Drone Robotic Construction

A methodology for simulating the construction performed by drones using virtual and augmented reality

Nuno Pereira da Silva[1], Sara Eloy[2], Ricardo Resende[3]
[1,2,3]Instituto Universitário de Lisboa (ISCTE-IUL), ISTAR
[1]Nuno_Antonio_Silva@iscte-iul.pt [2]Sara.Eloy@iscte-iul.pt [3]Ricardo.Resende@iscte-iul.pt

The economic and social impacts of robotic construction in Architecture, Engineering, and construction (AEC) are hard to assess and quantify without physical in situ testing, which is expensive and time-consuming This paper presents a methodology for the simulation of robotic construction technologies, namely drones, in a human-machine cooperation (HMC) using virtual (VR) and augmented (AR) reality environments. The developed methodology for robotic construction has the potential to be applied before the start of construction and to use real, virtual and augmented environments for robotic construction simulations. The application of such simulation methodology allows to test HMC scenarios and has the potential to increase construction precision while predicting both construction duration and cost. We present a review of the literature on drone and hybrid automatic construction solutions, as well as VR and AR construction simulations. Then a HMC simulation methodology is proposed and detailed. Three cases of application of the methodology are presented testing different approaches and cooperation scenarios in robotic construction. These cases are: (i) a drone construction in a real environment, (ii) a VR robotic construction simulation and (iii) an AR HMC. The application cases assess how the developed methodology is applicable to a set of different types of simulations that include different criteria.

Keywords: *Robotic Construction, Drones, VR/AR, Simulation, Human-Machine Cooperation.*

INTRODUCTION

This paper elaborates on a methodology developed for the simulation of the construction of brick walls by drones alone or in collaboration with human workers. Simulations are used to foresee and prevent future problems in real-life robotic construction, as well as their acceptability and applicability in a Human-Machine cooperative (HMC) work environment. Although significant development in robots has been achieved in recent decades, most industries still require human cooperation in a hybrid assembly line process. Its by combining the strengths of humans and robots that efficient industrial environment can be achieved (Tsarouchi et al. 2017).

In the field of Architecture, Engineering, and Construction (AEC), robotic tools ranging from manually operated mechanical equipment to remote-controlled semi-automated or automated systems have been employed.

Robotic arms that can build architectural elements using a variety of materials and procedures, as well as vehicles that can mark or screw, are examples of fixed and mobile robots. The robotic arm and drone are two major construction technologies being thoroughly studied and tested, providing flexibility and advantages to the construction sector. By introducing a methodology and applying it to specific application cases, this study suggests that drones might replace manual labour or work alongside human workers in the construction industry, bringing both strengths and weaknesses.

Goals
The main goal of this paper is to define a methodology developed for the simulation of the construction of walls performed by drones alone or in collaboration with human workers. This methodology will enable to simulate processes based on VR/AR that: 1) test human-machine cooperation scenarios in pre-construction; 2) has the potential to test the precision in construction scenarios; 3) detects construction and cooperation restrains before the process starts. After the development of the methodology, and to test its applicability to simulation cases, we simulated the construction of a complex geometry element in a HMC construction environment using AR.

Organization
This paper is divided into four sections. The first presents the research gap and objectives, while the seconddiscusses the current state of the art in drone robotic construction experiments. The third section describes the methodology developed, while the fourth describes applied cases and their significance within each step of the methodology. The discussion and conclusions emphasize our methodology's benefits and limitations for the development of robotic construction experiments in HMC building environments.

STATE OF THE ART
In this section we present a brief state-of-the-art regarding robotic construction, use of VR and AR in AEC, and HMC.

Robotic construction
Still rarely employed on construction sites, drones are mainly being used in research facilities to conduct research for AEC.

