Augmented Steelworker

An experimentation of augmented reality (AR) technology in assisting manual steel structure construction

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In the rapidly evolving digital architectural practice of today, the integration of high-tech methods and low-tech techniques is transforming the dynamics of human and machine collaboration, and the interplay between digital and physical processes interact in design and construction. Within this context, this paper introduces an ongoing research, Augmented Steelworker, which investigates the potential of augmented reality (AR) to facilitate the manual construction of steel structures. By combining AR, high-tech portable technology, with low-tech craftsmanship, this study examines the innovative strategies for achieving geometrically complex and adaptable construction solutions. Considering the existing research on AR-assisted fabrication, this research helps to explore the possibility of the above integrations experimentally, focusing on analysing the responsibilities and scope of AR to assist manual construction under current technology constraints, and providing references and suggestions for future development. This attempt at high-tech methods and low-tech techniques integration, demonstrates the transformative potential, and offers a framework for precision, adaptability and sustainable innovation in digital architectural construction practices, using steel structure as a case study.

Keywords: *Augmented Reality (AR), Digital Fabrication, High-tech and Low-tech Integration, AR-assisted Craftsmanship, Steel Structure Construction.*

INTRODUCTION

The increasing impact of digitalisation and digital empowerment on architectural design and fabrication has prompted a reevaluation of the relationship between humans and machines (Knippers et al, 2021, p.123). There is a crucial need to explore how to maximise the advantages of both humans and machines, and develop frameworks that facilitate effective cooperation between the two in the era of digital transformation. With the development of AR, humans are augmented by this visualisation technology to be as capable and knowledgeable as "machines", which breaks the boundaries between the two (Daugherty and Wilson, 2024, p.155).

The integration of AR technologies into physical production in architecture, using various materials and construction techniques, has seen rapid growth over the past five years. However, at the construction site, large precision equipment such as CNC machine tools and industrial robotic arms are difficult to integrate into the complex physical environment. At the same time, these related factories are far away from the construction site (Le et al, 2022, p.106). In comparison, what is easier to achieve is to guide low-tech techniques, such as manual fabrication strategies, through high-tech portable machines, such as AR, to fabricate onsite (Verdelho Trindade et al, 2023). Thus, instead of emphasising using AR as a machine in digital construction, it would be more effective to focus on the combination of this high-tech method with low-tech techniques, and to explore the potential outcomes of this integration.

Head-mounted devices (HMD) and smartphones equipped with AR functions have become more and more popular, which can be taken and used easily to construction sites with their high portability, especially the specialised precision AR equipment – Microsoft HoloLens. This provides the necessary conditions for the development and popularisation of this high-tech method. Consequently, now, it is time to explore the possibility and integration between humans and machines, which will provide valuable application scenarios and unique guidance for future construction practices.

Considering the above, this research investigates the potential of integrating high-tech portable AR machines assisting low-tech manual fabrication, using steel structures as a case study. Processes such as cutting, bending, assembly, welding, etc., are explored without reliance on specific digital fabrication machinery. This research also discusses the intervention functions and procedural steps of AR interventions in digital fabrication scenarios.

RELATED BACKGROUNDS

Steel Structure Fabrication

Steel structures play an irreplaceable role in modern architecture due to their high strength, lightweight, fast construction speed, and environmental protection. It not only meets the functional needs of the building, but also provides more possibilities for architectural design and promotes technological progress and sustainable development in the construction industry (Baddo, 2008). However, as He et al point out, there are also some shortcomings in the construction of steel structures, particularly in processes such as bending and welding. Due to limitations in material properties, steel will experience a certain amount of elastic rebound after bending, causing the final shape to be inconsistent with the design and requiring repeated adjustments (Yang et al, 2012). Although high-precision manufacturing can be achieved by professional machines, this limits the flexibility of architectural design and the convenience of onsite construction to a certain extent (Baddoo, 2008). Additionally, the quality of steel welding is highly dependent on the technical level of the welder, making it susceptible to human error. The above-mentioned limitations also make this research more valuable, further improving the performance and application scope of steel structures.

