ABSTRACT

Over the past two decades, advances in computation, digital fabrication, and robotics have opened up new avenues for the design and production of complex forms, emergent processes, as well as new levels of efficiency. Many of these methods, however, tend to focus on a specific tool, such as the industrial robotic arm. Due to their initial costs and space/power/safety requirements, difficulties associated in creating automated workflows and custom tooling, as well as the need for reliable/repeatable procedures, these tools are often out of reach for the average designer or design institution. Additionally, these tools are typically treated as methods of production rather than collaborators, leaving outcomes that can feel void of craft, with the appearance of a typical CNC-machined object.

Rather than focusing on a specific production tool for manufacturing, this paper investigates a novel method for holographic handcraft-based production. This holographic augmentation—of simple and easily attainable analog tool sets—allows for the creation of extremely complex forms with high levels of precision in extremely short time frames. Through the lens of the recently completed steam-bent timber installation [BENT] produced at the Tyler School of Art, this paper discusses how Microsoft HoloLens in conjunction with the Fologram software plug-in can be integrated into the entirety of design and production processes as a means of producing a new typology of digital craft.
1. INTRODUCTION
There exists an emerging research trajectory within digital design focused on automation and robotics (Gramazio & Kohler 2014; Burry et al. 2016; Daas et al. 2018; Testa 2017). While we acknowledge the exciting and potentially transformational developments in robotic production, machine vision, and learning algorithms that may allow our robotic co-workers to complete increasingly complex tasks, the future in which industrial robots replace all acts of making can be seen as dystopian and naive. Approaches are needed that can improve precision while reducing the time, cost, and risk of constructing buildings (or parts of buildings) by hand and by eye, while also creating opportunities for collaboration, learning, adaptability, and experimentation. This paper documents a novel pathway towards the evolution of traditional craft through the blurring of analog and digital approaches for making.

2. RELATED WORK
Steam bending timber is notoriously difficult due to the need to anticipate spring back caused by variability in timber grain and moisture content. This is especially true in projects working with inconsistent material dimensions, imprecise working conditions, and extremely short time frames.

Traditionally, sturdy, precise, and expensive molds for both forming and drying processes must be fabricated for each bent part leading to exponential increases in project cost and complexity. As a result, artifacts constructed from steam-bent timber are typically standardized and mass produced (perhaps most famously in the case of the Thonet bentwood chairs) with significant waste accumulating from material failure, formwork, and offcuts (Schulte 2011).

Augmented reality (AR) environments lend themselves well to fabrication tasks that require the precise setout of objects or points within 3D space because digital models describing part locations can be accurately positioned within, and overlaid upon, the fabrication environment (Shin & Dunston 2008). Augmented reality environments have been demonstrated to assist with assembly of linear timber elements (Abe et al. 2017), irregular foam blocks (Sun et al. 2018), bricks (Fazel & Azadi 2018) and bent steel (Jahn et al. 2018).

3. METHODOLOGY
We present a novel approach to forming timber boards using adaptable formwork. Combined with uniquely bent steel connections and slide-in-place parallel timber connections that are visualized through an AR production environment, this system assists fabricators with the customization and placement of formwork and with the registration of bent parts to digital design models. By observing variation between built and digital parts, fabricators could intuitively adapt workflows to accommodate errors introduced from uncontrolled material spring-back or any other inaccuracies that may arise during the production process.

3.1 Design
The installation [BENT] is a 6.5’ x 12.5’ x 8’ prototype that acts as a physical intervention within a gallery. It builds upon research and fabrication processes developed for an award-winning large-scale pavilion that is currently in production. The prototype was designed over a period of several weeks and produced during a two-day collaborative build workshop with students, faculty, and Fologram staff. Time constraints during the workshop contributed to the formal and spatial considerations of the structure. Commonplace practice generally derives formal variation from a unique collection of parts that needs to be individually pre-fabricated. Instead, [BENT] utilizes an adaptable collection of formwork to achieve complex variation using dimensionally standard material. The language of the installation is a product of this process, with twisting and curving timber boards performing as form, structure, surface, and silhouette.