In 2012, Gramazio Kohler's research group developed the Flight Assembled Architecture project, using drones to autonomously lift and assemble a 1500 polystyrene parallelepipeds tower in FRAC centre in France (Augugliaro et al. 2014). The Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart completed, in 2017, a research pavilion to explore building-scale fabrication with glass and carbon fibre-reinforced composites. To create a large structure, a collaborative setup was developed involving two stationary industrial Robotic Arms placed at the end of the construction while an autonomous, custom-built drone transported the carbon-fibre cables between them (Menges and Knippers 2017). Cyber-Physical Macro Materials, another ICD project, demonstrated a new dynamic and intelligent architecture for public areas in 2017. The building is made of lightweight carbon fibre filament-based cyber-physical modules with integrated electronics for communication and sensing that work in tandem with a fleet of drones. It challenges preconceived notions of robotic digital fabrication and pre-fabrication for architecture, enabling novel architectural behaviours capable of rapidly transforming public spaces in a dynamic way (Wood et al. 2019). Research groups at ETH Zurich and ICD/ITKE explored drone construction, both combined with Robotic Arm (RA) and drones alone and their ability to build the complex. Notwithstanding the differences, these projects adhered to a five-step methodological framework described in the following sections.

Virtual and augmented reality in AEC
Virtual reality (VR) is a computer-generated environment that can be used to enhance design, safety, and training, as well as reduce calendar and cost overruns. Currently, it is being successfully used

to train construction workers in more accessible and safer environments (Pottle and Robertson 2018; Güray and Kısmet 2022).

An example is the study conducted by Hong et al. (Hong et al. 2023) researchers assessed the impact of construction noise exposure on the productivity of masonry work, a labour-intensive sector. To this end, workers were placed on used virtual reality headset on a temperature chamber to imitate their work environment. In a second stage, researchers analyzed the statistical correlation between psychological and physiological responses and productivity levels.

Augmented Reality (AR) is a digitally augmented version of reality that combines physical and digital elements to create real-time interactive experiences (Chen et al. 2019; Güray and Kısmet 2022; Nigam and C 2022). Gramazio Kohler's research group developed Augmented Bricklaying in 2020 to explore the manual construction of intricate brickwork through AR. The system is based on an object-based visual–inertial tracking method to achieve dynamic optical guidance for bricklayers with real-time tracking and 3D registration features (Mitterberger et al. 2020).

The Steampunk pavilion developed in 2019 was built from steam-bent hardwood using primitive hand tools and intelligent holographic guides displayed on a HoloLens. AR software was used as the communication medium between the worker and the computer, showing a holographic representation of the bent wooden board with symbols indicating where to make connections. The project showed that AR technologies can be successfully used to build complex shapes (Jahn et al. 2022).

Human Machine Cooperation

The ICD/ITK at the University of Stuttgart completed research for the KUKA Innovation Award to facilitate Human-Robot collaboration (HRC) in the AEC sector. The aim was to develop a set of technologies to facilitate an interactive HRC workflow for the construction industry. The project developed a proof-of-concept fabrication workflow to create a one-to-one scale wooden construction system (Kyjanek et al. 2019). The CoBuilt project developed an HMC carpentry construction workflow using a Landcom building site as a case study. The project established a novel workflow to capture and analyse the body movements and tasks of human carpenters through photos and videos. The new RA construction workflow developed based on capturing and analysing human physical activity on a building site was later translated into cooperative Men-Machine construction environments (Reinhardt et al. 2019). Another case is a framework for HCM in the construction of timber structures developed by SDU Robotics. The project outlines an extended automation process that incorporates learning by demonstration (LbD) strategies and Dynamic Movement Primitives (DMP) to teach robots how to assemble structures made of interlocking wooden joints. An in-situ experiment was conducted to test the effectiveness of the framework on a timber structure assembly (Kramberger et al. 2022).

The three projects explored the ability of HMC construction combined with RA to build architectonic shapes in a cooperation environment and concluded that greater investment in software and hardware is needed to apply these technologies in real life scenarios. Despite differences in the final architectural objects, technologies used, and cooperation tasks, they all adhered to a five-step methodological framework.

METHODOLOGY FOR THE SIMULATION OF ROBOTIC CONSTRUCTION

The methodological approaches used by ETH Zurich and the University of Stuttgart are as follows: i) definition of the building process and architectural object; ii) definition of the robot building trajectories and building order; iii) simulation of the building process; iv) analysis of the simulation result; and v) perform the real-life construction (Augugliaro et al. 2014; Menges and Knippers 2017).