AR for Digital Fabrication

The adoption of AR has seen significant growth in both design processes and digital fabrication applications recently, driven by the technology's increasing maturity, which provides users with real-time engagement capabilities through holographic displays that are visually superimposed on their physical surroundings (Le et al, 2022). This tool not only expands aesthetic possibilities but also redefines the dynamics of human-machine collaboration (Morse et al, 2022). In recent years, the combination and exploration of AR technology with different materials in the construction process has become increasingly popular, such as AR guiding timber assembly (Naboni et al, 2024; Cousin et al, 2023), timber steam bending (Jahn et al., 2019), steel bending (Jahn et al, 2018), standard bricks (Mitterberger et al, 2020; Song et al,2022), etc. These initial explorations have verified the feasibility of AR, as a potential wearable portable device, for guiding low-tech handicraft construction in architecture. However, there remains a gap in understanding the specific role of AR in high-tech-assisted construction processes and how it can be effectively integrated with low-tech craftsmanship strategies. This area warrants further exploration to unlock the full potential of AR in construction practices.

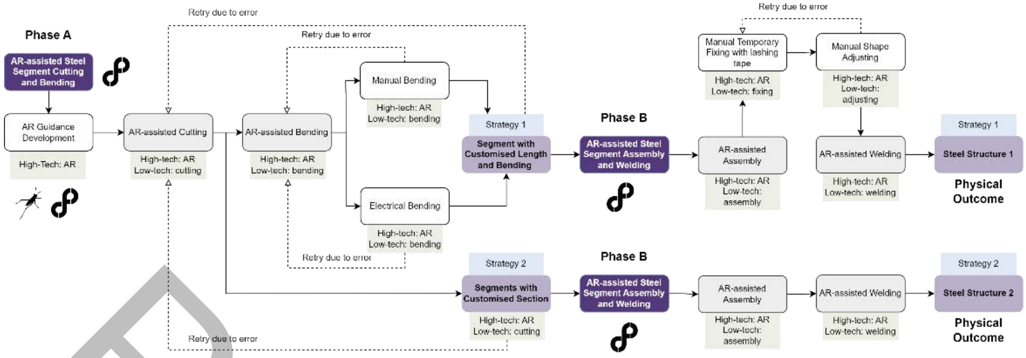

Figure 1
Augmented Steelworker research method flowchart

RESEARCH METHODS

This research investigates AR in assisting the manual steel structure construction process, divided into two key phases: a) AR-assisted steel segment cutting and bending and b) AR-assisted steel segment assembly and welding (Figure 1). To focus on the combination of the AR high-tech method with low-tech techniques for steel construction, and explore the potential outcomes of this integration, an irregularly shaped pavilion was designed and constructed as a research prototype. This pavilion is composed of steel structures, which are connected at extremely complex angles with foam blocks attached. Each segment of the steel structure is customised in length and angle, and cannot be mass-produced. This research greatly challenges conventional steel structure manufacturing methods, verifying the strategy of combining AR with manual craftsmanship, while exploring the boundaries of their integration.

In this research, AR technology is utilised to enable the seamless holographic fabrication guidance, generated in Rhino/Grasshopper, for steelworkers constructing the irregular structure. The hardware for this experiment includes the HMD – Microsoft HoloLens2 and a handheld device - iPhone14 ProMax for AR, as well as a laptop for back-end debugging and transforming the information between digital and physical. The HMD functions as a portable visual guide for manual fabrication, while smartphones are mainly used to supervise the construction process. The software includes Rhino/Grasshopper, which was applied for the fabrication guidance algorithm developments; as well as Fologram, an AR plugin for Grasshopper, which was utilised to visualise and interact with the digital model and AR holograms. All of these devices and software are connected to a WIFI router in the same IP address network environment for communication and integration.

