# Extended Reality (XR) Workflows for Multi-Material Assemblies



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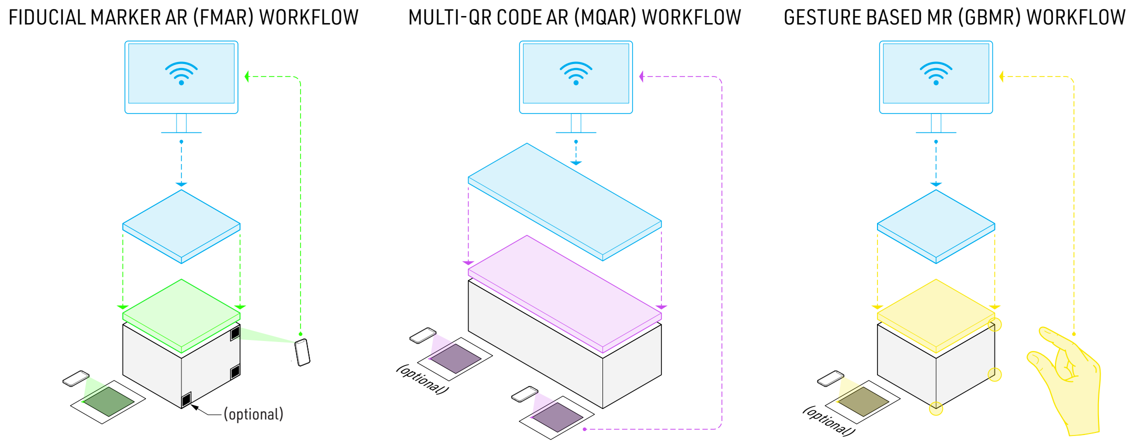
1

1 Eye-level perspective of the *Unlog Tower*

## ABSTRACT

The architecture and construction industries have been developing methods to integrate Augmented Reality (AR) and Mixed Reality (MR) workflows into the building industry for 1-to-1 scale design, visualization, and paperless fabrication. While these AR workflows have been primarily focused on mono-material assemblies, this paper investigates the potential of AR and MR for multi-material fabrication, combining various materials and structural components throughout each phase of the construction of the *Unlog Tower*. The installation uses infested and dying ash trees to construct a 36-foot-tall triangular, lightweight timber structure. The *Unlog Tower* leverages bending active elastic kinematics to stretch robotically kerfed logs braced by threaded rods and tube steel. Three extended reality (XR) workflows were explored for the construction of this bespoke timber structure: (1) fiducial marker coordinated AR instruction, (2) multiple QR code AR instruction, and (3) gesture-based MR instruction. These XR workflows incorporate feedback-based construction notation and animation for the assembly of non-standard natural materials and standardized parts through three construction phases: materials to parts, parts to prefab modules, and onsite assembly. The research highlights the potential of AR and MR workflows for human-machine interaction in robotic fabrication, analog means of making, prefabrication, onsite construction, and coordination. The result of this investigation has demonstrated many advantages and disadvantages of varying AR/MR workflows in facilitating the construction of multi-material and multi-phase structural assemblies.