3.2 Computation
A computational model was developed in Rhinoceros 3D and Grasshopper that allowed the design team to manipulate the form of the installation through a series of curve control points that describe the center line of each timber board. Once center lines had been modeled, all other elements of the design were determined parametrically. The surface model of each board was derived by aligning cross sections to the curvature tangents at sample points along the centerline (Figure 2). This surface was then used to derive the position and orientation of formwork required for fabricating each board.

During the design process, any geometry within the parametric model could be live-streamed to AR devices (mobile phones and HoloLens headsets) using Fologram, a third-party plug-in for Grasshopper. This enabled the design team to make changes to the model and immediately
experience those changes at scale and within the context of a mixed reality environment. Designers could also build interactivity into the model by associating gesture events within the AR environment with input parameters to the model (Jahn et al. 2018).

To reduce the fabrication time and complexity of the project, all geometry in the model was rationalized to a set of pre-determined lengths. Formwork was rounded to increments of 5-degrees from the vertical to simplify requirements for measuring, cutting, and selecting required supports. Boards in the design model were segmented into 4, 5, 6, 7- and 8-foot lengths using an algorithm that optimized segments for planarity (Figure 3). Brackets in the design model were rounded up to the nearest 20mm by adding any additional length to the folded faces attached to the boards (Figure 4). This reduced the number of measurements and cuts required while still allowing for precise and variable spans between boards.

Issues with the design identified during the fabrication process could be addressed by making minor changes or additions to the parametric model that would immediately be reflected within the AR environment. These included adding labels to steel brackets, re-orienting holographic models to more accurately match physical parts, modifying display information pertinent to a specific task, and adjusting the layout of parts to respond to on-site obstacles.

3.3 Production
Fologram allowed the fabrication team to precisely locate the origin of a CAD model at a known position within the workshop using a fiducial marker. For instance, by aligning the holographic model of a steel bracket with the bending axis of a bar bender, the holographic model could be used as a visual guide describing the required angle and orientation of the bends in the bracket. This reduced the fabrication time for each bracket by eliminating the need for measurements, templates, or drawings. The holographic model could also be used as a guide to select and place physical formwork elements by aligning the physical formwork with the hologram by eye (Figure 5). Following a visual guide for correct bend angles or formwork placement required little training or skill, and enabled participants in the workshop to effectively jump between tasks.

The fabrication of the installation involved several parallel processes allowing for the steaming and bending of individual timber strips and their aggregation into braced pairs and triplets. These processes included laying out formwork
for boards, and forming and clamping boards to formwork, bending brackets, attaching brackets to boards, and assembling boards together to form rigid components that could then be removed from formwork to allow the process to be repeated. Interactive holographic applications were developed and used to assist with each process.

The development of each of these holographic applications involved dividing the desired end state of a task into simpler steps by creating sequences of geometry within the parametric model. Users could iterate through the task sequence by interacting with holographic buttons (Figure 6) in the augmented reality environment. This eliminated the need for participants to understand how to manipulate the parametric model itself and dramatically reduced the learning curve required to participate in fabrication tasks. Typically one or two participants would work within a shared augmented reality environment and direct other participants performing more manual tasks that would become difficult if wearing a headset or holding a mobile phone.

### 3.3.1 Platform & Reconfigurable Formwork

A 12’ x 8’ platform was constructed from three 4’ x 8’ sheets of ¾” thick particle board decking, elevated off the ground through a traditional 2” x 4” framing method. The platform was utilized as a robust base where the angled formwork could be attached throughout the steam bending and assembly processes. The platform provided sufficient space to attach formwork for 8 boards at any given time. Prior to the steaming of the timber elements, the formwork for each individual piece was set up.

Utilizing HoloLens, a series of four strips were visualized on half of the platform. Each strip was tagged with a unique part number, along with the location and type of all formwork pieces. A single participant (“lead”) used the holographic model as a guide to arrange all of the formwork necessary for each board on the platform. After securing the formwork to the base with 1½” wood screws, each location was verified through the HoloLens with minor adjustments made to any elements that had shifted during fixing. Once secured, the “lead” marked how the holographic model of each timber board intersected the angled formwork with strips of masking tape, ensuring that each piece fell into its correct location and orientation during the bending process.