To construct the proposed steel structure, each steel pipe segment needs to be precisely cut, bent, assembled and welded to its predetermined position. Given the irregular geometry of the structure, every physical deformation parameter is unique. These deformations will be generated by Rhino/Grasshopper and transmitted to the AR device through Fologram, providing steelworkers with real-time visual guidance for manual fabrication. These approaches ensure accuracy and efficiency in constructing the complex, customised steel structure.

EXPERIMENTS AND FINDINGS

According to the load-bearing requirements and the construction order, we divided the structure into two hierarchical organisations, namely: first and second hierarchical structures, with 20mm hollow steel pipes and 5mm solid steel pipes, respectively. The first hierarchical structure is connected to the foundation and the second hierarchical structure (Figure 2). We also calculated the shortest path to develop structural optimisation algorithms for generating the steel structure path and construction sequence. The structure is chamfered at the corners with different angles from the calculation results, and the length of each segment is different, so that it cannot be mass-produced in modular form. Therefore, we need to integrate AR visual guidance and manual craftsmanship methods to produce each segment.

AR-assisted Steel Cutting and Bending

In the AR-assisted steel segment cutting and bending phase, the process combines high-tech AR devices with low-tech tools such as portable metal saws, manual benders, and electric steel benders. A custom framework with associated scripts was developed in Fologram to provide holographic guidance for cutting and bending steel pipes. First, the augmented steelworkers equipped with AR headsets, measure and cut the steel pipes to prepare the segments. Using AR, they can scan the QR code for physical virtual positioning, preview the end markings of each steel pipe, and mark them for the efficient customised length-cutting process (Figure 3). Next, the augmented steelworkers will place the prepared segments into the bender, scan another QR code for the alignment, and manually or electrically bend the pipes until they align with the holographic target (Figure 4) (Strategy 1).

This phase relies heavily on AR holographic guidance, the material properties of steel (such as thickness and resilience), and workers' experience when bending metal. Challenges arise from insufficient bending angles caused by rigid rebound, or excessive angles due to the metal's irreversible deformation, both of which impact the accuracy of the final product (Figure 5). These uncertainties and manual factors can lead to tolerances that, if excessive, prevent the proper assembly of the steel structure (Figure 6). A visual comparison between the finished segments and the AR targets reveals noticeable tolerances in each segment.

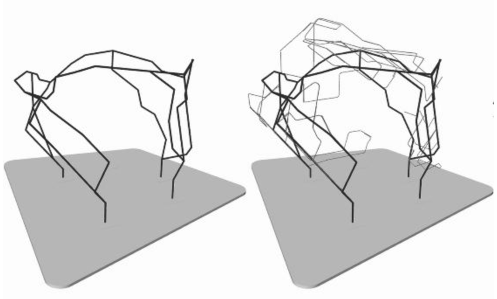

Figure 2
Two hierarchical of steel pipes, the first hierarchical pipes are on the left and the second are on the right

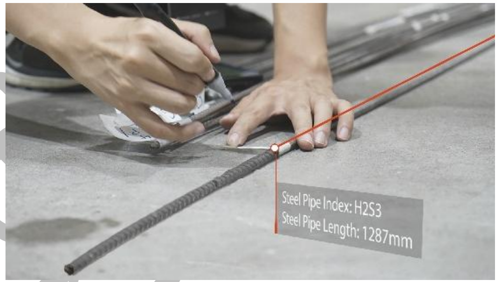

Figure 3
Mark the end and index number of each segment in customised length with AR guidance, and cut them later

Figure 4
AR-assisted steel segment bending, manual bending on the left and electrical one on the right (Strategy 1)

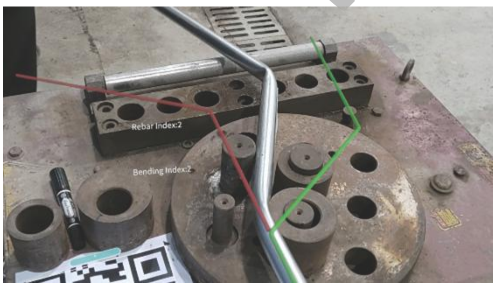

Figure 5
The AR-assisted bending process is prone to tolerances (Strategy 1)

To address these issues, we eliminated the relatively tolerance-producing bending step. Instead, the cutting method was optimised by converting bending angles into precise splicing joints between two segments (Figure 7). In AR, the steelworkers will see the holographic cutting angle and sections overlapping on the pipes. Guided by AR, steelworkers just need to use a metal saw to cut the segments with detailed section information provided (Figure 8) (Strategy 2).