2 Different AR and MR methods of interaction with different QR code types. 2

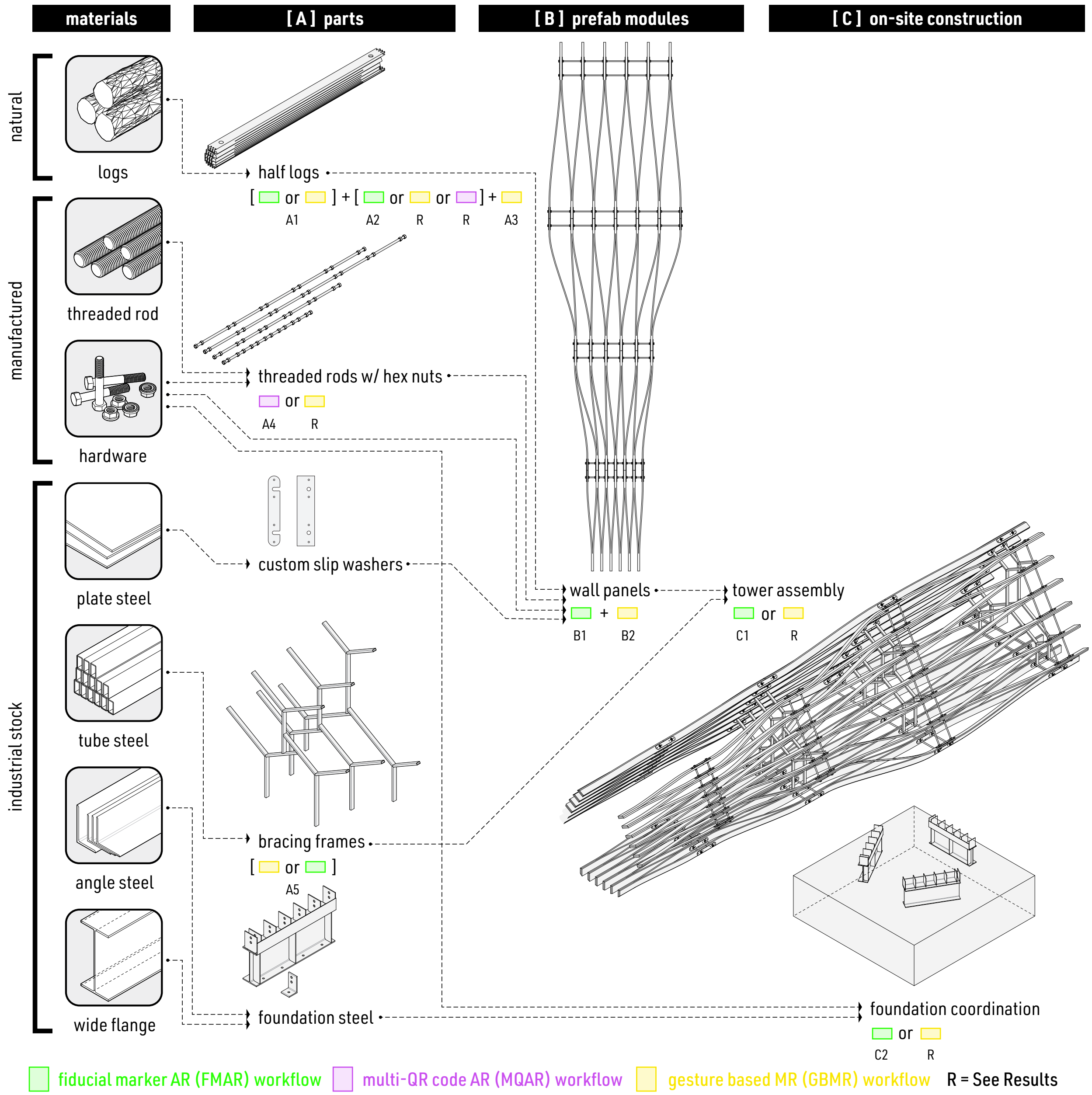
## INTRODUCTION

Easily deployed and assembled, the *Unlog Tower* (Figure 1) stretches several logs into a triangular, lightweight timber tower through robotic kerfing and bending-active kinematics (Schleicher et al. 2011). The research utilizes robotic kerfing techniques and extended reality (XR) instruction to transform Emerald Ash Borer (EAB) infected logs (Flower, Knight, and Gonzalez-Meler 2012) into a materially efficient and locally available timber resource. As a bending-active timber structure, the *Unlog Tower* is comprised of several material types ranging from recently harvested ash logs to various hardware (such as nuts, bolts, washers, and threaded rods) and extruded/rolled steel profiles. The structure also utilized an existing concrete foundation at the installation site. The fabrication and assembly of the tower are broken down into three construction phases: materials to parts, parts to prefab modules, and onsite assembly. These three construction phases utilize the three AR and MR workflows for the fabrication methods, ranging from robotic fabrication, analog making, prefab assembly, and onsite construction coordination.

These materials were processed through computer-aided manufacturing techniques such as computer numerical control (CNC), plasma cutting, and robotics along with analog techniques such as welding, drilling, and cutting. Throughout the design and construction of the *Unlog Tower*, a set of three distinct augmented reality (AR) and mixed reality (MR) workflows were developed to address the diverse range of materials and processes involved. These include (1) fiducial marker AR (FMAR) instruction, (2) multiple QR code AR (MQAR) instruction, and (3) gesture-based MR (GBMR) instruction, each tailored to facilitate the fabrication and assembly stages of the installation. Within architecture and fabrication, current research on AR and MR technology has showcased the potential of AR in aiding 1:1 scale design, visualization, and paperless fabrication. While previous approaches have primarily focused on AR workflows for mono-material fabrication, this paper introduces workflows for multi-material assemblies.

## STATE OF THE ART

The following precedents demonstrate that different XR methods of instruction and fiducial marker placement have varying degrees of physical and digital interactivity, 3D user interface (3DUI) customization, and accuracy for digital-physical object alignment for both mobile devices and head-mounted displays (HMD). Most architectural fabrication research projects, such as H*olographic Construction*, *Code-Bothy*, *Woven Steel*, and *Augmented Feedback* have developed interactive 3DUIs to instruct the fabrication of complex assemblies using the FMAR workflow (Jahn et al. 2020; Lee 2022; Jahn, Newnham, and Beanland 2018; Goepel and Crolla 2022; Lok and Bae 2022). This workflow uses a single QR code to superimpose digital geometry into or onto the physical environment (Figure 2). Further interplay between digital and physical objects can be conducted through the tracking and use of ArUco markers (Figure 2). In *Holographic Construction* and *Code-Bothy*, a single QR code is used to superimpose digital “buttons” to toggle between rows of bricks as they are laid (Lee 2022; Jahn et al. 2020). *HoloWall* superimposed an interactive MR work surface to process salvaged lumber into boards for a hollow-core, cross-laminated timber (CLT) panel (Lok and Bae 2022). *Woven Steel* uses interactive menus to instruct the bending of tube steel, which is then checked by the placement of ArUco markers (Jahn, Newnham, and Beanland 2018). *Augmented Feedback* places ArUco markers at each joint location on a bending-active, bamboo, gridshell structure to track and check the elastic displacement of each joint until the structure finds a natural stable position (Goepel and Crolla 2022). ArUco markers have also been used to index and instruct the assembly of a




3 Workflow Diagram

curvilinear wall surface made of discrete recycled wood boards (Parry and Guy 2021). Each of these research investigations relies on the placement of a single QR code for digital geometry localization and orientation with the optional added interactive instruction through custom digital menus and the use of ArUco markers.

