hologram with a small mesh sphere (referred to as endpoints/ termination points). When two of these endpoints are selected, a connecting line is drawn and projected up onto the target form matching the users desired trajectory. When enough lath trajectories are modeled digitally, viewed in AR, and the target form is clad to the users liking, they can switch into "fabrication mode" by flipping a custom programed toggle (either within the AR UI or the GH window) which allows the lath trajectories to be selected in MR one by one. The toggle enables and disables portions of the GH script, switching what elements in the model are selectable with MR gesture recognition. Upon selecting a lath trajectory, its numeric length is projected in MR alongside its 2D unroll and intersection points for 1:1 comparison. Upon repeating this process of cutting, predrilling all laths, and assembling, it became clear that avoiding material overlap would be critical to the successful deployment at a larger scale.

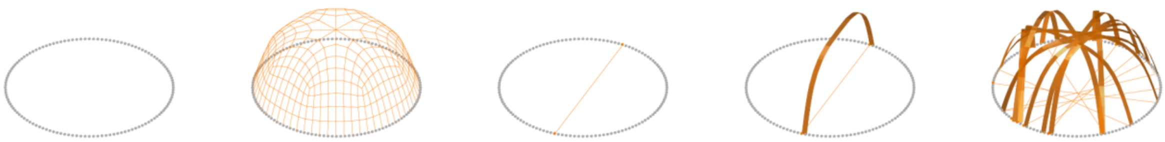

Figure 4: Initial lath modeling procedure - two points are selected in MR, resultant lath is projected upon the target form and visualized in headset view for user discernment.

A follow up trial used the same system to draw and fabricate laths however this version incorporated a tolerance condition. If more than 2 laths were within a specified distance of an intersection, the third is automatically removed from the fabrication phase. While this improved lath distribution around the target form, we discovered that a simple vertical projection would be insufficient to fully wrap around a target volume with double curvature. Further, the projected, non-geodesic lath intersections were far from flush resulting in near impossible intersections. To address this shortcoming, an additional "adjustment mode" was added in the workflow, allowing the user to adjust the endpoints of a drawn lath such that the user can decide on a trajectory that better wraps the target form. The drawing phase then became a way to identify the highest point of the lath which would then function as a hinge point during the adjustment phase. Adjustment mode is also paired with a color gradient for each lath based on how close each respective unroll was to being straight, providing the user feedback on constructability. This mode was later deemed unnecessary by performing the geodesic computation in real time with the endpoint selection. The results were considered satisfactory for the initial trials and greatly informed future versions of the workflow.

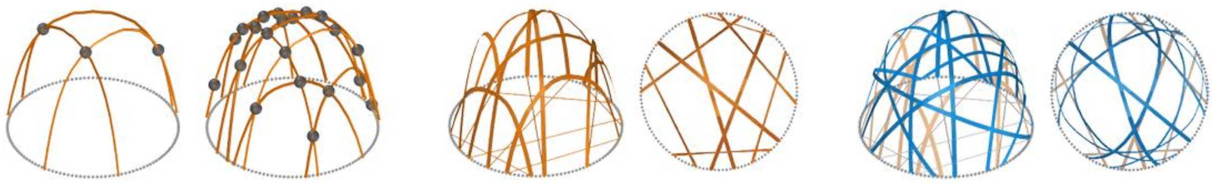

Figure 5: Screen captures of MR model – guided lath distribution, lath projections (global z-axis), lath projections after curvature adjustment (local mesh tangents).

4.2. Prototype 1: Partial Geodesic

To further evaluate the successes and limitations of the previously created MR workflow, a surface consisting of both positive and negative curvature, anchored to a curved base with both positive and negative inflection points, is modeled as a target geometry. It is worth noting that the target geometry is free-form and modeled without awareness of the exact locations of the laths. This was an intentional challenge to find the limits of ad-hoc form finding and assembly. Like previous trials, we designed a double-layered 1.5" (~36mm) thick plywood base with pre-drilled holes to locate the selectable end points in the hologram and where a base connection can be placed in the physical assembly.

A hierarchical strategy for lath placement was discussed by the team both prior, and during the assembly sequence. This replaces the phased approach from previous iterations. It was decided that three lath layers, referred to as primary, secondary, and tertiary, would provide enough stiffness for the enclosure to safely stand. The primary layer consists of a series of projections, vertical in orientation and with end points at the base. The role of the primary layer is to approximate the height in as many points as possible while limiting "within-layer" intersection (in other words, to be as free standing as allowable within the geometric constraints). The within-layer intersections were only allowable under a height threshold that constrained them to rest within the mostly vertical sides of the target geometry.

