Augmented Human, Extended Machine

Extended reality systems for robotic fabrication in architecture, engineering, and construction

How can we trigger the process of digital embodiment and corporeality in human-robot collaboration through extended reality and digitally enhanced environments?

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> **"These machines are responsive. They communicate. They're warm. They talk back."**
>
> **—Composer and musician Suzanne Ciani discusses the synthesizer [1].**

Human augmentation describes the ability to enhance a person's perception, movement and/or cognitive abilities through the assistance of machines and tools. At the same time, human augmentation also entails the extension of the machine by expanding machine capacities with human abilities. Doug Engelbart is a crucial figure in the field of human augmentation, changing the tech industry profoundly by introducing the NLS system on December 9, 1968. NLS is short for oN-Line System, a system that lets users work and communicate with others in countless ways. This system includes many essential inventions such as the computer mouse, online software, and window-like interfaces. Users could edit text, draw images, manipulate and organize files, send messages, and even do video conferences. Engelbart's underlying idea was to augment human intellect through collaboration. In his 1962 proposal, he explains it as such: "We refer to a way of life in an integrated domain where hunches, cut-and-try, intangibles, and the human 'feel for situation' usefully co-exist with powerful concepts, streamlined terminology and notation, sophisticated methods, and high-powered electronic aids" [2]. The following year, Ivan Sutherland, a contemporary of Doug Engelbart, submitted his dissertation outlining Sketchpad, a graphical user interface (GUI) to allow users to interface with a machine [3].

Researchers such as Engelbart and Sutherland enabled the development of different software to create, display and edit computer-aided designs that allowed designers to communicate their ideas via a screen-based interface. Even though these inventions are more

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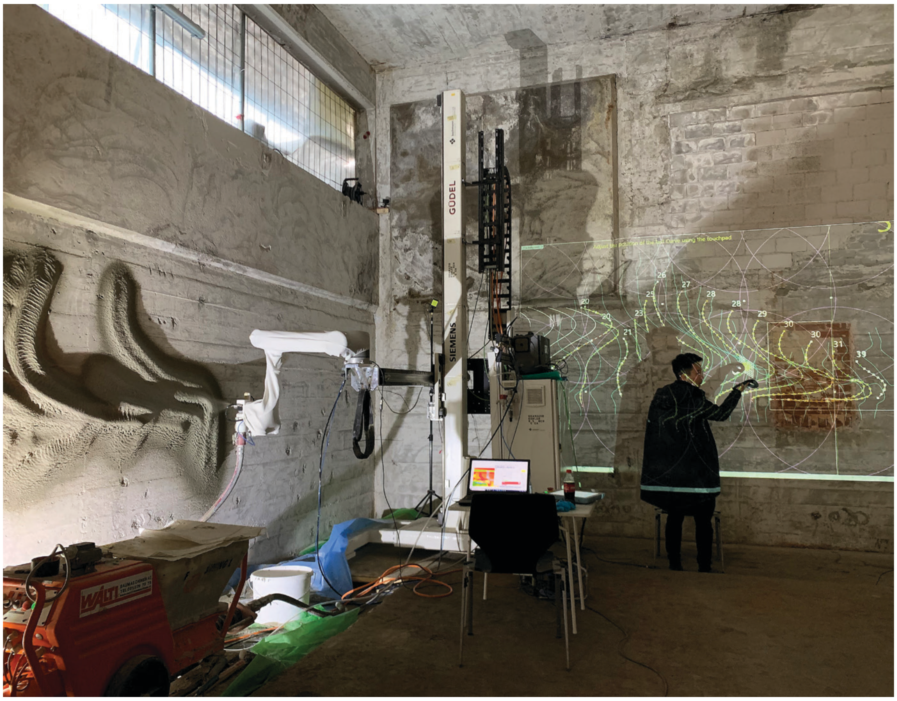
than five decades old, most common workflows in architecture engineering and construction (AEC) still focus on similar GUIs and do not offer digitally embodied workflows. Furthermore, current technology regarding direct and interactive manipulation of design and fabrication outcomes is still in its infancy. Contemporary design-to-fabrication workflows are based on a linear data communication workflow. In contrast, interactive manipulation and human-machine interaction require real-time bi-directional communication and the development of novel design modes and interfaces. Recent advances in augmented reality (AR) have opened up exciting new opportunities for novel human-machine interaction systems. AR overlays context-sensitive computer-generated information onto the real world, which depends on observed objects and the environment [4]. This context sensitivity is crucial for human-machine interaction involving robotic fabrication in the domain of AEC.