The MQAR workflow uses multiple fiducial markers for the accurate superimposition of digital geometry on physical objects (Figure 2). This workflow has been commonly tested and employed in both large-scale construction projects using building information modeling (BIM) and high-precision fabrication projects. One such research project investigated the accuracy of using AR with precision marker registration to instruct contractors on the installation and inspection of outfitting parts of large-scale, offshore ship building without the use of paper drawings (Choi and Park 2021). The research demonstrated a method in which fiducial markers were placed in measurable locations relative to existing physical objects, the markers then tracked through a fish-eye camera using simultaneous localizing and mapping (SLAM) technology to reduce pose drift despite the large scale of the BIM model (Choi and Park 2021). Also using SLAM technology, the authors of this paper have previously employed a multiple non-rotational, QR code workflow for accurate post-processing of glulam beams (Kyaw, Xu, et al. 2023). Still, others have tested the digital-to-physical accuracy of object overlay using only a global positioning system (GPS) and the internal measuring unit (IMU) on a mobile device (Ashour and Yan 2020). Though the method did employ several QR codes, the drift error was on average two meters between tests (Ashour and Yan 2020). This issue has also been observed by the authors in previous research when using the FMAR workflow with SLAM technology (Kyaw, Xu, et al. 2023).

The last workflow utilizes gesture recognition for interactive MR instruction. The GBMR workflow method records the user's 'pinching' motion, and saves it as a point in space (Figure 2) (Kyaw, Spencer, et al. 2023). This method can be employed to place points in digital space relative to physical objects to enable interactive assembly instructions that correspond to the user's actions (Kyaw, Spencer, et al. 2023). This novel interaction enables a seamless way to integrate analog habits of making with MR assembly instructions.

## METHODS

This research employs the three above-mentioned XR workflows to instruct the users throughout each phase of the construction process (Figure 3). The *Unlog Tower* encompasses a multi-material assembly of logs, threaded rods, standard hardware, custom steel slip washers, and extruded/rolled steel profiles. The project uses a 6-axis robotic arm on an external track with a 5-HP bandsaw end effector to kerf 6 logs into 12 operable leaf-spring half-logs, which are stretched along threaded rods to form individual panels. The stretched half-log panels are then assembled into three prefab panels connected by six triangular steel tube frames to resist lateral buckling. Each prefab panel is composed of four tiers (Figure 1). Finally, the connected panels were lifted to the existing foundation pad. Each of the three construction phases: (A) parts, (B) prefab modules, and (C) onsite assembly, uses several of the XR workflows that are further elaborated upon in the subsequent sections for this multi-material assembly.

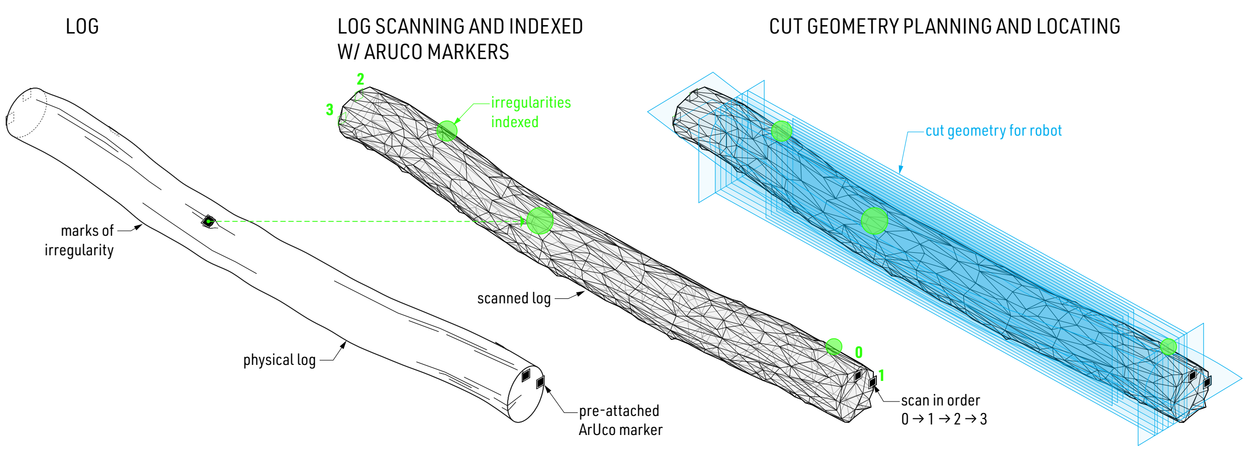
### Materials to Parts

The first phase, materials to parts, includes (A1) log indexing and mounting for robotic fabrication, (A2) robotic log kerfing, (A3) half-log finger jointing, (A4) hex nut placement on threaded rods, and (A5) tube steel coordination, as illustrated in Figure 3. The materials to parts phase involves converting raw materials, custom hardware, and standard hardware into specific parts for the *Unlog Tower*.

