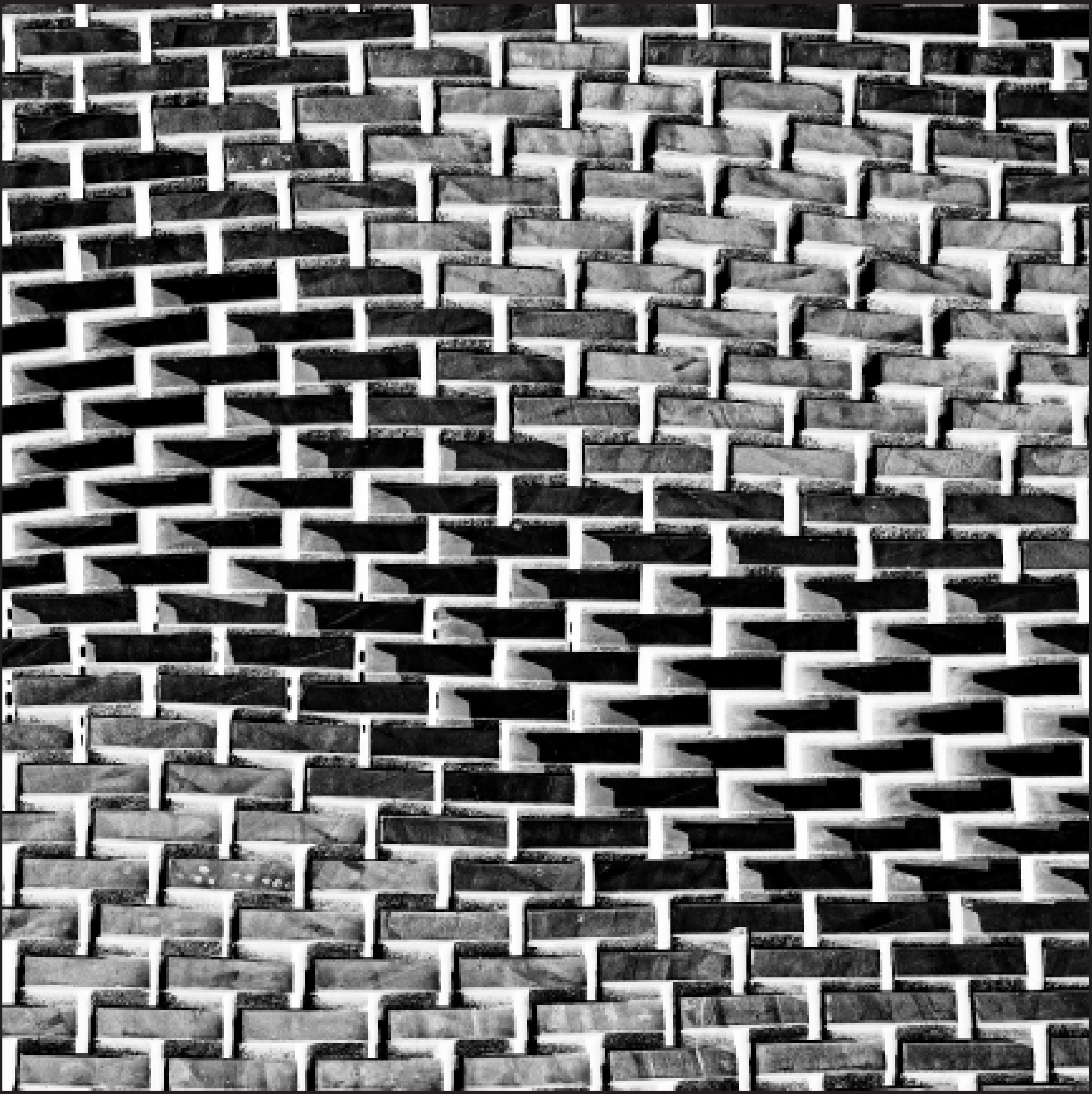


Augmented Human & Extended Machine:

Adaptive Digital Fabrication and Human-machine Collaboration for Architecture

by Daniela Mitterberger

DISS. ETH NO. 29197

DISS. ETH NO. 29197

Augmented Human and Extended Machine:

Adaptive Digital Fabrication and Human-machine Collaboration for Architecture

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES
(Dr. sc. ETH Zurich)

presented by

DANIELA MITTERBERGER

Master of Architecture (MArch), Academy of Fine Arts Vienna

born on *09.10.1988*

accepted on the recommendation of

Prof. Matthias Kohler
Prof. Fabio Gramazio
Prof. Dr Kathrin Dörfler
Prof. Dr Patrick Baudisch
Prof. Dr Christopher Lloyd Salter

2023

Augmented Human and Extended Machine:

Adaptive Digital Fabrication and Human-machine Collaboration for Architecture

"The final goal should not be an automatic surgery machine, but a machine with the capability to help a surgeon as a skilled assistant."

