InterLattice

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INTRODUCTION

This is a process-based design research project that reimagines traditional manual tube bending techniques with the precision and efficiency of digital formative fabrication. Leveraging the positional accuracy of industrial robots using custom tools to bend and interweave metal tubes in geometrically complex and spatially precise loops, the research follows a lineage of projects[1&2] exploring the application of robotic bending of linear elements, primarily in solid-core rod form[3]. The material limitation of rod diameters conducive to bending constrains the span and length of the members, indirectly limiting the overall size of the resultant product. Solid profiles also prove far from ideal in terms of material efficiency when considering structural cross-sections for scaling up to larger inhabitable structures.

To overcome this material limitation while building on similar methodology, the project's focus shifts towards the use of hollow tubes to engage their potential in larger scale constructs. Previous projects highlight the use of traditional bent pipe methods, notably the large-scale installation work of Oyler Wu[4], Warren Techentin Architecture[5], and FUTUREFORMS[6]; while the projects achieve the scale and capacity to be inhabitable, they are typically realized through use of elaborate jigs, large fabrication spaces, and intense manual labor.

The project attempts to integrate the material efficiency and scalar advantages of tubes with the precision and repeatability of industrial robot-based formative fabrication. Using a Kuka KR 125/3 6-axis industrial robot and a DKP-400 Kuka Positioner as a turntable, a custom 3d-printed gripper with pneumatic control enables gripping, rotation, and feeding into the external axis turntable with a center die of 100mm diameter and an outer roller forming pin. The setup produces clockwise bends of variable angles within a horizontal bending plane parallel to the floor. For out-of-plane bends the robot feeds the tube forward to the correct location, then grips and rotates the tube axially to the correct orientation for the turntable to execute the next bend.

The computational workflow uses a Grasshopper[7] parametric definition to reference simple polyline geometry and fillets the corners with a fixed diameter due to the static bending die diameter. The filleted curve geometry is analyzed and broken down into straight sections which correspond to feed distance, and curved sections which correspond to bend angles. The geometry is parsed and sequenced into Kuka KRL[8] code from Kuka|PRC for robot movement simulation, collision detection, as well as external axis instructions for the turntable and gripper. A series of twelve simple planar bends ranging from 5-180 degrees on 1-meter long tube segments were carried out in order to calibrate the digital model to the physical results. A machine-learning-based linear regression model[9] allowed for automated springback compensation to be incorporated within the Kuka KRL code output, ensuring the bending results achieve the desired angle with acceptable tolerance for more complex bends in the same tube segment.

SERIAL INVESTIGATION

A series of experiments were conducted to explore possibilities and configurations for weaving, bundling, and joining. The first prototype tests accuracy of the workflow as a continuous single curve with pentagonal rotational symmetry; each segment consists of three unique bends that form a multiplanar element. Due to the continuity of the overall geometry the start and end points of each segment need to seamlessly transition and each segment needs to be precisely formed in order to achieve a continuous whole. To emphasize the precision of the workflow, the prototype eschews parallel joints commonly seen in previous rod/pipe-based bending projects.

InterLattice is a 2.3 meter tall construct consisting of two interwoven continuous loops designed to interlock and intertwine to offer opportunities for joinery and structural triangulation. Building upon principles developed in the previous prototype, the two color-coded loops are folded upon themselves in pentagonal symmetry, while demonstrating the precision of this fabrication method and its ability to create complex interwoven structures. The accuracy of the irregular multi-planar bends required to realize this piece would be impossible to achieve manually with a similar level of speed and consistency. Automated segmentation of long continuous loops are achieved with the Galapagos[10]

Figure 1. InterLattice on exhibition at a local heritage village. Image credit Authors.

Figure 2. Detail looking up of InterLattice showing mettalic finish. Image credit Authors .

evolutionary solver, optimizing for constraints such as material length, build space, and average number of bends per segment.

While recent advances in augmented reality make manual fabrication of complex parts feasible (demonstrated in projects enabled by mixed reality platform Fologram such as the Steampunk Pavilion), the inherent advantage of the approach lies more in the ability to adjust and react to deviations across the entire structure, and not necessarily the accuracy of the single element. During the construction of the Woven Steel Pavilion, the team "observed that using a 3D holographic guide to accurately reproduce bend angles required significant skill, as even small errors in bend angles accumulate across the part and result in deviations from the digital model."[11]