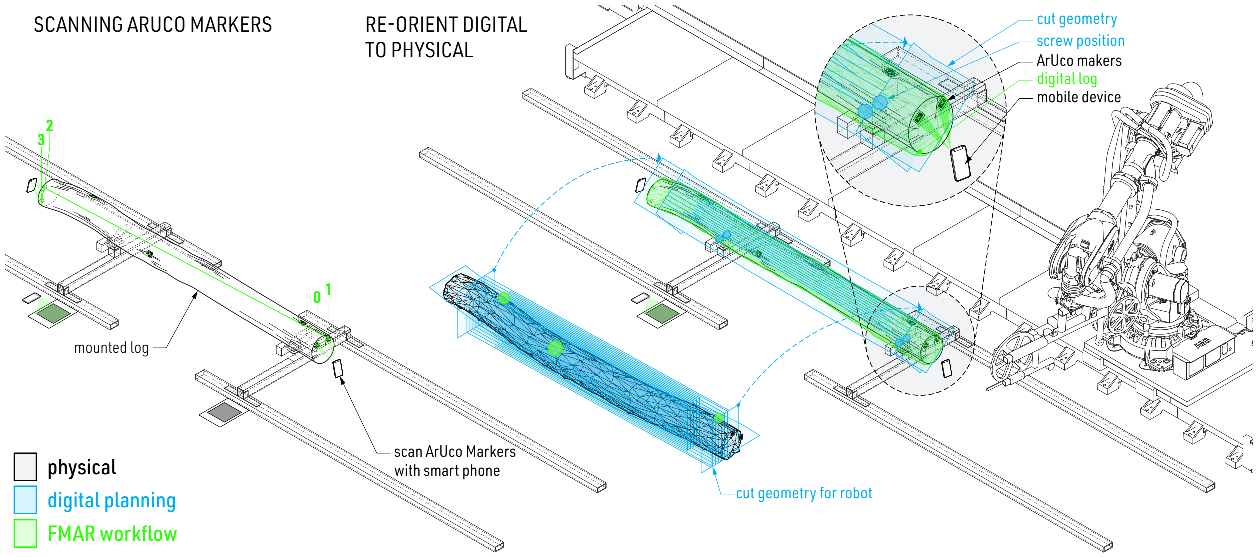
### Log Indexing and Mounting for Robotic Fabrication

Logs are organic material that naturally come with many defects and irregularities. The presence of defects, such as knots and significant checking or splitting, affect the structural integrity of the material. On the other hand, the curvature of logs can also introduce significant irregularity. To index the curvature and irregularities of log geometries for robotic fabrication, the FMAR method was employed. First, ArUco markers were placed on the log at points of irregularity (knots, splits, et cetera), then two ArUco markers were placed at either end of the log (Figure 4). By using an HMD, the location of the ArUco markers could be registered as either points or planes within the digital environment. After the ArUco markers were placed, the log was scanned, creating a digital mesh of the physical object. Once the digital mesh was saved, the cut geometries were planned based on the irregularities and curvature of the scanned mesh. After the log indexing process was complete, the log was mounted in the robot cell.

For the robotic fabrication procedure, the physical location and orientation of the mounted log in the robot cell are required (Figure 5). The first robotic procedure involves cutting the log into halves. A reference plane of the




4 Log Indexing and Planning.

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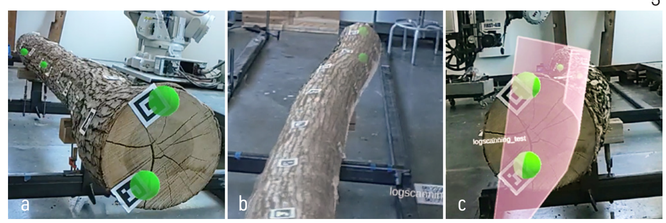


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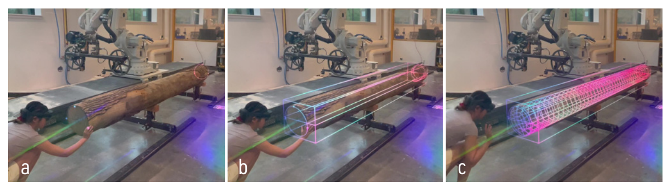


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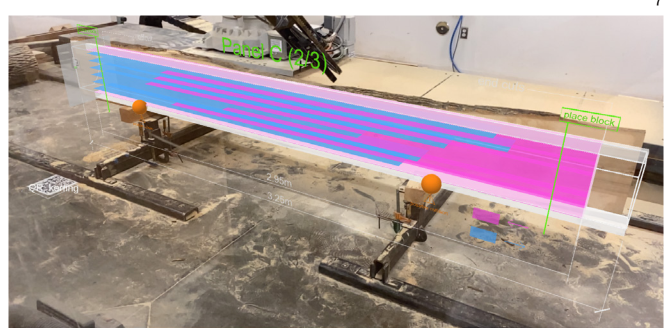


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mounted log in the robot cell is constructed by registering the coordinates of the four physical ArUco markers placed at the log's ends using an HMD (Figure 6a). This coordinating plane is used to reorient the scanned log mesh and the associated cut geometry to the actual position of the physical log in the robot cell (Figure 6b). The digital log, along with the associated cut geometry, is then displayed back to the user as feedback in MR (Figure 6c). Based on this visual feedback, the fabricator can re-orient the log on the robot mounts, if necessary, or adjust the cut geometry.