As the primary layer is completed in MR, it is simultaneously modeled on the computer. This is obvious since the holographic display requires the digital model; an alternative phrasing is that the digital model is created by the interactive gesture recognition that tracks point selections upon the physical base condition, made possible by the HoloLens. The user is digital modeling at 1:1 by hand and viewing the results in MR through the feedback loop between the model and headset. The center-line trajectories of the newly modeled laths making up the primary layer are then parametrically divided into a new series of equidistant points, and when viewed in MR, are selectable as end points of the new laths that make up the secondary layer. By team discussion after viewing the results, it was decided that the secondary layer would approximate the top-most portion of the target geometry. The "as-built" condition (output from the primary layer) had little to no strength at the top of the form which informed us where we needed to fill out next to create an overall rigid pavilion. The end points are selected in MR from their positions along the previously constructed primary laths and above the same height threshold used previously to limit primary layer intersection. These laths were again modeled using vertical projection to the target geometry, providing more stiffness as primary and secondary laths connect to enclose the top of the volume.

Finally, the tertiary layer was modeled as a geodesic line between two points selected from the primary after center line division, such that the laths would wrap the target geometry in a mostly horizontal direction. The geodesic lines were computed between two input points using Grasshopper's native algorithm. Drawing the geodesic line between selected points along the first two layers is advantageous for these laths since they cannot be simply projected vertically from the ground plane like previous layers. The selectable end points for the tertiary layer were again kept below the specified height threshold to wrap the sides of the form, providing enough overall stiffness to the structure, resulting in an inhabitable gridshell.

Figure 6: Sequential assembly with mixed reality guides developed in real time. The team switches from design mode (top) and fabrication mode (bottom).

4.3. Prototype 2: Full Geodesic

The trials described reveal the limitations of a truly ad-hoc process. While the workflow can be easily adjusted to accommodate a range of linear and flexible materials, each will require specific details to ensure successful implementation at the architectural scale. For example, a flush, face-to-face overlap between each of the plywood laths was impossible in the previous iterations since they were modeled as a vertical projection without reference to the bending and twisting of other laths, and without the criteria that the laths lay flat along the target form.

To ensure that flush overlaps would occur at every intersection regardless of the user-selected positioning of each lath, a series of adjustments were made to the workflow; a) every trajectory drawn between two selected points is drawn geodesic to the target surface, b) each trajectory drawn now needed to be confirmed (this reduced the amount of "restarting" if one lath was drawn in an unideal location and allowed us to explore trajectories more in depth), c) the target surface is modified to include distinct openings for entry (previously entry points were left to the user to determine by avoiding lath placement in areas they considered best).

The geodesic trajectories wrap the target form more evenly, making it harder to distinguish a clear layer hierarchy (an agreed upon aesthetic criterium). The geodesics also ensure that the laths, no matter where they wrap the target, will intersect flush for ease of assembly and much stronger connections. As with previous iterations, we acted out a scenario of users interacting with the MR modeling-to-assembly pipeline by first establishing the hierarchy of lath layers. The primary laths were again determined to be anchored base-to-base (by necessity since they are the first in the process) but this time, are prohibited from intersecting.