LOOKING TO THE NEAR FUTURE

As a prototype in a series of explorations meant to gradually scale up in size and complexity, the project uncovers possibilities for bundled and interwoven tubular structures that represent a paradigm shift in how tubular structures might be designed and fabricated in the future with minimal falsework and scaffolding that would not be practical in settings that require constant setup and teardown. The precision at which individual elements

can be fabricated lends to a more "puzzle-like" assembly process and dimensional accuracy is reinforced as the assembly sequence progresses. However, even in this scenario mixed reality technology can be useful to expedite the process and verify positioning and alignments, and is to be incorporated into future larger, more complex assemblies. Finally, joinery is a primary area of development, specifically to avoid welding and its accompanying safety and labor restrictions. End-to-end butt joints have already been achieved with smaller diameter fittings, but crossing joints with arbitrary angles is a more complex issue that would require a mechanically-fastened joinery system developed to handle complex crossing angles. This involves marking joinery locations, precision pre or post-processing with drilling or cutting, and external clamping mechanisms. The advantage is that these assemblies can then be constructed with minimal welding and training, greatly improving the speed and ease of erection or disassembly.
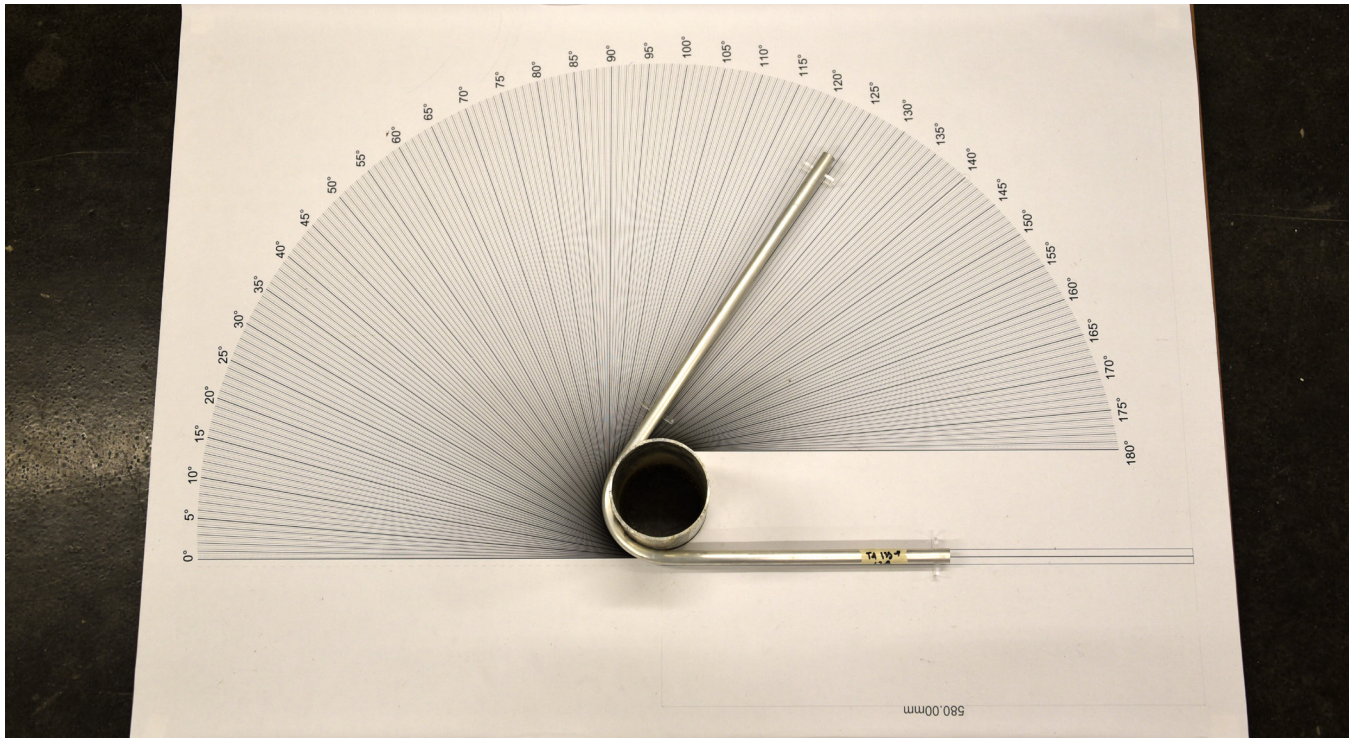
PROJECT

Figure 3. The test pieces were aligned against a degree printout and results were input into a machine learning linear regression model, with a resultant prediction accuracy of less than 0.25 degrees deviation. Image credit Authors.