Another procedure using the GBMR workflow was developed for straight log mounting without ArUco markers. By using the "pinch" gesture, the user can register three points at each end of the mounted log to generate two circles that represent the log ends (Figure 7). These two circles are lofted to create a digital log mesh to orient and locate the physical mounted log in the robot room. This method is more efficient, as it only takes one step to generate and locate the digital geometry relative to the physical log in the robot cell, thus, reducing the steps, such as 3D scanning and additional re-orientation adjustment.

### Robotic Log Kerfing

For the coordination of the second robotic procedure, the FMAR method was utilized to situate the robotic kerfing cut geometry. The users can place an ArUco marker at the desired location they want to situate the cut geometry (Figure 8). The cut geometry and fabrication notation are oriented by scanning the ArUco marker via one's mobile device or HMD. In the AR 3DUI, the digital geometry is displayed in two different cut directions, (1) in cyan, the bandsaw will enter the half-log from the left, and (2) in magenta, the bandsaw will enter the log from the right. Additionally, a digital twin of the robot cell is modeled to

5 Digital log planning and re-orientation in robot cell using ArUco markers.

6 Orientation of digital geometry to match physical: (a) ArUco markers are used to determine the physical log orientation; (b) Overlay of digital geometry; (c) Pink surface illustrates first cut for robot.

7 GBMR generates the location of a cylinder according to the diameter(s) of the log which digitalizes the location of the log for robotic fabrication.

8 Robot Cut Geometry: in cyan: bandsaw end effector cuts left to right; in magenta: bandsaw end effector cuts right to left; in orange: potential collisions; and in green: added instruction through notation.

provide collision feedback to the user. In AR 3DUI, the probable locations of the mounting screws are indicated in orange notation. This provides valuable guidance to the fabricator in assessing potential intersections between the cut geometry and the screws. Lastly, the green notation provides the location in which to place a stop block, which helps the bandsaw blade from being pinched by the wood as it backs out of the log.

### Half-Log Finger Jointing

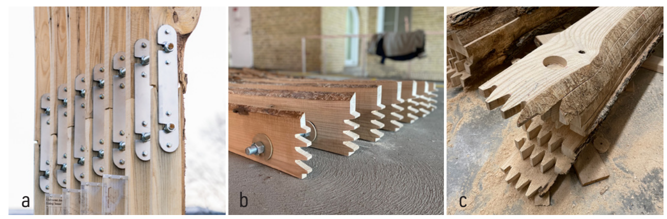
In order to create panel components that can be assembled into prefab modules (Figure 9a), finger joint connections are fabricated at either end of each half-log (Figure 9b). The location of the finger joint is often staggered between layers of boards within the half-logs (Figure 9c). The GBMR method was utilized to display the location of the finger joint template corresponding to the board layer of the user's recorded gesture. By using gestural recognition, the user can pinch their index finger to their thumb to register a digital point at the corner of the board in the MR environment. The recorded "z" value of this digital point is used as the parameter to locate the template per each board layer (Figure 10). The template illustrates the finger joint outline and the location of the hole for the threaded rod to pass through. Once the template was correctly placed, it was marked then the finger joints were cut with a handheld oscillating saw.

### Hex-Nut Placement on Threaded Rods

As mentioned previously, each half-log part was stretched along two threaded rods (Figures 9a and 9b). The threaded rods have pre-located hex nuts to determine the kerf spacing; therefore, the location of the hex nuts required a high degree of accuracy to ensure that the kerfed logs would spread correctly. A jig was designed to secure the hex nut holder in place using the MQAR method. Each hex nut holder was placed as instructed by the digital notation and screwed into the mounting board (Figure 11a). Then, the threaded rod was screwed through the hex nuts using a drill. The notation provides the user with information about each threaded rod (green), a notation about the hex nut locations (blue), and an overlay of the digital threaded rod and hex nuts (purple) for visual quality control (Figure 11b).

### Tube Steel Frame Coordination

To brace each of the prefab wall panels from lateral buckling, several tube steel frames were designed. Three unique frames were designed to be placed in between the top three tiers of the installation. Each frame was comprised of three different tube steel lengths with three different cuts on the end of the tube steel, resulting in nine unique types and lengths of tube steel. Using the GBMR method, the tube steel length was used as a parameter to distinguish between each member. The user can "pinch" at the ends of a tube steel component; the recorded distance was matched to the nearest length value of the steel tubes to correctly identify each member through visual feedback (Figure 12). The feedback displayed a notation for the tube steel type as well as a 1:1 AR model of the member within the tube steel frame and a 1:10 coordination model of the frame within the whole tower. These virtual coordination models were used to instruct the welding of each tube steel frame. Here, the GBMR method is a more streamlined method of interaction that doesn't require the arduous placement of ArUco markers.