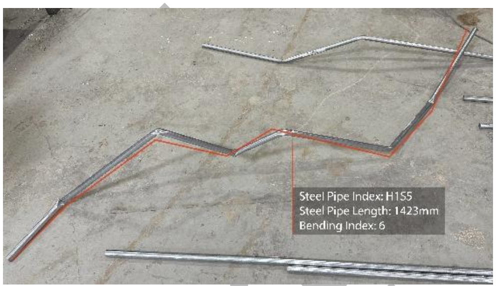

Figure 6
The tolerance of each imprecise bend will be accumulated (Strategy 1)

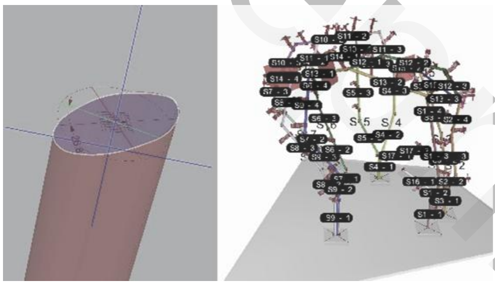

Figure 7
Section data for each rigid chamfer (Strategy 2)

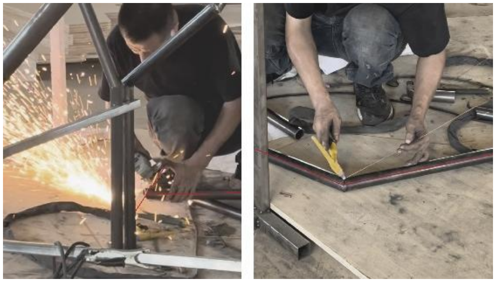

Figure 8
Cut and measure the sections for the splicing joints (Strategy 2)

By replacing the bending process with precise AR-assisted section cutting, the accuracy of the steel segment outcomes improved significantly, reducing tolerances and enhancing the overall quality of the fabrication process.

AR-assisted Steel Assembly and Welding

For the AR-assisted steel segment assembly and welding phase, besides the high-tech AR devices, a portable metal welding machine is required as a low-tech technique tool. A framework with associated scripts was developed in Fologram to provide holographic guidance for assembling and welding steel pipes.

First, the augmented steelworkers position the baseboard accurately using AR holograms aligned via a QR code. The first hierarchical steel segments will be temporarily assembled at the baseboard position by the binding tape, with their positions displayed in AR based on the results of an AR welding algorithm optimised for sequence efficiency (Figure 9). Then, the steelworkers will weld the steel segments together in sequence with the correct segment sections and angles according to the AR guidance (Figure 10). Finally, using the same method, the second hierarchical steel segments are assembled and welded after the completion of the first hierarchical structure.

This phase involves the parallel assembly and welding of segments produced using two strategies from the previous phase: Strategy 1 (cutting and bending) and Strategy 2 (cutting only). This allows for a direct comparison of the accuracy achieved by each AR-assisted fabrication approach. The only difference is that Strategy 1 is to assemble and weld the bent steel pipes according to the specified connection points, while Strategy 2 is to weld the steel segments by section position and angle. This comparative analysis highlights the responsibilities and scope of AR to assist manual construction in achieving precision.

Tolerance Analysis

Both Strategy 1 and Strategy 2 successfully resulted in assembled and welded steel structures, but the quality of the final outcomes differed significantly (Figure 11).

For the Strategy 1 outcome, due to the large amount of human tolerance in the steel segment bending process, they were accumulated and amplified in the assembly and welding phase. In particular, since each steel segment has a certain amount of offsets, in the assembly process, there is a large deviation in the location. Steelworkers were forced to continuously adjust the positions manually, which disrupted the smoothness and precision of the process. Compared with the designed structure target in AR, the final steel structure using Strategy 1 has a tolerance of ±500mm in each direction (Figure 11).