In the past decade, robotic fabrication in AEC has become more ubiquitous and robotic fabrication has become increasingly more critical. Robotic fabrication brings advances such as the customization of building elements, production speed, and precision that open new design opportunities [5, 6]. Besides the named advantages, robotic fabrication still poses challenges, especially in complex work environment, such as construction sites, ambiguous material systems, and non-linear fabrication processes. Robotic fabrication functions well for distinct tasks and workflows involving stable environmental conditions. Most complex environments do not offer these stable and predictable conditions. Therefore, in such environments, humans still need to interact with robots. This human interaction may include cleaning up work environments, joining elements, preparing materials, or placing elements within the robot's reach. Even though human presence is vital in such scenarios, human-in-the-loop processes in AEC are still perceived as a limitation rather than a source of potential. Only a few studies have examined how to include human-in-the-loop processes in larger-scale robotic fabrication [7]. The lack of research on human-machine collabo-

Figure 1. IRoP, interactive robotic plastering system.



ration in AEC is manifold. One reason is the lack of understanding of the complexity of robotic manufacturing processes in unstructured environments such as construction sites. Robotic fabrication setups in such environments require holistic concepts that involve multiple actors, flexible systems, and diverse interaction scenarios. Another reason is the lack of customizable user interfaces. Traditionally, human interaction with robots relies on preprogrammed actions or internal physical or visual feedback capabilities [8]. These interaction modalities have several fundamental limitations such as a lack of flexibility regarding environmental changes, imprecision, and human interaction. AR interfaces have the potential to address these challenges, as they enable human-in-the-loop fabrication by offering custom user interfaces without constraints of physical reality. Furthermore, AR tightly couples the physical interaction space with visual feedback, simplifying the user's cognitive load. Robotic fabrication combined with AR can enable human-in-the-loop fabrication, splitting fabrication tasks between the human user and the robotic unit. Fabrication tasks that require higher flexibility and tacit interaction can be outsourced to the human user, whereas tasks that require precision or heavy lifting can remain within the robotic unit.

Developing AR applications for robotic fabrication in AEC is challenging, requiring real-time tracking and computation to synchronize between the physical and virtual worlds. AR applications for AEC are hardware and software-intensive to enable a smooth interaction between a user and a robot. In order to track human interaction, the user must be equipped with devices such as sensors and trackers. Trackers register human interaction, while a computational setup translates this human interaction into valid input for the robotic setup. The selection of appropriate tracking systems depends on the task and the level of information a user wants to transmit. The level of information ranges from low-level user input to complex user interactions. Complex user interactions, such as robotic toolpaths, stylistic inputs, and design adjustments, require a more sophisticated tracking system. Users can interact intuitively with a robot on a multi-modal level, including visual, acoustic, gestural, and motion-based interaction cues. Especially for embodied interaction, these trackers and interfaces should be as unobtrusive as possible. Research projects such as Sprayable User Interfaces by Wessely et al. [9] and ObjectSkin by Groeger et al. [10] show the potential of user interface systems with which humans can interact naturally instead of using conventional methods such as CLI (command line interface) or GUI. Advances in tracking technology produce increasingly smaller sensing devices [11], sometimes so ubiquitous that the user cannot even notice them. In such systems, the user might perceive the sensor as an extension of their own body, which means using the tool requires no additional mental force and the interaction feels natural and easily predictable.

> **Design-synthesizer and "workmanship of synthesis" support interpersonal human-computer interactions while allowing for uncertainty and risk.**

Besides sensors and trackers, AR hardware includes a visualization feedback medium. This medium can be placed on the user's body (head-mounted display, phone-based AR), on the robot, or in the environment (projection-based AR). Projection-based AR can augment the environment around the robotic fabrication, whereas handheld and head-mounted displays allow for a more mobile augmentation. Furthermore, the AR application must include a computational pipeline, enabling a feedback-based interactive algorithmic system to synchronize the digital and physical model. This design system enables a user to interactively engage with an artifact in-situ, instruct a robot by demonstration, or collaborate in a virtual design realm. Our work with IRoP combines an interactive design system with a projection-based AR setup [12]. The system enables users to engage intuitively with an in-situ robotic plastering process using the user's hand movements to program intricate robotic spray paths. The system capitalizes on the embodied knowledge of designers and skilled workers. Users can design complex digital models in minutes and preview them on-site on a 1:1 scale via a projection-based AR system. The user's interactions are tracked with a motion capturing system and remapped using an interactive computational model. The model translates user input into robotic trajectories and parameters using design and editing tools and an audio-visual guidance system. The fabrication setup consists of a robotic plaster spraying system. The user and the robotic arm are situated next to each other, where the 3D design is first interactively designed and then fabricated. Such collaborative systems leverage the unique strengths of machine precision and tacit human knowledge, combining robotic and digital fabrication with the aesthetic and technical potential of human-in-the-loop manufacturing. IRoP focuses on the advantages of projection-based AR for on-site robotic fabrication with the user co-located to the fabrication system. The combination of AR hardware and software in IRoP, such as a motion-capturing system, projection-based AR system, and an interactive computational setup, creates a digitally enhanced environment enabling users to understand and control feedback loops. A digitally enhanced environment is required to instantiate different configurations between the physical body of the human and the robot in a shared digital-physical workspace.