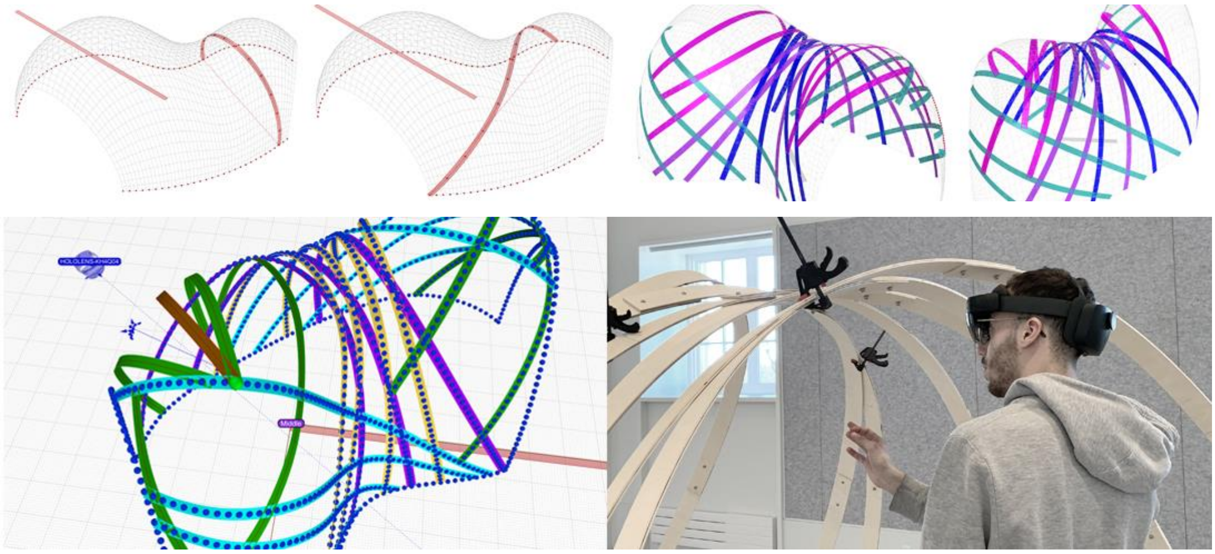

Figure 7: Geodesic lath trajectories are modeled and viewed in MR based on user specified end points.

The secondary layer required the same base-to-base anchoring and is allowed to intersect with the primary laths but still not within layer. This helped us achieve a “cross-grain” along the form and fill out the corners along the base. The tertiary layer went from the base to an outline of the intended openings visible in MR, to begin to fill in the two peaks. These are again not allowed to intersect within the same layer but did intersect with both the primary and secondary layers due to a more horizontal trajectory. This layer was successful in determining the lengths that we would need to fill in the top of the form, but the openings themselves are not drawn geodesic to the target surface. This remains an area of improvement, easily solved with a more carefully designed and construction-aware target geometry. The quaternary layer is added to continue filling in the peaks of the target form, tie the tertiary layer into place, and help approximate the two openings of the pavilion. Finally, the quintenary layer adds additional rigidity to the gridshell and helps enclose the space within.

As with previous trials, this final iteration of the ad-hoc gridshell consists of ¼” (~6mm) thick, 2.5” (~63mm) wide Finnish birch laths cut to various lengths, with one #10-32 (~M5) SS bolt with washers and locknuts securing each lath crossing. 6mm material was particularly appropriate at this scale since it maintains tension, resists permanent deformation, and allows torsion. The bolted connections are fabricated manually and in situ, by first securing the lath to one or both endpoints, clamping the crossings one-by-one to find the shape of material overlap, and drilling the hole through both laths after constructing the center point with pencil lines. While the digital model can locate the exact bolt locations upon a lath in MR, we found that the manual steps provided the most accuracy to the work-in-progress, as-built condition.

5. Conclusions and Outlook

5.1. Suggested Improvements

Due to complex target geometry, the apex of the primary lath geodesic trajectory tended toward the “saddle” between the two high points, as they are algorithmically drawn as the shortest distance between the two selected points. To fill out the high points of the target geometry with the most extreme curvature, smaller lath segments are required. While this challenge was addressed throughout the assembly through team discussion and problem solving, it was decided that an improved workflow would rely on a form-finding process of the target volume that better matches the material limitations. Further attention to the user interface would enhance the MR workflow, making it more amenable to users with less experience in design or fabrication. For example, easier manipulation of control point location, or the ability to locate the locations of splices along the holographic laths with a hand gesture allows for more in situ decisions. Implementing real-time visualizations such as structural analysis, deformations under loading and self-weight, and active bending simulation could give users more feedback throughout the assembly sequence. Additionally, MR guidelines that reveal principal curvature lines along the target surface would be useful to show the user where the geodesics would have the least amount of torsion, thereby influencing next steps toward a more rationalized topology.

