# VIZOR: FACILITATING CYBER-PHYSICAL WORKFLOWS IN PREFABRICATION THROUGH AUGMENTED REALITY

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**Abstract.** This research presents Vizor, a software framework to facilitate Human Robot Collaboration (HRC) in fabrication using Augmented Reality (AR), specifically within the environment of high Level of Automation (LoA) prefabrication for the AEC industry. The framework supports skill set extensions of fabrication setups via the integration of human craft and automation through AR and improves the accessibility and adaptability of these fabrication setups. It features a *Grasshopper* plugin for low-barrier-to-entry prototyping and an integrated *HoloLens* application for operation. The tool is demonstrated through three use case examples and validated in a proof-of-concept case study involving a craftsperson and a 14-Axis robotic setup, which demonstrates a novel interactive task-sharing process. Vizor opens new opportunities to extend robotic prefabrication with craftspeople who are skilled yet untrained in robotic control and provides greater access to tools for prototyping HRC workflows.

**Keywords.** Augmented Reality; Human Robot Collaboration; Cyber-physical Fabrication; SDG 8; SDG 9; SDG 12.

## 1. Introduction

Industrial prefabrication brings benefits such as higher productivity and reduced waste production (SDG 12) to the construction industry. While sustainable industrialisation fosters job creation and economic growth (SDG 9), automation also changes the profile of human labour. Technological progress has catalysed major shifts in the labour landscape, such as industrialisation in the 1800s that saw a decline in the crafts profession, yet many factory jobs created. Ensuring productive employment and decent work for all (SDG 8) thus calls for a better understanding and integration of traditional labour and skilled craft in high Level of Automation construction processes.

Augmented Reality (AR) has shown promising potential in bolstering human capacity in non-standard fabrication tasks in the Architecture Engineering and Construction (AEC) context. It aids in the extension of craft-based fabrication procedures by enabling collective assembly of complex structures (Jahn et al., 2018),

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achieving higher geometric complexity with manual labour (Mitterberger et al., 2020), and utilising unpredictable, unconventional materials in large-scale fabrication (Yoshida et al., 2015). In combination with machines and robotic tools, AR has been applied towards creating intuitive interfaces for interactive fabrication, which leverages unique human and machine capacities to build novel structures (Mueller et al., 2019).

This research proposes a software framework for AR integration in Cyber-physical fabrication, to not only extend manual procedures, but also facilitate interaction between human and other fabrication units on a network, such as industrial robots. Incorporating the human in the loop allows the sharing and transfer of human skills into automated systems (Garcia et al., 2019) and can be an effective strategy to increase process flexibility (Amtsberg et al., 2021). This is particularly relevant in the project-based construction industry, where the high precision and standardisation of prefabrication methodologies alone are not sufficient to address the variety of building geometries and processes necessary (Wagner et al., 2020).

Existing tool sets for Mixed-Reality fabrication (Jahn et al., 2018) and real-time robot control (Garcia del Castillo y López, 2019) streamline important elements of AR-integrated robotic fabrication. However, a bridge is required for a system to combine humans and robots in a single workflow. For instance, while Fologram offers rich features for Mixed Reality experimentation (Fologram, 2021) it provides little integration with robotic fabrication tools. Projects that combine the two are often based on one-off setups, which limits the reusability and accessibility of such workflows to a wider audience, as well as their adaptability to new production scenarios. Vizor aims to address this by proposing a reusable and extensible framework that incorporates humans and machines in a joint fabrication workflow, to adapt and extend high LoA prefabrication setups.

## 2. Context

### 2.1. BACKGROUND

Augmented Reality head-up displays have been proposed towards enhancing manufacturing and assembly tasks since the 1990s (Caudell & Mizell, 1992). In addition to visual cues, non-visual AR assistance has also been applied for task execution in construction, such as haptics-based robotic teleoperation.

Cyber-physical Systems (CPS) are relevant for industrialised prefabrication as they involve physical processes with a high level of digital integration and networking capabilities (Ruiz Garcia et al., 2019). The translation of CPS into architecture has also opened novel design possibilities that 'unfold in the material realm through explorative processes' (Menges, 2015).

Application of AR in CPS in the environment of high Level of Automation (LoA) prefabrication brings the benefits of 1) **flexibility & collaboration**: coordination, skill extension and integration between human (e.g., decision-making, adaptability, flexibility, mobility) and robots (e.g., speed, precision, payload, endurance); and 2) **transparency & connectivity**: keeping people informed and integrated within the highly networked, automated processes.