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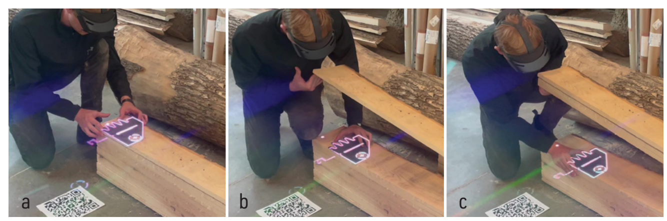

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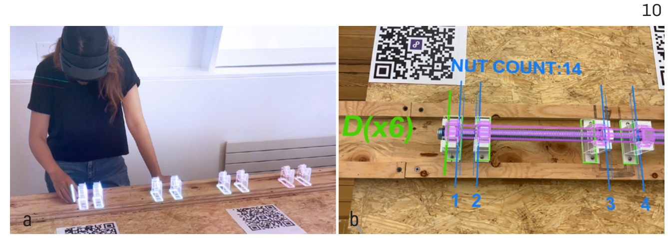

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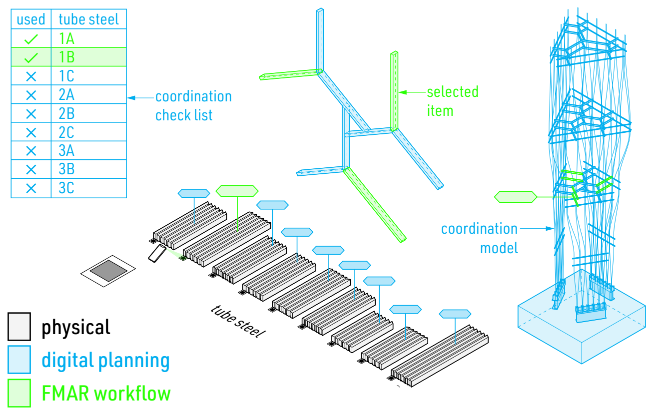
9 Finger joints and threaded rod holes: (a) two connected kerfed panels; (b) kerfed log spread out along threaded rod with temporary plywood slip washers; (c) finger joints and threaded rod holes staggered through robotically kerfed half-log.

10 Gesture Recognition is used to identify physical components and instruct the user on where to place the finger joint template per board layer.

11 Pre-locating hex nuts on threaded rod: (a) 3D printed jig pieces placed using AR 3DUI; (b) notation on threaded rod.

12 GBMR is used to catalog and distinguish between tube steel lengths.



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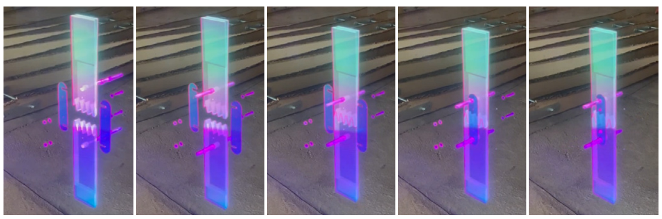
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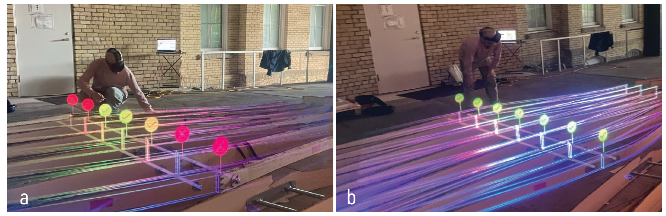

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13 Notation and coordination of steel tube placement for welding.

14 Assembly sequence of finger joint connection between kerfed timber components with interactive slider.

15 Assembly of components into prefab elements with detail notation.

16 Quality Control – overlay of AR on physical construction.

The FMAR method was also tested using ArUco markers to identify and distinguish between the 9-tube steel lengths which were pre-grouped. Each unique set of tube steel geometry was assigned an ArUco marker with an identification number (Figure 13). When the fabricator taps the ArUco marker, a tube steel checklist would highlight the name of the item, along with the two types of coordination models listed above. The GBMR method did not require individual members to be pre-grouped according to length; individual members could be distinguished within an unsorted pile.

### Parts to Pre-fab Modules

The third phase, components to prefab modules, includes (B1) finger joint connection and (B2) panel assembly. This phase involves connecting the panel components into prefabricated modules that can then be assembled onsite.