Building from the previous approaches we present a methodology for the simulation of the construction of walls performed in a HMC environment. The aim of this methodology is to simulate, using VR/AR, the entirety of the construction process (from planning objects, drone operation on the building site, and HMC construction interaction) and obtain data on: a) the cooperation between human-machine construction scenarios – strengths and weaknesses; b) the precision of construction in hybrid HMC construction scenarios; c) the detection of construction constraints.

The methodology used by ETH Zurich and the University of Stuttgart, developed mainly to use on-display simulations, was adapted to accommodate immersive visualization (VR/AR) and hybrid human-machine cooperation (HMC) in the construction processes.

The methodology (Figure 1) includes the following steps: i) definition of the architectural object; ii) definition of the building process; iii) development of the building process in computer simulations; iv) test of the building process in VR/AR with different stakeholders; v) analysis of the results. The following sections detail each one of the five stages of the methodology.

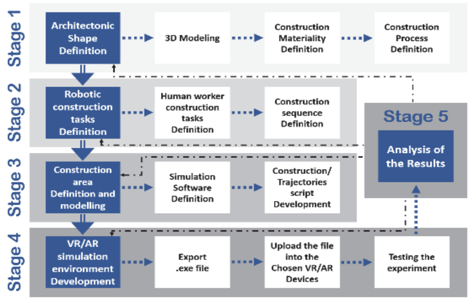

Figure 1
Methodological diagram divided into five stages and shows how the results affect the experiment definition. By authors.

Stage 1 - Definition of the architectural object

The first stage of the methodology is the definition and 3D modelling of the architectural element to be built and the building techniques to be employed. A tridimensional architectonic shape is established using either predefined building elements (such as bricks, prefabricated walls, or slabs) or custom-designed precast elements. The methodology requires the use of 3D modelling software capable of building closed meshes and objects while also employing parametric plugins, such as Rhino 3D [1] with Grasshopper [2], if a parametric design is envisaged. The construction process of the architectural object is defined by specifying the materiality (e.g., brick, wood, concrete) and the assembly aspects, (e.g., supported by own-weight, employing binding materials, joint system, using auxiliary structures). For each construction process different types of planning and programming are requested, ranging from robotic and human construction tasks to binding materials thickness, auxiliary structure positioning or removal, and interlocking system shape and placement.

Stage 2 - Definition of the building process

In the second stage the building process is defined and the chosen robotic technology and human intervention sequence and tasks are determined according to the architectural element and construction process. This stage is divided into two steps:

1. The chosen robotic technology is one of the builders on the process performing specific tasks that need to be defined and programmed. In this step, the lifting positions, landing positions, charging positions, trajectory, building tasks, and the construction sequence for the architectural element are defined. The drone's goal is to build the architectural object and land in a specific location at the end of the process.

2. The human worker's can assist the drone in constructing the architectonic object or have a more relevant task. Depending on the building process, tasks may vary from adding mortar over bricks to adding/removing auxiliary structures or other. In this stage, the building positions, trajectory, and building tasks are defined.

The goal of the human worker is to cooperate in the construction of the object by performing tasks that are simple for a human worker but too time demanding to program and therefore not worth to be performed by drones. The construction area, key coordinates, tasks, and sequence are determined in this stage.

Stage 3 - Development of the building process in computer simulations

The third stage involves developing the building process and AR/VR simulation platform in computer simulation software. This stage is divided into three main steps:

1. Definition/modelling of the construction area. Both the sequence and building requirements for the construction area can be modelled in 3D to be later imported into the simulation software. This stage is crucial to determine construction trajectories.
2. Definition of the simulation software to develop the experiments in AR/VR. Game engines such as Unity and Unreal Engine can develop simulations for construction and VR/AR experiences. They allow for modelling, animation, and scripting of experiments in one platform. Depending on the construction sequence and simulation process specificities, the software can differ.
3. Development of construction and drone trajectories script. A script is developed according to the construction sequence, number of drones and construction area layout to create construction trajectories and flight simulation. The number of construction elements and their sequence are introduced in the script and basic rules to prevent collisions are set in place. The launch, rest, and dispenser coordinates are converted into points in 3D space and connected by lines to create each drone or construction element trajectory. This creates a dedicated trajectory for each drone and each construction element, allowing all processes to be tested and analysed before construction starts, preventing problems in both construction stability, trajectory and cooperation.