## 2.2. STATE OF THE ART

Recent work in Human Robot Collaboration for AEC fabrication has explored many exciting possibilities using various interaction modalities and custom architectures. On an abstract level, we consider AR-integrated HRC systems to generally require four components: AR client, information generation, process management, and machine control. On an implementation level, the four components can be executed using a variety of tools and frameworks.

Augmented Materiality (Johns, 2017) uses projection-based AR interface for interactive fabrication with highly stochastic material properties. Information generation occurs on the fly based on depth information, topological optimisation, and user inputs. RoMA (Peng et al., 2018) proposes an interactive 3D printer using a custom AR goggle with Oculus controllers as the AR client, a Rhino plugin for information generation and process management, and a printer sub-module for robotic control. CROW (Kyjanek et al., 2019) demonstrates a HRC process for timber prefabrication using a NoSQL database to store CAD information and ROS-based process manager connected directly to a KUKA Sunrise controller, and human interacts through a HoloLens. Prototype as Artefact (Atanasova et al., 2020) showcases a live HRC assembly process using a custom mobile application. Assembly information is generated on the fly while as-built structures are registered through visual-inertial tracking on the AR device.

Vizor presents an architecture that leverages the visual programming tool Grasshopper to generate and operate Human-Robot collaborative tasks. It enables designers and architects with little software development experience to build and run such workflows and facilitates runtime orchestration and participation by a human worker or craftsperson who is unskilled in programming robots.

## 3. Methodology

Introducing human labour in high LoA prefabrication opens new opportunities to rethink traditional robotic fabrication workflows. Human and machine tasks should be considered in conjunction during planning and design phases, and a higher level of information integration at run-time is necessary.

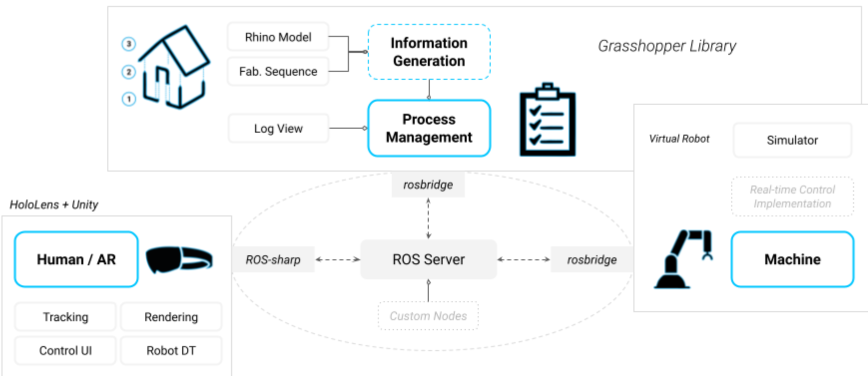


*Figure 1. Augmented Reality Human Robot Collaboration System*

The prototyping environment is accessible to designers via a Grasshopper plugin, which integrates with a HoloLens application that supports a user interface and Process Digital Twin for both the robot and work tasks. The overall system architecture is shown in Figure 1, and the main design considerations are summarised below:

- Information generation and process management are encapsulated in Grasshopper's visual programming environment, allowing direct access to Rhino geometries.
- AR client is built on the all-in-one device, *HoloLens*, and equipped with a modular interface to simplify interaction with key system components.
- Communication framework is built on the Robot Operating System, allowing easy integration with robotic tools and resources available from the ROS ecosystem.
- Message and topic structures related to HRC workflows are defined in a general way, allowing potentially different, enhanced implementations of system elements. (e.g., HoloLens can be replaced with mobile devices, or statically determined task information can be replaced by adaptive, procedurally generated information based on real-time sensor inputs.)

## 3.1. AR CLIENT

The HoloLens application is developed using Unity. Its modular interface allows users to control important system elements, namely: marker detection and tracking, robot digital twin and simulation, human task information, 3D model access, and system status overview. These UI elements make use of simple interaction widgets available on *HoloLens 1*, shown in Figure 2.

A Digital Twin of the robot platform, TIM (Wagner et al., 2020), allows fast robotic visualisation through robot joint values streamed through the network. Relevant work geometries are also updated during execution to support visualisation of the Process Digital Twin. Marker-based localisation for workpieces and robots is implemented using the Vuforia Engine, which handles marker detection and tracking. ROS-sharp is used to integrate message publication and subscription with other system elements.