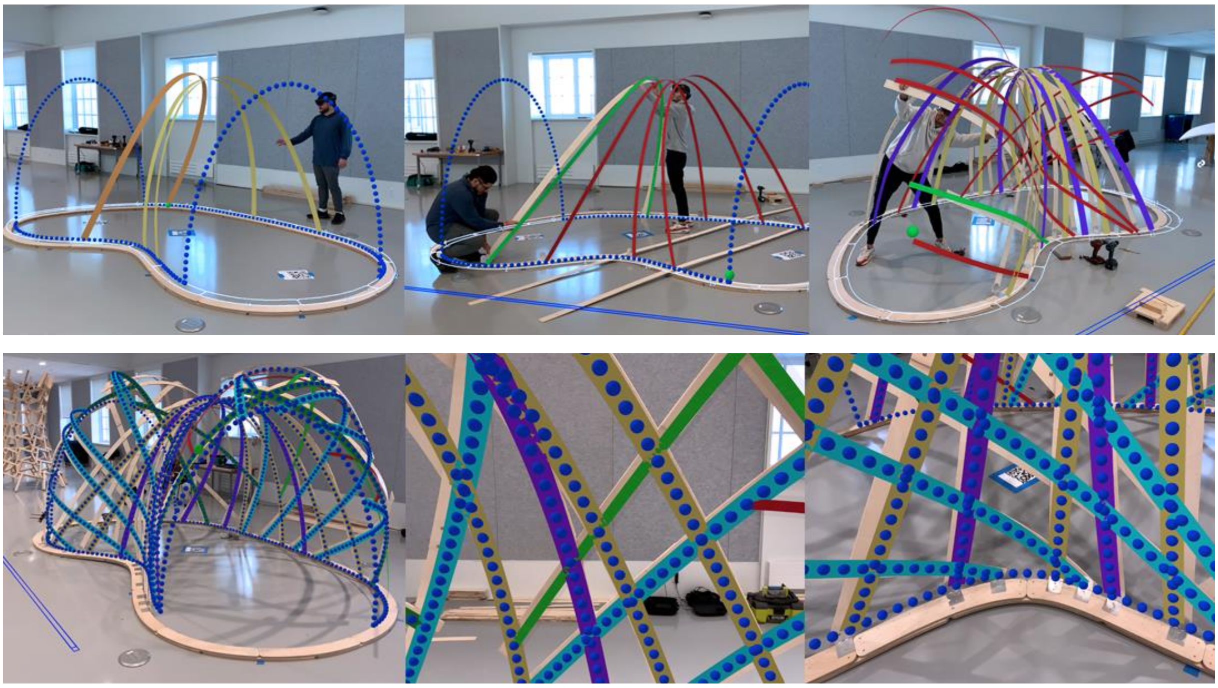

Figure 8: Sequential assembly using mixed reality guides in an interactive and conversational workflow.

5.2. Comparisons to Premeditated Modeling and Fabrication

During our trials, we found it helpful to understand the trajectory that we attempted to create in MR prior to attempting the bend with the physical lath. This aided in us assembling the pavilion with the craft we desired when making small decisions such as whether to place a lath on the inside or outside of an existing lath, or weave between them. In the pre-confirmation phase, while testing various geodesic trajectories, there were many times where the trajectory would frequently "flip" or lock into a different position based on a potential endpoint only one sphere away. Seeing this in MR allowed us to get the longest possible lath while filling in the gaps between the existing laths.

Since the geodesic trajectories are drawn digitally and without the physical properties of the material, portions of the built pavilion vary from the MR guides. This discrepancy is mostly found in the areas with the most extreme transition from positive to negative curvature. This is likely because the target form is of a freeform geometry that was not modeled with geodesics in mind. However, the discrepancy between the MR guides and the limitations of the material was mitigated by in-situ conversation among the users as we determined the best outcome intuitively. These small adjustments helped us coach these off-trajectory laths back into a position that better matched the material behavior. Here, there is much less of an expectation that the final construct matches the digital model exactly. This has its pros and cons. The built result may be less restricted to predetermined optimization that lacks human intuition, but the structure may also underperform structurally or spatially. It is assumed that experienced users would be able to mitigate this by adjusting the physical construct and the digital workflow when necessary.

The described MR workflow is not presented as replacement for premeditated modeling and fabrication. Instead, our aim is to investigate synchronized modeling and fabrication while gaining experience with what MR offers that other design to production workflows do not. Our workflow could easily be adapted for use in a more traditional sequence consisting of a predetermined model and subsequent fabrication and assembly instructions, where the latter is assisted by MR. For example, it may be a useful tool to verify how close the physical construction meets the digital model (assumed to be an optimization), which can be especially helpful for elastic materials with inherent variability and for inexperienced users, unexpected behavior.