Stage 4 - Test of the building process in VR/AR with different stakeholders

VR/AR simulations are developed in this fourth stage, and an immersive visualisation is created. VR and AR were utilized to simulate human interaction with drones in a safe and realistic manner, effectively testing our HMC simulation tool in a real-scale environment.
The option between VR or AR depends on the specificities of the architectural object to be built, the site where it will be built, the construction agents cooperation mode and the available technology. This stage has three steps:

1. A VR/AR simulation environment is created in the selected software. A first-person main character camera is added to the environment and Physical Collision rules are added. A executable version is the deployed in the AR/VR Device such as Oculus Quest 2 [3], Oculus Rift [4], Pico 4 [5], Vive Pro [6] or Microsoft Hololens 2 [7]. At this methodology stage, the experiment is ready to be tested and analysed.
2. Depending on the simulation's goal, a set of tests and experimental subjects are defined. Architects, engineers, contractors, workers, researchers, and others can visualize the simulation for different purposes, such as checking inconsistencies, learning how to build and collaborate with the drone, etc.

Stage 5 - Analysis of the results

The methodology's final stage is the analysis of results from both construction simulation tests, which can be used to determine data such as construction duration, trajectory, placement accuracy, external factors influence, tasks, and battery life.

APPLICATION OF THE METHODOLOGY IN THREE CASE STUDIES

This section presents three cases of application of the methodology, each following the sequence described in section 2 with minor adaptations. All cases present different combinations of drones and human workers, in virtual and real environments.

Case 1 describes the development of a construction performed by a drone in a real environment, Case 2 simulates hybrid drone-human construction in VR, and Case 3 is a human-drone construction simulation in AR.

Case 1- Real Construction

This case involves programming a real drone to fly along a straight trajectory between two places while carrying a wooden block. The ultimate purpose is to examine the drone's capacity to pick up an object, transport, and deposit it in a precise/predefined coordinate. A real drone, a real wooden brick and a real outdoor environment were used (Figure 2).

This case adheres to the developed methodology in the following ways:

Stage 1 - Definition of the architectural object. No 3D virtual environment was required. The architectonic element is a wooden block held in place by its weight.

Stage 2 - Definition of the building process. The drone task is to take off from one location carrying a wooden block and place it in specific coordinates. The drone follows a straight trajectory. It begins its trajectory by speeding from 0 to 58 km/h until it reaches a height of 15 meters, where it pauses, hoovers, and rotates to follow the second part of the trajectory. Once it arrives at the destination, it stops, hoovers and starts descent. At 7 m height, it comes to a halt, recalibrates, and recentres to land. The drone then releases the brick and returns to its starting position. Besides monitoring the flight trajectory, this experiment has no human cooperative task.

Stage 3 - Development of the building process in computer simulations. An autonomous trajectory script was developed to guide the drone from the take-of location to the building coordinate. ArduPilot's Mission Planner software was chosen as being comprehensive and capable of planning autonomous missions. The drone's trajectory, flight speed, and accuracy were pre-set before the experiment. Additional hardware, such as internal and external GPS sensors and a High Precision Multi-Band RTK, were employed to assist navigationin the exterior.

Stage 4 - Test of the building process in VR/AR with different stakeholders. As this case was carried in the exterior on flat ground with a researcher and a drone partaking, no VR/AR simulations were done.

Stage 5 - Analysis of the results. This case allowed to retrieve data such as drone flight time, speed, drone battery life, block placing accuracy, external factor impact.

Figure 2
Photo of Case 1 showing the drone landing on the brick placement area.

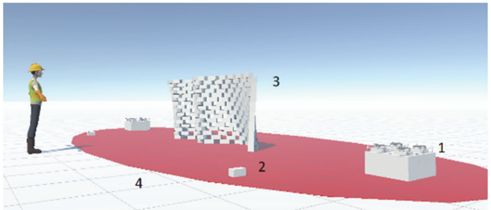

Figure 3
Image retrieved from the VR environment of Case 2. This image shows the construction process with four drones in mid-air carrying bricks. (1) the landing stations, (2) brick dispenser, (3) construction coordinates and (4) construction area.