In contrast, the Strategy 2, it simplifies the process. The augmented steelworkers assemble the pre-cut steel pipes of the specific length in the corresponding location and orientation in the sections, and then weld these segments together. This approach eliminates much of the guesswork and manual adjustments required in Strategy 1. By refining the AR-assisted fabrication responsibilities and minimising errors from low-tech techniques, the precision of the steel structure outcome has been greatly enhanced (Figure 12). Strategy 2 has smaller deformation compared to Strategy 1, as well as the designed structure target in AR, which is acceptable and negligible.

In the end, we chose the steel structure with higher precision (Strategy 2), and covered it with foam blocks to complete the construction of the entire designed installation (Figure 13).

DISCUSSION AND CONCLUSION

This research investigates the potential of integrating high-tech portable machines, AR, with low-tech manual fabrication techniques to achieve complex construction tasks, using steel structures as a case study. The initial result provided unique feedback on the potential outcomes of the above integration.

From a high-tech perspective, AR demonstrates significant effectiveness in assisting manual fabrication tasks, providing intuitive, real-time guidance that reduces dependency on 2D drawings and improves precision in complex structures. Through AR assistance, we have the potential to achieve highly customised onsite processing with no need for specialised digital machinery. It broadens the application scenarios and possibilities for future portable intelligent digital construction. However, current AR equipment and technology still have limitations. Although there is no loss when design data is transmitted through holograms, the positioning of AR holograms is not perfect. As AR technology advances, the above limitations will be greatly improved. Nevertheless, this research the feasibility of the integration between AR and traditional craftsmanship.

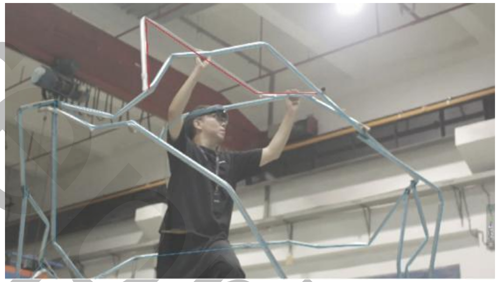

Figure 9
Temporarily assemble the steel segments and weld them together with AR guidance (Strategy 1)

Figure 10
Weld the sections together with the AR guidance (Strategy 2)

Figure 11
Steel structure outcome with high tolerance (Strategy 1)

Figure 12
Steel structure outcome with high precision (Strategy 2)

Figure 13
The final installation outcome

From a low-tech perspective, with the assistance of AR, steelworkers can indeed create more complex results using familiar low-tech craftsmanship, such as cutting, bending, assembly, and welding, as demonstrated in this research. However, the responsibilities and scopes of AR-assisted craftsmanship are constrained by technological limitations. For instance, tasks involving flexible deformations or materials with high rebound properties can result in significant manual tolerances through AR guidance. Therefore, AR-assisted strategies are more suitable for assembly tasks with specified connection methods and positions, or rigid deformation of materials, such as shearing and cutting, which will not be affected by the material properties and human errors. In this way, combined with the experience, AR can significantly enhance the efficiency of low-tech techniques for rigid deformations and improve the accuracy of assembling complex shapes.

Digitally empowered information has enabled design and fabrication to transcend traditional limitations imposed by physical methods, while fostering more intuitive and complex interactions. This shift prompts a reconsideration of how human is treated and how the ideal relationship between high-tech methods and low-tech techniques is envisioned in the digital manufacturing process. This integration is a promising area of study and offers inspiration for future digital construction practices. When using AR technology as a high-tech method, it is necessary to conduct a preliminary analysis of the low-tech techniques it can support and to define the rules and boundaries of AR-assisted construction strategies. Only by doing so can the unique strengths of both high-tech and low-tech approaches be fully leveraged, paving the way for innovative and efficient construction methodologies.

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