### 3.3.2 Steam Bending

Prior to the initiation of production, a timber steaming station was designed and setup. The station consisted of four steamers situated on top of a 4’ x 8’ sheet of particle
individual timber strip, the “lead” reverified the placement of the strip, and adjustments were made as necessary. Industrial fans were then blown across the timber to expedite the drying process, and the next bending process was initiated.

A significant disadvantage to steam-bending was that each element should have remained on the formwork for around 24 hours to dry. Due to the short duration of the production process, it was only possible to keep pieces secured to the formwork for up to two hours. As a result, even with the use of industrial fans for rapid drying, the removal of individual boards from the formwork resulted in significant spring back. Additionally, shallow bend angles did not sufficiently compress timber fibers to remain bent. To address this problem, the 49 boards in the design model were manually arranged into groups of 8 boards that could be assembled together to form 4 rigid pairs (Figure 7).

3.3.3 Brackets

A system of “C” and “Z” shaped brackets were developed as a means of connecting and spacing the individual bent timber members. Each of the 245 brackets connecting the 49 strips together were unique in form and constructed from pre-cut and drilled 1” x ¾” cold rolled steel bar. The bending of the brackets was achieved using a manual industrial bender overlaid with an interactive holographic model displaying bend locations, orientations, and angles on the HoloLens.

An interactive holographic model was developed that allowed fabricators to select and display each of the steel brackets in the structure, as well as their part name, length and attachment location along a given timber board. The holographic model of the steel bracket (and the associated construction information) was aligned precisely to the bending axis of the tool using a fiducial marker. Users could select the bracket and bend angle to be fabricated by interacting with a collection of holographic buttons displayed above the bender using hand gestures. During production, the “lead” would use the holographic interface to select a desired bracket and instruct an assistant in the length of stock material required, mark the direction of the bracket, and indicate the side that would be bent first.

For each bend in the bracket, the “lead” would first locate the position and orientation of the bend by aligning the holographic representation of the part with the physical stock material. The stock would then be locked in place and the assistant would bend the metal until it aligned with the holographic representation of the completed bend, at which point they were instructed to stop. Material spring back...
was minimal and could be intuitively accounted for after observing two or three bends. After the first bend had been completed, a button within the holographic user interface was used to flip to digital model of the part so that the opposite side was aligned with the bending axis of the tool, and the bending process was repeated.

Brackets were bent in groupings based on individual timber boards. As boards were steam-bent and fixed to the temporary formwork, brackets for each board were installed by two people, one using the HoloLens, the other using a driver and socket wrench. Just as with the previous processes, the set of four boards was made visible through the headset. The “lead” selected the desired four boards by toggling their visibility in Rhino and aligning them to the board in physical space using a fiducial marker, while the assistant drilled the corresponding holes through the timber and bolted them in place.

3.3.4 Board Pairs
A fabrication sequence was developed that allowed boards to be assembled into rigid pairs while still attached to the formwork. While held in place on the formwork, brackets could accurately be located and fixed along each length of timber using a holographic guide. The matching board was then removed from the formwork and allowed to spring into an incorrect shape. This board was then elastically re-bent by fixing it to the brackets on the board attached to the formwork (Figure 8). The two boards together could then be removed from the formwork with significantly reduced springback due to the bracing effect of the brackets.

3.3.5 Assembly
The assembly of pairs into three large chunks was the most challenging and time-consuming aspect of the construction process. As they were assembled off the platform in an undefined space, there was no declared origin or location for the physical and holographic models. To initiate the process, a single pair from each of the chunks was oriented on the floor. The corresponding digital model was isolated in Rhino and streamed to the HoloLens. The digital orientation was then manipulated in the headset through hand gestures to align the digital and physical objects as closely as possible. Upon achieving alignment, the part was fixed to an immobile object on the floor.