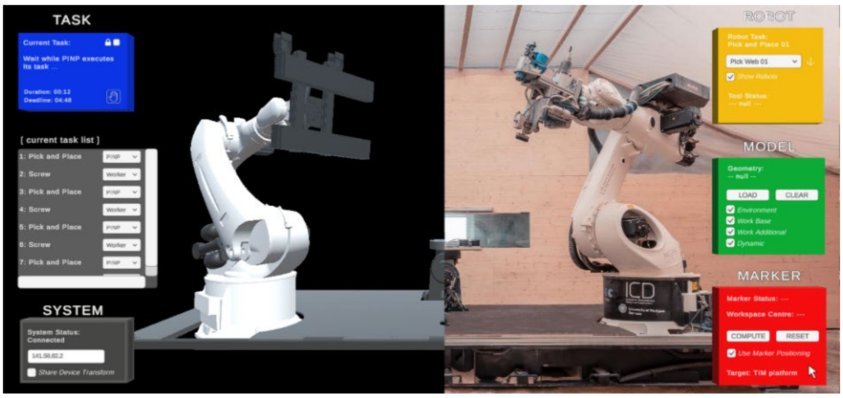


*Figure 2. AR Client Interface allowing User Control for Marker Detection (red), 3D Model Access (green), Robot Simulation (yellow), System and Task Overview (grey), Task Information (blue) and the Digital Twin of the Robot Platform TIM in Unity*

## 3.2. GRASSHOPPER PLUGIN

By providing bidirectional information between the AR device and the Grasshopper environment, prototyping Mixed Reality workflows is more rapid and accessible to an audience with little programming or application development experience (Jahn et al., 2018). In addition to supporting the basic exchange of geometry and marker information between Grasshopper and the AR device, Vizor provides components for task definition, process control, and robot simulation to facilitate human-robot collaboration in high LoA prefabrication environments.

An overview of the plugin library at the current stage of development is shown in Figure 3. Controller components are key to running and managing the task execution process, as they respond to inputs and update the Digital Twin as the fabrication process unfolds, in addition to providing a text-based log output. The respective use cases of these elements are elaborated in Workflow Examples.

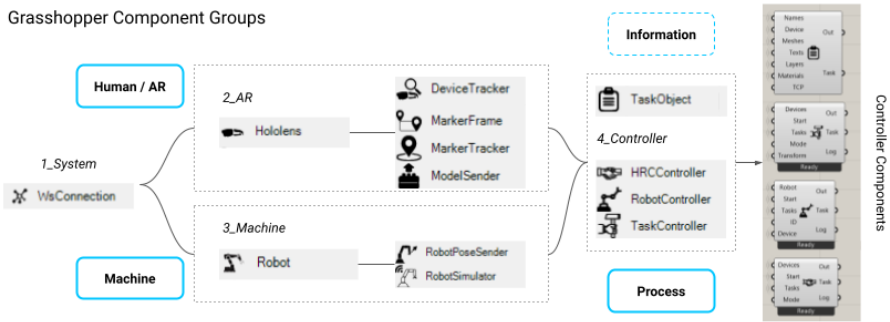


*Figure 3. Component Library*

## 3.3. COMMUNICATION STRUCTURE

The ROS-based communication framework allows integration with other system elements through rosbridge. For instance, to facilitate the orchestration of multiple AR clients, a custom ROS node is implemented to manage the process based on the 'sharing mode' defined in 'Task Controller'. This is relevant when multiple units share the same work process, and their task assignment and completion logic need to be tailored to needs of the relevant processes.

To support the basic information flow necessary for human robot collaboration, pre-defined topics and message structures are incorporated in the main nodes of the system. Shown in Figure 4, these topics encompass three main categories: Process/System-initiated (red), AR/Human-initiated (orange), and Machine/Robot-initiated (green). The participating elements subscribe to the relevant topics, and the list of topics can be extended when more system elements are added.

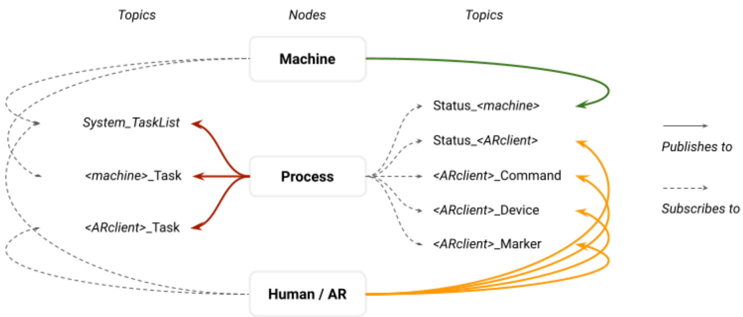


*Figure 4. Topic and Communication Structure*

## 4. Workflow Examples for Illustration

Vizor's Grasshopper library is the cornerstone on which three proof-of-concept workflows are shown. They demonstrate the use of the framework in Human-System, Robot-System, and Human-Robot interaction to adapt to different use cases in prefabrication scenarios.