Figure 4. Twelve test bends ranging from 5-180 input degrees were executed in order to calibrate for material behaviour in terms of the desired bend angle, resultant bend angle, and springback. Image credit Authors.
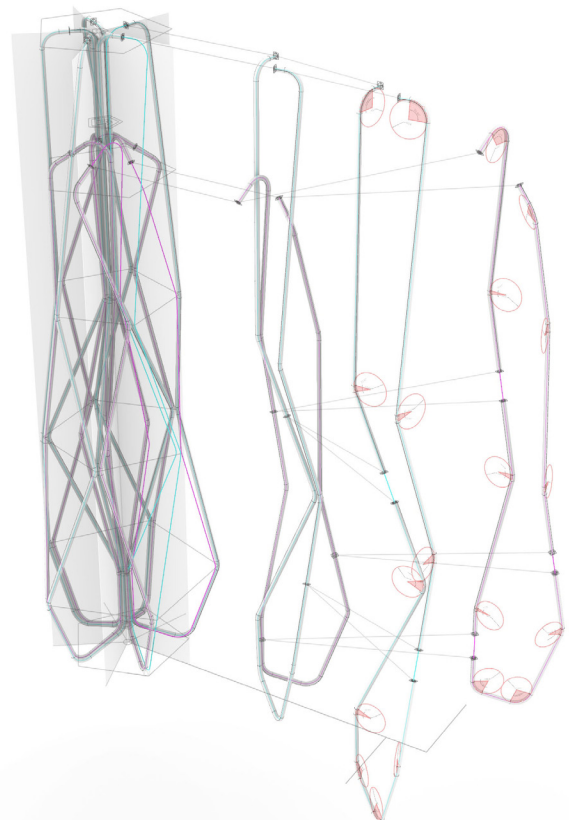
Figure 5. Utilizing pentagonal rotational symmetry while introducing more complex overall geometry and larger scale, Interlattice consists of two interwoven continuous curves, designed to interlock and intertwine to offer opportunities for joinery and structural support. Image credit Authors.
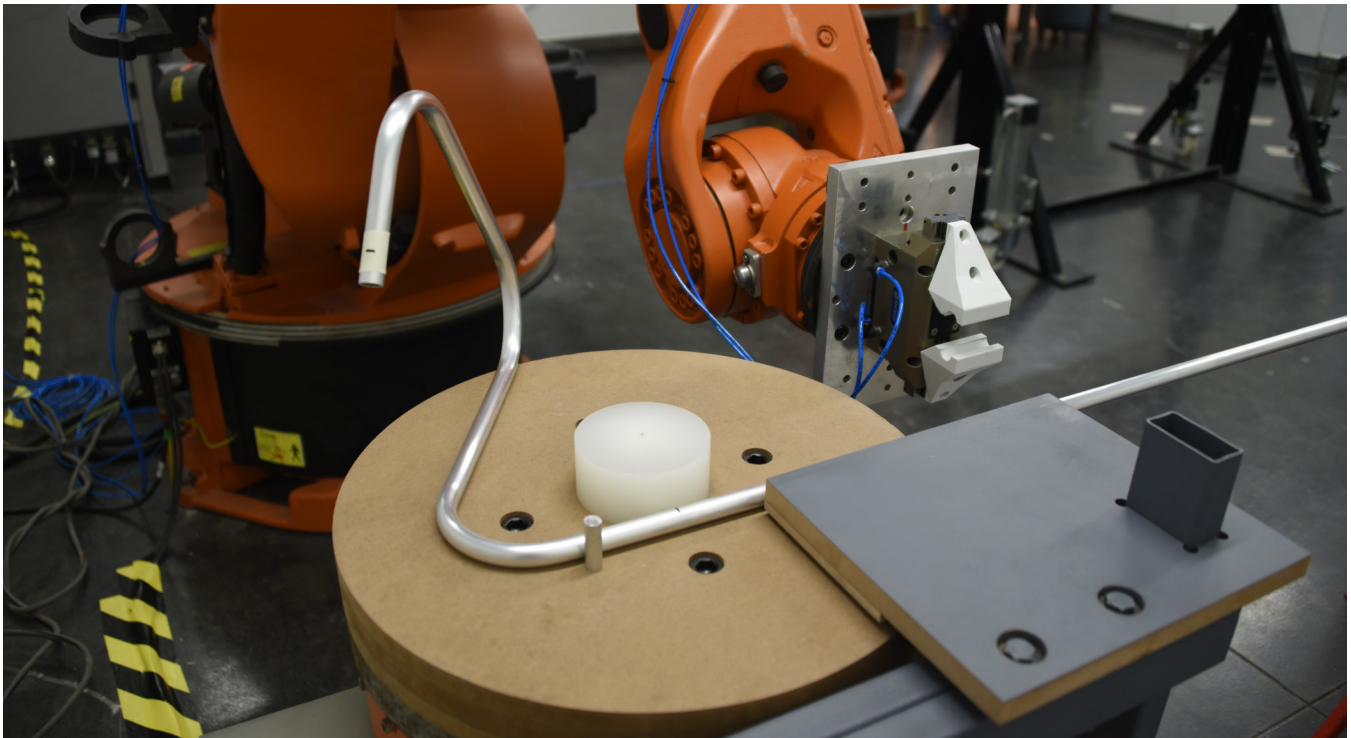
Figure 6. A multiplanar piece to test for additive bending accuracy in 3-dimensional space. Accurate feeding, clockwise bending, and multiplanar elements made possible through coordinated interplay between the 6-axis Kuka robot and the 2-axis Kuka positioner. . Image credit Authors.

Figure 7. The completed initial prototype served to test accuracy of the developed workflow in three-dimensions while doubling as the structural table base. Image credit Authors.

PROJECT

Figure 8. The multiplanar bent tube components that form InterLattice. Image credit Authors.

Figure 9. Test fitting of InterLattice loops shown with raw aluminum finish and temporary connections. Image credit Authors.

Figure 10. Perspective of Neonomads MK V installation proposal for the Seoul Biennale of Architecture and Urbanism representing the continued development of robotic mulitplanar tube bending fabrication. Image credit Authors.

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