Case 2 - VR construction simulation

Here drones build three distinct dry-staked masonry walls in a VR environment. The simulation aims to visually highlight the building process's eventual problems and strengths and acquire quantitative results to evaluate the efficiency of robotic construction (Figure 3).

This case adheres to the developed methodology in the following ways:

Stage 1 - Definition of the architectural object. Rhino 3D and Grasshopper were used to develop the model of three parametric designed walls. The first wall consists of a six-brick-high vertical tower, the second is a vertical brick masonry wall with mismatched rows, and the third wall has a more complex geometry based on double-sided curvatures and is composed of rows of bricks with voids between them. All three walls are supported only by the blocks' self-weight.

Stage 2 - Definition of the building process. The drones' task is to build the desired shape placing each brick on the correct coordinate. The construction sequence for the walls is the following: a drone takes off from the departure point and travels to a dispenser, lands and grabs a brick using its claw, then takes off for the brick destination coordinate, where it lands again and releases the brick. A circular route was created to guarantee that the drones were always on different sides of the trajectory. No collaboration with human workers was devised.

Stage 3 - Development of the building process in computer simulations. Rhinoceros 3D and Grasshopper visual scripting languages were used to create drones trajectories. Cinema 4D (C4D) [8] software was used to develop the animation of the construction process, splitting the construction into keyframes.

Stage 4 - Test of the building process in VR/AR with different stakeholders. Unity Game Engine was used to render the experience in the Oculus Rift 2 VR device, with colliders and modifiers components added to give physical attributes, and a character with a first-person camera uploaded to the scene. This case was visualised, tested, and analysed by the team of researchers.

Stage 5 - Analysis of the results. This case allowed to retrieve data concerning drone construction viability, construction duration, flights per battery life, block placing accuracy.

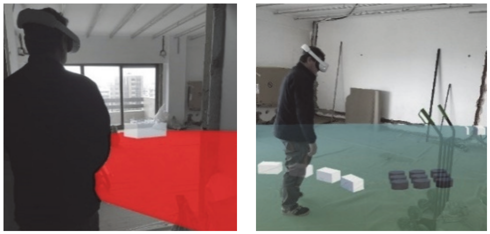

Figure 4
Image simulating the AR experience from the perspective of the human worker in Case 3. (Left) The human worker, while the construction area is red and inaccessible. (Right) When the construction area changes to green the worker enters the construction area and starts his construction tasks.

Case 3 - AR construction simulation

This case aims to create an AR simulation environment to evaluate HMC processes with drones in the construction sector. It's a construction simulation in AR of a complex double-curvature brick wall with eight virtual drones and human workers cooperating in shared tasks. The purpose is to use a hybrid Human-Machine Cooperation building process to construct complex geometry brick walls.

This application case adheres to the developed methodology as follows:

Stage 1 - Definition of the architectural object. The 3D model of the double-sided curvature wall from case 2 was used.

Stage 2 - Definition of the building process. The drone's task is to build the desired shape placing each brick on the correct coordinate and land in a specific location at the end of the process. The construction begins at a predetermined coordinate where the resting and charging positions of the drone are located. Four drones take off from the starting point, accelerating from 0 to 58 km/h until they reach a height of 3 m. They then fly to the brick dispenser, land, and take one brick each. They then proceed to the brick placement coordinate, where they stop, hoover, recalibrate, and recentre to land on the exact final coordinate.

The human worker task is to cooperate in the construction by placing mortar on top of each brick. Once the colour of the building area changes from red to green, black oval shapes, simulating mortar, appear on either side of the built row of bricks. The human operator is instructed to enter the building area, grab and place mortar over each brick before the area turns red again. The construction/assembly sequence for the drones is established, as is the location and construction task for the human worker. This process is repeated until the wall is complete.

Stage 3 - Development of the building process in computer simulations. Within Unity, a script was created to record the drone's movement, coordinates in space, and communicate with the human worker. The script first calculated the trajectories using the starting coordinate, brick dispenser coordinate, and landing coordinate as anchor points. The trajectories for each drone and brick were automatically calculated to follow the construction order, avoid drone collisions, and alternate between drone flight and recharge time.