### 4.1. HUMAN - SYSTEM (TASK CONTROLLER)

Human-System interaction allows work tasks that are difficult, or impractical to achieve by robotic prefabrication to be executed manually with AR (i.e., extending the fabrication space of the robot through the flexibility of human craft).

As an example, consider a robotic setup without an end effector for screw insertion and a worker needs to complete the task. First, the designer inputs a list of CAD geometries and auxiliary information such as rendering options to create a 'Task Object'. The objects feed into the 'Task Controller' component, which becomes active when the 'Start' toggle is triggered. As the AR client detects markers in physical space, their positions are streamed to 'Marker Frame' which automatically computes the transform matrix to localise the workpiece. The task controller supplies necessary visual and text assistance as the worker signals task completion with the Task panel on *HoloLens*, and the designer sees a real-time overview of the task progress (Figure 5).

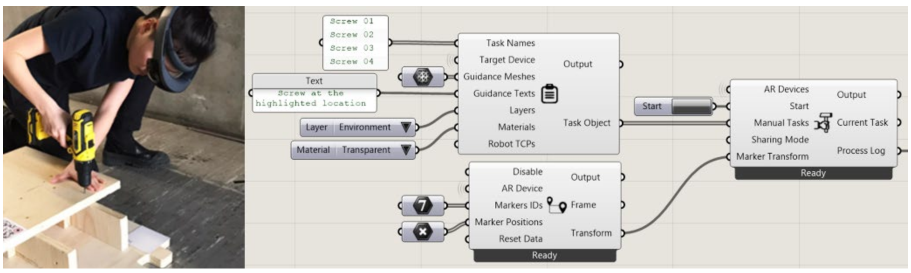


*Figure 5. Task Controller Workflow (Screw Insertion)*

### 4.2. ROBOT - SYSTEM (ROBOT TASK CONTROLLER)

Robot-System interaction allows robot planning to be augmented by the AR system, which helps designers visualise robot paths in situ (e.g., to account for unplanned obstacles missing from the digital model). At the current stage, the component serves as a 'virtual' controller for simulation while physical robot control is not integrated.

The robot object is defined using an existing robot library for kinetic simulation. The library is a custom in-house development independent of the developments described in this paper. Robotic tasks are defined using frames along the programmed trajectory, together with an optional programme name for each action (Figure 6). The 'Robot Simulator' runs a given task virtually, by looping through each point on the trajectory, converting it to joint values using an Inverse Kinematics function in the robot object, and triggering updated visualisations of the Digital Twin on HoloLens. The list of robot tasks is sent to HoloLens in a dropdown menu, allowing the operator to select and visualise selected simulations as needed.

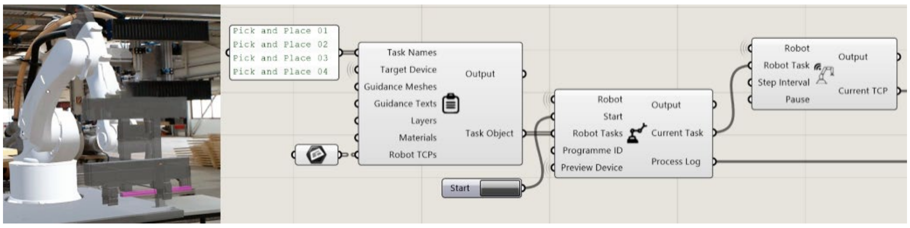


*Figure 6. Robot Controller Workflow (Pick and Place Simulation)*

## 4.3. HUMAN - ROBOT (HRC CONTROLLER)

Human-Robot collaboration combines the two mechanisms above and allows both units to collaborate in a task series. The workspace is not oriented around the workpiece, but around a shared workspace with the robots. The 'HRC Controller' converts the task objects defined generically for both humans and robots and dispatches the information to either the AR device or the robot for execution.

As an example, we imagine a scenario in which a human and a robot collectively disassemble a structure where the blocks are in known locations, but the screws are not. Since the robot cannot be programmed for unknown locations and angles, a sequence can be built with the HRC component (Figure 7), where the human unscrews while the robot first holds and subsequently removes the block at pre-programmed positions. Each human task ends when the AR client signals completion; each robotic task ends when every point on the path has been looped through. The human and robot take turns to execute in a sequential manner.