The assembly of the inner “loop” and adjacent two “wings” of the structure was completed in parallel (Figure 9). The “loop” was assembled by joining matching pairs end to end (Figure 10). Once the loop had been closed it formed a rigid base from which to attach additional pairs of timber boards. Where necessary these boards could be elastically bent and mechanically fastened to account for any springback resulting from insufficient drying time or shallow bend angles. The “wings” were assembled by joining matching pairs face to face to form rigid surfaces of 6 to 8 boards (Figure 11). These surfaces served as bases to attach subsequent pairs of boards end to end with lap joints. This method did not allow boards to be elastically bent back to their correct shape and introduced significant deviation in the built structure from the holographic mode.
9 “Loop” in center surrounded by two “wings”

10 Assembly order for closing the “loop”

11 Assembly order for left “strand” section

12 Springback in boards removed from formwork do not accurately match their board pairs without additional over-bending; (Left) Demonstrates deviation in demounted board compared to when constrained by formwork; (Right) Over-bent formwork compensating for springback
The final structure—measuring roughly 6.5’ x 12’ x 8’, and consisting of 49 uniquely formed timber boards, and 245 bent steel brackets—was successfully assembled by a rolling team of 6-12 participants over the course of two long days. The use of holographic models to guide participants in setting out formwork, locating timber boards on the formwork during bending, fabricating bracket geometries, and locating brackets on timber boards allowed each of these tasks to be carried out to a high degree of precision without requiring the time or expertise that would have been necessary if working from drawings, templates or with robotic or CNC processes. The success of these approaches can be attributed to the ability to work from predictable physical materials (timber attached to formwork, or steel clamped within a bender) that closely align to digital models, thereby allowing the digital model to serve as a useful guide to achieve a desired physical outcome or end state. However, holographic models were poorly suited to assisting with assembly tasks when physical objects no longer matched their digital counterparts, and this introduced significant uncertainty in the fabrication process as participants were required to perform assembly tasks with insufficient or inaccurate fabrication information.

After allowing for only two hours of drying time, timber boards would not hold their shape after being removed from the formwork and would spring back towards their pre-bent shape. Springback was most evident in boards with very slight bends as lignins in the timber were not sufficiently compressed to hold their shape. As formwork was evenly distributed along the length of the board, and the boards tended to be most compressed at their center, we observed the greatest springback at the end of the board regardless of bend angles. These issues could be alleviated by allowing for longer dry times, developing computational models that introduce slight overbend in areas of shallow curvature, and creating continuous extensions of board ends that could be trimmed back to the correct length (Figure 12).

Boards that were removed from the formwork were often attached to their pairs without correcting for the springback due to the difficulty of elastically bending the timber to a holographic guide model. Occasionally, pairs of boards did not join along their entire length due to staggering lap joints in the structure (Figure 13), and this limited their usefulness as bracing to prevent springback. These conditions also exaggerated the straight condition of the board ends, as pairs rarely aligned at their ends, and as a result, brackets could not be used to pull the timber into the correct curvature.

Determining the correct orientation of similar and symmetrical ‘Z’ and ‘C’ brackets by eye from a holographic model proved to be a challenging task and brackets were often fixed in incorrect positions and orientations. Since these same brackets were often used to determine how to connect neighboring boards without referring to a holographic model, a single incorrect bracket could misalign the remainder of the structure (Figure 15). These challenges with orienting similar part geometries by eye could be addressed by design (using asymmetrical bracket geometries or implementing well defined labeling), or by introducing computer vision tools to check marker placement (such as attaching fiducial markers to brackets and comparing the detected position to the correct position). Although making corrections to the structure once these errors were identified was time consuming, comparing the as built structure to a holographic model to identify errors was easier than attempting to make the same comparisons on a laptop screen.

5. CONCLUSION

By providing designers and fabricators with a constant reference to a desired end condition—without constraining the ways and means by which they reach or dismiss that end condition—we aim to describe an approach to hand craft that enables opportunities for greater intervention, participation, and experimentation than would be afforded with entirely automated or analogue processes. This approach to holographic handcraft enables high degrees of precision when physical and digital objects are aligned but does not facilitate such precision when material begins to behave unexpectedly, alignment is lost, and models cannot be validated by eye.

While we can identify several clear improvements to our process that would result in a simpler and more accurate assembly process, our interest is in developing techniques that facilitate the rapid and collaborative construction of complex and non-uniform structures from hand tools and traditional craft techniques. To this extent, the degree
to which these approaches are resilient and tolerant of unexpected errors while maintaining a desirable formal language or faithfulness to design intent is more valuable than precise registration to preconceived digital models.

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REFERENCES


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