The script was also used to define an oval construction area and a system of color codes to guide the human worker. By alternating between red and green, the construction area gives vital information to the human worker about when it is safe to enter and start the cooperation tasks, as shown in Figure 4. Once the color changes from red to green, the script creates a series of black oval shapes representing mortar on each side of the constructed row.

Stage 4 - Test of the building process in VR/AR with different stakeholders. Unity game engine software was used to develop the robotic construction process and render the experience on the Oculus Quest 2 device. Components such as colliders and modifiers were added to give the components physical attributes, and an avatar with a first-person camera was added to the scene. 3D representations of the user's hands were included to ensure Human Machine Cooperation. A group of 28 participants were divided into two groups (20 recruited in the university and 8 in construction sites) and were asked to participate in this experiment. The AR simulation was here used to test human-machine collaboration environments, platform's usability, user satisfaction, and safety perception in HMC environments.

Stage 5 - Analysis of the results. This case allowed to retrieve data concerning drone construction viability, construction duration, flights per battery life, block placing accuracy and degree of cooperation.

DISCUSSION AND CONCLUSIONS

The main goal of this paper is to define a methodology for the simulation of the construction walls by drones alone or in collaboration with human-workers in a human-machine cooperation (HMC), using real life, virtual (VR) and augmented (AR) reality environments

A methodology with five stages (Figure 5) was defined and three cases of application capable to

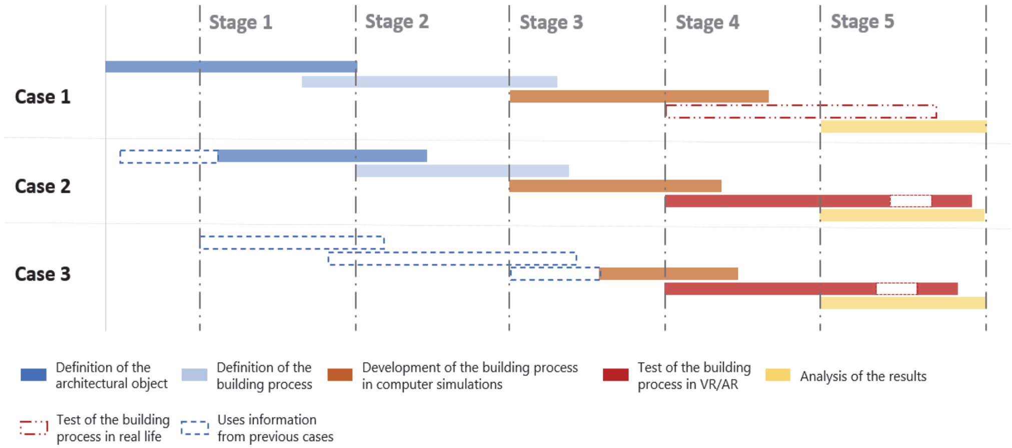

Figure 5
Diagram depicting how each of the three applied cases correspond to the five stages of the methodology.

test it were developed. Three goals were set for the definition of the methodology:

1. *The methodology should allow to test human-machine cooperation scenarios before construction starts.*

Case 1 demonstrated that HMC workflow can be used from the development stage of a robotic experiment, with human worker and drones cooperating in programing and placing blocks inside the claw. Cases 2 and 3 demonstrated that VR/AR simulation can be used to test different degrees of HMC environments and tasks.

2. *The methodology should have the potential to test the precision in construction scenarios;*

The three cases proved that precision can be tested within construction simulations. Case 1 was used to test and establish realistic simulation drone behaviors for Case 2 and 3, allowing for accurate and precise brick placement in VR/AR environments.

3. *The methodology should allow for the detection of construction and cooperation restrains before the process starts.*

Case 1 was used to assess block placement precision, error margin, and human cooperation hazards to identify cooperation opportunities. Cases 2 and 3 demonstrated that the VR/AR simulation methodology can be used to test new cooperation tasks, structures, robotic construction trajectories and environments before application in real scenarios.