### Finger Joint Connection

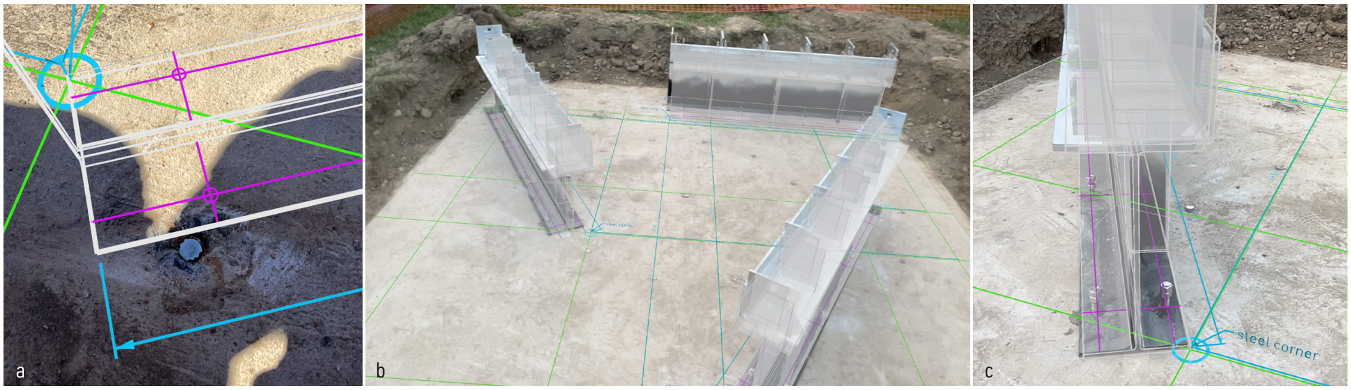
The panel components are connected to each other via a splice connection through the finger joints. The splice connection includes four 0.375-inch bolts that fix the 0.25-inch-thick plasma cut slip washer into place. The custom slip washers are designed to slide onto the threaded rods with pre-located hex nuts. The connection is made rigid by four 0.375-inch bolts. To communicate this complex joint to the assembly team, an AR assembly instruction is animated by a slider within the 3DUI using the FMAR workflow (Figure 14).

### Panel Assembly

A wall module is comprised of four panels joined through 28 splice connections. The *Unlog Tower* consists of three total prefab modules. Each module is comprised of four tiers resulting in 84 total splice connections. To coordinate fabrication between each prefab module, the assembly team used the GBMR workflow to coordinate the joining of each kerfed timber half-log, and ensure the correct spacing of each splice connection (Figure 15). By using gestural tracking, the user can place a digital point at the center of the finger joint after the splice connection is fastened. The distance between this digital point and the center point of the closest digital board is calculated. If the deviation is less than 0.125-inch, a green notation is displayed. If the deviation is more than 0.125-inch, a red notation is displayed, indicating that the splice connection is not connected or properly calibrated. The notations can also be seen by all other users in the fabrication team using a mobile device or an HMD. Therefore, the assembly team can also use this step for quality control to ensure that all splice connections are properly spread and spaced along the threaded rod.

### On-site Assembly

The last phase, onsite assembly, includes (C1) panel bracing and (C2) foundation coordination. In this section, the three prefabricated modules are joined and braced together before connecting them to the foundation.




17 Placement of foundation steel with AR; cyan illustrates notation including dimension and corner of steel for alignment, green illustrates construction lines for corner of steel placement, magenta illustrates location of threaded rod holes to be drilled, and white lines are for physical objects: (a) location of new threaded rod (magenta) adjacent to threaded rod from previous project (photo taken with HoloLens 2); (b and c) placement of foundation steel with AR overlay (photos taken with iPad Pro).

### Panel Bracing

The prefabricated panel modules and the steel frames were transferred to the site and assembled horizontally. The three prefabricated panel modules were assembled into a four-tier triangular structure. The bracing frames were attached to the panel lying on the ground, then the other two prefab panels were attached to the bracing frames. Using the FMAR workflow, the notations display the associated detail drawing, as well as any misalignment, between digital geometry and the physical object(s) (Figure 16).

### Foundation Coordination

Lastly, the *Unlog Tower* is sited on an existing foundation from a previous installation (Chong 2015). In the drawings provided by the previous engineer, the reinforced concrete pad measures 9’9” x 9’9” x 2’10” thick, and sits 12” below grade. The previously used foundation pad contains exhibits several threaded rods. To keep the timber for the *Unlog Tower* from absorbing water from the ground, the base of the tower sits two inches above the ground on top of three W14x30 wide flange steel beams. The W14x30 has welded steel plates on angle steel to fasten the base of the timber to the foundation steel. Each wide flange member was connected to the foundation with eight 0.5-inch-diameter threaded rods. The FMAR workflow was employed to detect potential overlaps between new foundation beam locations and the embedded thread rods. The QR code was placed at one corner of the slab, once two edges of the existing slab aligned with the digital geometry. AR was used to instruct the placement of the foundation steel. Here, the digital model was adjusted so that none of the new holes for the threaded rods would overlap with the embedded rods from the previous installation (Figure 17a). Once the digital model was revised to an acceptable configuration, the foundation steel was then placed into location (Figure 17b), and then checked with measuring tapes for inaccuracies that might occur due to pose drift (Figure 17c). The resulting misalignment was no greater than 0.125 inches.

## RESULTS

After the foundation steel was installed, the 36-foot-tall *Unlog Tower* was lifted into place with a boom forklift. The tower stretches, both literally as an assembly and figuratively as a locally available natural resource devastated by the EAB epidemic (Figure 18). Through structural simulation and XR workflows, the *Unlog Tower* questions our habits in the Anthropocene, by stretching a material resource that would otherwise be discarded or burned for firewood. This paper studies the application of three different XR workflows, according to various degrees of interactivity, accuracy, and set-up difficulty during each of the nine multi-material construction steps.