Such balanced, collaborative human-machine systems do not aim to replace current computational and robotic fabrication processes but rather aim to extend them.

In this shared digital workspace, humans are informed by digital spatial data, and robots are programmed by user interactions. A shared digital-physical workspace augments the user and extends the machine as it extends the natural structure of both human and machine synthetically. This extension supports the transfer of information and the registration, translation, and communication of data. Interfaces visualize this data to the user in a simplified way, ensuring that complexity resides within the task, not the tool's operation. Developing user interfaces for fabrication requires a thorough study of the right user group, e.g., a bricklayer, a plasterer, or a carpenter. This user study allows the designer to implement existing tacit knowledge of the craftsperson into a craft-specific user interface to enable an intuitive interaction between the craftsperson and the machine. By that, the craftsperson finds familiar motion sequences and instructions. Interaction, therefore, becomes faster and more intuitive, while at the same time, existing tacit knowledge is integrated into the digital world, enabling a more intuitive human-robot interaction.

INTERACTIVE DESIGN REALM: THE OVERLAP OF DESIGN AND FABRICATION

AR enables such human-robot interaction and offers the potential to overlap the fabrication realm with the design realm. Design is a complex cognitive process that involves creative skills, artistic intuitions, and a rich repertory of experience and knowledge. When designing, a user achieves a specific aim while compromising on a set of constraints and limitations. Mitchell describes the act of designing as an exploration of possibilities instead of a predefined outcome [13]. In traditional design practices, such as sculpture, painting, and craftsmanship, the user involves cognitive skills and the rich sensory information gathered in the user's body. Professional skill, in these cases, is, therefore, a combination of tacit and embodied knowledge and symbolic cognition. Symbolic cognition enables the understanding of abstract concepts while embodied

Figure 2. ERC system connecting geographically separated users via a collaborative virtual environment

cognition describes tacit knowledge through the dynamic connections between brain, body, and world. Computerization can often inhibit tacit knowledge even though embodied knowledge and physical action are often faster and more nuanced than symbolic cognition. Furthermore, even though bodies are the principal organ of expression in most creative disciplines, they are seldomly explored in computer systems. Digital embodiment defines the integration of bodily actions and activity within digital environments and offers users faster and richer interaction paradigms. Augmented and extended reality systems are profound human-machine interaction tools supporting digital embodiment and enhancing individual corporeality. This process of corporeality through extended reality is sustained through the combination of haptic and visual interfaces. Visual and manual tacit knowledge is essential if we work with interactive design, which overlaps and weaves the design space with the fabrication realm. Traditionally, design and fabrication space are geographically and temporarily separated, leading to conventional design strategies constituted by linear workflows with straightforward task sets. Interactive design, in contrast, allows the user to change and adapt the design model on-site during fabrication [14, 15]. This design strategy enables humans to intervene creatively in the fabrication process, offering novel design-to-fabrication workflows within human-machine interaction systems. In such systems, the artifact becomes part of the digital design process and key component to cooperate and collaborate with other users and machines. Furthermore, real-time feedback directly informs the design. For this, the user needs to be informed about potential machine, structural, or material limitations and failure. AR is an excellent method to provide this information and bringing together the physical embodied input of the user with the physical robotically fabricated output. The key for this are AR and extended reality interfaces that support real-time interaction and fabrication and digitally enhanced environments. Combined with an interactive computational model, these systems enable interactive design with fabrication and machine-informed modeling. Such systems inform the user in real-time about the constraints of the current design realm and its boundary conditions. This computational logic introduces the concept of "real-time" into architectural design, making human physical or teleoperated presence a critical part of the digital fabrication setup.

Robotic fabrication combined with AR can enable human-in-the-loop fabrication, splitting fabrication tasks between the human user and the robotic unit.