The research showed that VR/AR simulations of HMC construction experiments can become vital tools for the future of human machine hybrid scenarios. AR/VR offer advantages for HMC construction processes, allowing users to anticipate future robotic routes, relative human-machine positions, and cooperation risks. This technology can potentially change how we build and design construction sites and locations.

ACKNOWLEDGEMENTS

This research was funded by the Fundação da Ciência e Tecnologia (FCT) PhD grant SFRH/BD/146143/2019, and by the research unit project UIDB/04466/2020, also funded by the FCT.

REFERENCES

Augugliaro, F. et al. 2014. The Flight Assembled Architecture Installation. *IEEE Control Systems Magazine*, pp. 46–64.

Chen, Y., Wang, Q., Chen, H., Song, X., Tang, H. and Tian, M. 2019. An overview of augmented reality technology. *Journal of Physics: Conference Series* 1237, p. 022082. doi: 10.1088/1742-6596/1237/2/022082.

Güray, T. and Kısmet, B. 2022. *Potentials of VR and AR in Pre-Construction Phases*.

Hong, J. et al. 2023. Virtual reality-based analysis of the effect of construction noise exposure on masonry work productivity. *Automation in Construction* 150, p. 104844. doi: 10.1016/j.autcon.2023.104844.

Jahn, G., Newnham, C. and van den Berg, N. 2022. Augmented Reality for Construction From Steam-Bent Timber. pp. 191–200. doi: 10.52842/conf.caadria.2022.2.191.

Kramberger, A., Kunic, A., Iturrate, I., Sloth, C., Naboni, R. and Schlette, C. 2022. Robotic Assembly of Timber Structures in a Human-Robot Collaboration Setup. *Frontiers in Robotics and AI* 8. doi: 10.3389/frobt.2021.768038.

Kyjanek, O., Al Bahar, B., Vasey, L., Wannemacher, B. and Menges, A. 2019. Implementation of an Augmented Reality AR Workflow for Human Robot Collaboration in Timber Prefabrication. doi: 10.22260/ISARC2019/0164.

Menges, A. and Knippers, J. 2017. *ICD/ITKE Research Pavilion 2016-17*. Available at: https://icd.uni-stuttgart.de/?p=18905 [Accessed: 12 March 2019].

Mitterberger, D., Dörfler, K., Sandy, T., Salveridou, F., Hutter, M., Gramazio, F. and Kohler, M. 2020. Augmented bricklaying. *Construction Robotics* 4(3–4), pp. 151–161. doi: 10.1007/s41693-020-00035-8.

Nigam, S. and C, P. 2022. Augmented Reality in Education System. *International Journal for Research in Applied Science and Engineering Technology* 10, pp. 397–401. doi: 10.22214/ijraset.2022.45202.

Pottle, J. and Robertson, R. 2018. *W7 VR and AR in simulation: why and how?* doi: 10.1136/bmjstel-2018-aspihconf.86.

Reinhardt, D. et al. 2019. CoBuilt Towards a novel methodology for workflow capture and analysis of carpentry tasks for human-robot collaboration. In: *Blucher Design Proceedings*. São Paulo: Editora Blucher, pp. 207–216. doi: 10.5151/proceedings-ecaadesigradi2019_549.

Tsarouchi, P., Matthaiakis, A.-S., Makris, S. and Chryssolouris, G. 2017. On a human-robot collaboration in an assembly cell. *International Journal of Computer Integrated Manufacturing* 30(6), pp. 580–589. Available at: https://doi.org/10.1080/0951192X.2016.1187297.

Wood, D., Yablonina, M., Aflalo, M., Chen, J., Tahanzadeh, B. and Menges, A. 2019. Cyber Physical Macro Material as a UAV [re]Configurable Architectural System. In: Willmann, J., Block, P., Hutter, M., Byrne, K., and Schork, T. eds. *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 320–335.

[1] https://www.rhino3d.com/
[2] https://grasshopper.app/pt_br/
[3] https://www.oculus.com/experiences/quest/
[4] https://www.oculus.com/rift/setup/
[5] https://www.picoxr.com/global/products/pico4
[6] https://www.vive.com/us/product/#pro%20series
[7] https://www.microsoft.com/en-us/hololens
[8] https://www.maxon.net/en/cinema-4d