In the log indexing and planning step (A1 in Figure 3), the FMAR workflow was used to place ArUco markers at key locations along the log, then the log was scanned. The resulting digital mesh was used to plan the cut geometry for the log. The advantage of scanning the log with the ArUco markers already on the log is that the user could re-orient the log in physical space as many times as necessary and then just re-scan the ArUco markers to orient the digital geometry to the physical, which was used in the log-mounting step. A second test also showed the validity of using the GBMR workflow to locate a straight physical log quickly and accurately. Further investigations will improve upon this method to account for log curvature.

In the half-log cutting step (A2 in Figure 3), the FMAR workflow was employed to align the ArUco marker on the half-log to the physical space in the robot cell, which

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18 View stretched half-logs as Tier 2 and Tier 3 connection

19 Perspective of steel frames coordinated through the GBMR workflow.

was important to visualize the location of the mounting screws relative to the cut geometry. Because of the drift issue, and the difficulty of correctly orienting the ArUco marker, this step would have benefited from a more refined GBMR workflow. However, the visibility of the cut geometry and the added notation were helpful in ensuring that the half-log was large enough for the board width for each kerfed layer. Future investigations will test the MQAR workflow for improved accuracy, assuming it is required for the fabrication.

The half-log finger jointing step (A3 in Figure 3) employed the GBMR workflow. Though this step could have also been completed with the FMAR workflow, the GBMR workflow was faster to work with. This was due to the fact that the location of each template was based upon the distance of the gesture to ground as opposed to the indexing of many ArUco markers to many locations. The use of gestural recognition allows the user to display digital geometry through gestures, as opposed to ArUco markers.

The hex nut placement (A4 in Figure 3) used the MQAR workflow to accurately place the hex nut holder so that hex nuts would be correctly spaced along the threaded rod. This workflow also used graphic notation to call out which threaded rod was being used, as well as how many nuts would be used, along with location of the hex nut holders. In continued research, the GBMR workflow has proven to be useful in this step (Kyaw, Spencer, et al. 2023).

The tube steel coordination (A5 in Figure 3) was conducted using the GBMR workflow with the length of each tube as the variable to differentiate each unique part (Figure 19). Although it was faster to set up nine ArUco markers and use the FMAR workflow, an advantage of the GBMR workflow is that it allows the user to index individual members from an unsorted pile. An improvement would be to integrate a checklist to track progress similar to the one developed for FMAR workflow.

The prefab module instruction and assembly (B in Figure 3) had two parts: first, the interactive detail animation, and second, the quality control check. The FMAR workflow was particularly useful to instruct the assembly of a complex joint. The GBMR workflow was employed to precisely adjust and locate the kerfed boards at each finger joint, and to ensure overall geometric accuracy.

The on-site tower assembly (C1 in Figure 3) step used the FMAR workflow to coordinate the on-site assembly of the prefab panels as they were fixed into location with the steel tube frames. Because the tower was assembled horizontally on a sloped ground surface, it was difficult to align the digital geometry to the physical using the FMAR workflow. Future investigations could use GBMR workflow to register precise points on the physical structure as a means to better align and orient the digital geometry.

Finally, the FMAR workflow was quite valuable for the on-site foundation steel coordination (C2 in Figure 3). As there are no as-built drawings of the precise location of the existing embedded threaded rod locations, it would have been a time-consuming process to identify new drill locations for the foundation steel without an XR workflow. A future iteration of this step might also investigate the use of the GBMR workflow, as long as the accuracy is comparable to what was measured in the field (0.125-inch tolerance).

## CONCLUSION

Through the construction of the *Unlog Tower*, the integration of the three XR workflows provided an in-depth study and evaluation of the various AR/MR workflows for fabrication instruction and coordination. In the installation's three construction phases, there were pros and cons for each specific workflow that involved varying complexity of 3DUI development, degree of interactivity, and object alignment in relation to scale and unique material types, such as salvaged timber. The FMAR workflow allows both users and designers to develop custom 3DUIs for digital interaction that can inform and instruct the fabrication process. However, this workflow does require a tedious precise orientation of the base QR code to accurately overlay digital geometry with physical objects. The MQAR workflow allows users to be less precise with the rotation of the QR code(s) placed, yet the corner location of the QR code is imperative for an accurate overlay between digital geometry and physical objects. The advantage of this workflow is its capacity for a highly precise AR superimposition; however, it has yet to be employed for more interactive instruction, such as custom menus, assembly animations, and object indexing. For the GBMR workflow, whose precision is limited to the accuracy of the hand-based gesture, it is more compatible with human scale procedures and objects. The other advantage is a highly interactive and direct association with physical objects. However, the GBMR workflow is highly specific and customized per task, thus, it is more time-consuming to develop the 3DUI for each task. Like the *Unlog Tower*, building construction is a multi-material assembly; it is imperative to integrate multiple XR workflows for various degrees of interactivity, accuracy, and scale for the instruction between digital geometries and non-standard and standard/manufactured materials.

## ACKNOWLEDGEMENTS

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## IMAGE CREDITS

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