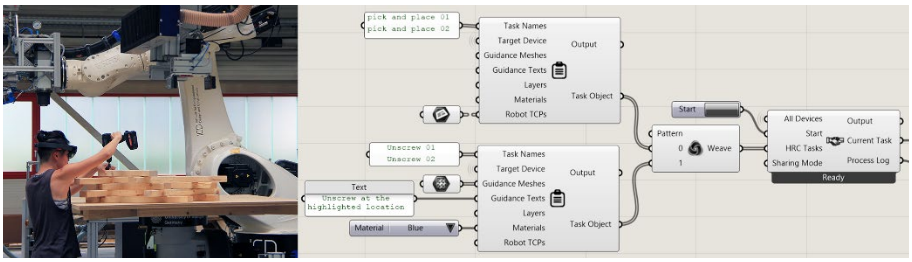


*Figure 7: HRC Task Controller Workflow (Sequential Task Sharing)*

## 5. Case Study

The Vizor framework is tested in a case study, where a human craftsperson, two 6-axis KUKA KR500 industrial robots, and one 2-axis tilt-turn table collaboratively assemble timber slats into clusters. It presents a dynamic, instructive Human Robot Collaboration (iHRC) process, where the sequential task sharing described in 4.3 is augmented with objects that implement real-time physical robot control, as well as a task reassignment mechanism for humans to interact with the fabrication process on the fly.

### 5.1. SETUP

One KUKA robot executes pick and placing the timber slats. The second robot inserts nails at the slat intersections with an automatic nail gun. The tilt-turn table adjusts its orientation to ensure the robots can reach target locations. The human is equipped with a *HoloLens* and an electric screwdriver. The craftsperson within the high LoA production setup carries out the following activities:

- Overseeing the execution of the task sequence through the task list
- Inspecting the timber slats, such that, when the nailing position has a knot hole (where a loose connection would likely result), he/she intervenes by reassigning the task from robotic to manual execution and inserts a 4x60mm screw
- Inspecting and potential manual intervention of the robot execution, where, if unpredictable contingencies occur, he/she intervenes by reassigning a robotic task to manual execution

### 5.2. SUMMARY

Vizor is applied to a collaborative fabrication process where humans are put in the driving seat of the robotic platform's operation. Each human-executed task is assisted with AR-rendered geometry to indicate location of the operation, as well as details of task description and timing. Each robotic task is executed with a human in the loop, accompanied by information on the robot's next movement, task information and timer (Figure 8). Geometric deviation between the robotically placed and manually placed slats should be better addressed in future studies.

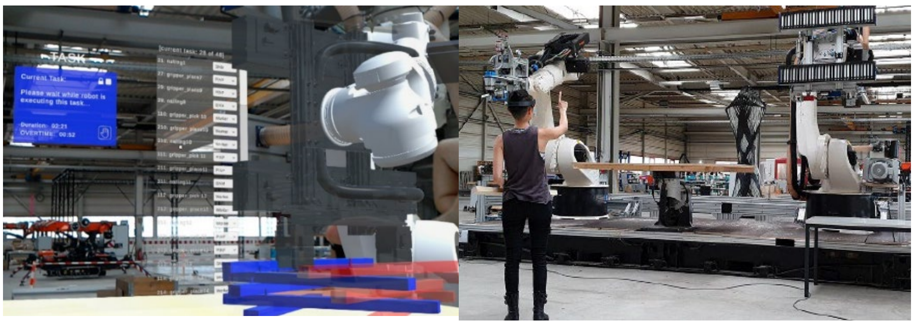


*Figure 8: AR interface showing the task information panel, task list, robot digital twin, and work geometries overlaid on the physical workspace (Left) and Craftsperson wearing HoloLens (Right)*

## 6. Discussion and Future Work

This research presents Vizor, a software framework developed with the aim of introducing human craft in high LoA prefabrication and streamlining the creation of HRC workflows integrating Augmented Reality. Its main design considerations, architecture, components, and their usage are presented. Its application in robotic prefabrication in both planning and execution phases are illustrated through use case examples and a case study.

The framework is the first step towards a more accessible, adaptable, and intuitive AR-integrated human machine collaboration workflow, which can be augmented with additional hardware, control, sensing, tracking, and AR client implementations. For instance, human-robot interaction modalities can be expanded to include haptics, voice, or more sophisticated gestural inputs available on *HoloLens 2*. The robotic execution module can be developed further and integrate higher sensing capabilities e.g., using depth cameras to capture structures as they are built.

Though the system has only been demonstrated in prototyping environments in this paper, it is currently used in a pavilion construction project under more realistic conditions for prefabrication. To further validate and improve the framework, workshops and seminars are also relevant avenues to test the use of the system with a wider audience, from workflow design, simulation, through to the fabrication stage.

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