We also found it helpful to use MR as a measuring tool, by simply locating two points along the MR model by hand to measure the length along curve between them. We used this technique to pinpoint where lath trajectories intersected different layers and identify lath splice locations that would have otherwise required parametric selection, which for some users may be counter intuitive. Further, we have found that engaging with materials directly through the MR environment creates a gateway for gaining expertise with the construction techniques associated with material characteristics. For example, by calibrating digital bricks to their physical counterparts, an immediate association is made to the actual weight and texture of the material. This brings a level of reality to the digital modeling experience which often feels disconnected from material reality. Likewise in our case, the bending characteristics of plywood were intimately understood after a few trials. This knowledge fed back into the development of the software that in turn guides the material assembly.

Acknowledgements

The work presented in this paper was produced with grant funding awarded to co-author Bruscia by the University at Buffalo, School of Architecture and Planning and the Buffalo Renaissance Foundation. Co-authors Archilla and Vargas, along with Peter Bua, developed an initial version of the project in the 'Fidelity and Tolerance: Phantom Fabrication' graduate research studio taught by Bruscia. Prototype 2 was developed and completed by the authors in collaboration.

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Responses to reviewer comments

Chapter 1-3: Introduces the context of the research but is missing clear reasoning as to why these pavilions and sculptures are built in the first place. For instance, what is the purpose of constructing these systems? There is no clear strategy for envelopes – how the lamellae-defined surface can be covered. The research is situated within commercially available systems but lacks a clear understanding of how this technology was developed and is mostly described from a hardware and software user perspective. This is perhaps a downside of Figure 3, as these pavilions are understood as the norm or architectural research but barely have real implications.

- Reasoning behind selected case studies:
  - two were carried out in educational settings, inspiring this project which is also educational. Of them, one provides knowledge of geodesics and the other asymptotic grids – both pair that knowledge with materials at a large enough scale to understand them as being applicable to architecture. Ours intended to do the same but with MR.
  - A third was mostly referenced due to their use of computational analysis to inform in-situ decisions, inspiring future steps
  - A fourth was a professional project – deployed indoors for a client, providing an example of a project executed with real implications and with a similar design methodology
- An envelope study fell outside of the scope of this project - there are many built gridshells with membrane enclosures, also left out due to page limitations. This project places more of an emphasis on building with MR and less on the comparisons to other gridshell buildings.
- The authors do have a clear understanding for why the technology used was developed and cited the authors of the technology for further reading

Chapter 4.1: Why does the workflow not provide a guideline of principle curvature lines where you would normally place lamellae to ensure minimal torsion? If the lamellae are placed not within the torsion-free curvature line, what implications does such a step have for the next iteration? The lack of clear strategy between the 4th and 5th steps is evident in Figure 4. It would be more interesting to have a full page of a single dataset where you place as minimal amount of elements e.g. 3-4, and how the initial guidelines would influence the next steps. Such workflow could have been studied in greater detail before starting the physical process.

- Helpful point for future work – added a note on this in the conclusion/outlook

Chapter 4.1: How are the thickness and the width of lamellae selected? Is there a structural or material-related criterion?

- The material is readily found and at 6mm was particularly appropriate at this scale – it maintains tension, resists permanent deformation, and allows torsion

Chapter 4.2: Why is the grid-shell called inhabitable?

- Revised

Chapter 4.3: Could you elaborate on what you mean by "visual density"? Why is this criterion necessary?

- Revised a few areas where this language was used

Chapter 4.2-4.3: The description lacks a clear scientific workflow: a) problem, b) methodology, c) comparison of results, and d) findings. If a future reader would like to replicate the methodology and learn from it, is there any well-maintained and open-sourced workflow? How could this workflow be reused in the future knowing the dependency on the commercial software that will definitely change over time?

- The Grasshopper/Fologram/HoloLens workflow is not yet open source, but could be shared

Chapter 5.1: What is the meaning of team discussion and problem-solving? What is the "aesthetic possibility" or "geodesic-aware target"? Before producing physical artifacts, these points should have been better analyzed and understood following your remark "Additionally, implementing real-time visualizations such as structural analysis, deformations under loading and self-weight, and active bending simulation could give users more feedback throughout the assembly sequence."

- "Geodesic aware" terminology edited out

Chapter 5.2: What is the meaning of "The MR workflow also helped us push the geodesic version of the pavilion to its most extreme"?

- Edited out

Chapter 5.2: What is the meaning of "a more correct position"?

- Revised