Such balanced, collaborative human-machine systems do not aim to replace current computational and robotic fabrication processes but rather aim to extend them. In the British Arts and Crafts movement, the architects Hermann Muthesius and Frank Lloyd Wright believed the opposition between craft and factory production was imaginary and the artist should work with the machine, not against it. In David Pye's *The Nature and Art of Workmanship*, the author offers two concepts of craft and workmanship [16]. According to Pye, machines produce a "workmanship of certainty" where the quality and aesthetic outcomes of an artifact are already predefined before the production starts. Processes of certainty can increase productivity because the dexterity and care required to form the product are reduced. In comparison, a craftsperson produces a "workmanship of risk," where the quality of an outcome still depends on the maker's judgment, decisions, and care during the process, even though machines and devices are used. The client can read multiple layers of information on the piece, similar to a cartography of events during fabrication. The craftsperson might have been tired, inspired, excited, or distracted for a short amount of time during fabrication and resultantly, what should be a perfectly straight line might have a shake, or a collection of patterns is surprisingly but beautifully arranged. To find a balance between certainty and risk, the craftsperson can be equipped with computational tools that regulate human input within specific quality standards while still allowing them to apply decisions during manufacturing [17].

The first commercially available tool that integrated the logic of translating analog human input into controlled output with a set of logical rules and an interactive interface was the synthesizer. One of the earliest and most famous synthesizers was developed by Robert Moog. It pioneered analog synthesizer concepts such as voltage-controlled oscillators, envelopes, noise generators, filters, and sequences by generating audio signals through the manipulation of input data. The synthesizer is therefore a great example of creative human-machine collaboration with design constraints. The user becomes an expert musician, a craftsperson for sound, by learning on how to control and interact with the machine mechanisms, rather than pure finger training. This composition and combination of human and machinic qualities lead to a "workmanship of synthesis," where the quality of the outcome still depends on the maker's judgment but is remapped within machine and material constraints. Translated to computation and digital fabrication such design-synthesizers allow users to make decisions during production while enabling productivity increase. Furthermore, design-synthesizer and "workmanship of synthesis" support interpersonal human-computer interactions while allowing for uncertainty and risk concerning the physical copresence of humans and robots.

These design-synthesizers shift the focus from the final product to the process of making, redefining the notion of site and user-specific design. AR systems enable such a "workmanship of synthesis" as the user can un-

A shared digital-physical workspace augments the user and extends the machine as it extends the natural structure of both human and machine synthetically.

derstand and predict complex interaction patterns on-site and on a real scale. It highlights that the emergence of extended reality systems could help define the notion and role of humans in the digital and robotic fabrication realm supporting a corporeal example of designing with risk in mind. Naturally, extended reality systems do not only support co-located users and machines but can bridge two geographically separated entities.

The advantages of extended reality systems between two geographically separated users are shown in the research "ERC: Extended reality collaboration" [18]. ERC focuses on the advantages of mixed reality systems for collaborative design activities such as design negotiation, task specification, and interaction between two distinct users.

Collaborative design activities in the field of AEC can involve many different users with diverse backgrounds and knowledge, ranging from on-site users to off-site stakeholders. Especially between two geographically distinct users, knowledge transfer is crucial. Current CAD software is perfect for distinct and asynchronous tasks without extensive synchronous collaboration and communication between users. These platforms are relatively task-specific and rigid, and do not provide an environment that fosters an immersive communication platform between users. This lack of computer-supported cooperative work systems can cause user frustration and inhibit creativity and knowledge transfer. ERC extends and complements the functionalities of existing collaborative virtual environment systems by providing functionalities that enable bidirectional communication between on-site and off-site users. Both users can access a shared digital twin of a construction site which functions as a collaborative virtual environment. This research focused on two distinct fields: a collaborative virtual environment in AEC and augmented fabrication defining collaboration protocols and improving interaction and communication workflows. Currently, ERC involves two human users but can easily extend and include a machine or a robot.

ERC and the previously introduced IRoP both offer a plethora of technological and aesthetical advantages of mixed reality systems concerning human-in-the-loop processes. They show potential benefits of "workmanship of synthesis" through design-synthesizer. These potentials include higher autonomy, increased social sustainability, improved supervision, and collaboration between co-located and geographically separated stakeholders. Furthermore, the researches show how mixed reality systems can assist in digitally embodied design workflows. Especially in unstructured work environments, such systems could provide an answer to several technical, social, and economic barriers that hinder the adoption and integration of robotized building construction and automation. Hybridized and dually augmented human-robot collaborative systems could form a paradigm shift in the field of AEC, combining machine capacities with the participatory engagement of builders and fabricators.

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Biography

Daniela Mitterberger is an architect and researcher with a strong interest in new media and the relationship between humans and machines in digital manufacturing and emerging technologies. Mitterberger is a Ph.D. researcher at ETH Zürich, focusing on augmented/mixed reality and human-machine collaborative processes in digital design and robotic fabrication. She is also a researcher at the University of Applied Arts and co-leader of the FWF PEEK project titled "Co-corporeality."