Ejiri, Masakazu (1996)

Abstract

This research aims to establish adaptive digital fabrication processes that include human-machine collaboration in digital fabrication. In the past two decades, digital fabrication in architecture engineering and construction (AEC) has significantly advanced, enabling more complex, customised, and precise fabrication results. Even though most digital fabrication processes aim for full automation, they still require human participation for either material deposition, quality control, or finishing. While humans are still needed, current digital fabrication processes are not adaptive enough to include humans in the digital control logic. This inflexibility limits the robustness and autonomy of digital fabrication and its applicability in areas that are more difficult to automate, such as on-site fabrication or fabrication with more complex material systems.

Therefore, this doctoral research aims to include human actions and decision-making in digital fabrication processes. This combination of human tacit knowledge and dexterity with the precision and endurance of machines has the potential to increase the productivity, adaptability and robustness of digital fabrication. To facilitate human-machine collaboration, this research establishes more adaptive digital fabrication processes, linking digital models with physical fabrication environments. For this, digital twins are developed to efficiently control and capture data from the entire fabrication process and all its components. These digital twins are linked with extended-reality interfaces, actuators and tracking systems to inform and track humans and machines during fabrication. The research results are obtained through physical experiments and four proof-of-concept case studies investigating various aspects of human-machine collaboration in architecture and digital fabrication. By solving practical and methodological challenges, this research demonstrates how human-machine collaboration supports a faster and more sustainable integration of digital fabrication in AEC. Furthermore, this thesis illustrates the aesthetic and technological benefits of such collaborative systems, as well as their potential to expand our repertoire of digital fabrication workflows.

Keywords human-machine collaboration, extended reality, digital fabrication, computational design, robotic fabrication, feedback-based manufacturing, interactive fabrication

Zusammenfassung

Ziel dieser Forschungsarbeit ist die Entwicklung adaptiver digitaler Fertigungsprozesse, die die Zusammenarbeit zwischen Mensch und Maschine bei der digitalen Fertigung ermöglichen. In den letzten zwei Jahrzehnten hat sich die digitale Fertigung im Bereich Architektur, Ingenieurwesen und Bauwesen (AEC) erheblich weiterentwickelt und ermöglicht immer komplexere, individuellere und präzisere Fertigungsergebnisse. Auch wenn die meisten digitalen Fertigungsprozesse auf eine vollständige Automatisierung abzielen, ist immer noch die Mitwirkung des Menschen erforderlich, sei es bei der Materialaufbringung, der Qualitätskontrolle oder der Verarbeitung. Der Mensch wird zwar immer noch gebraucht, aber die derzeitigen digitalen Fertigungsverfahren sind nicht anpassungsfähig genug, um den Menschen in die digitale Steuerlogik einzubeziehen. Diese Unflexibilität schränkt die Robustheit und Autonomie der digitalen Fertigung und ihre Anwendbarkeit in Bereichen ein, die schwieriger zu automatisieren sind, wie die Fertigung vor Ort oder die Fertigung mit komplexeren Materialsystemen. Daher zielt diese Doktorarbeit darauf ab, menschliche Handlungen und Entscheidungen in digitale Fertigungsprozesse einzubeziehen. Diese Kombination von menschlichem Wissen und Geschicklichkeit mit der Präzision und Ausdauer von Maschinen hat das Potenzial, die Produktivität, Anpassungsfähigkeit und Robustheit der digitalen Fertigung zu erhöhen. Um diese Zusammenarbeit zwischen Mensch und Maschine zu erleichtern, werden im Rahmen dieser Forschungsarbeit anpassungsfähigere digitale Fertigungsprozesse entwickelt, die digitale Modelle mit physischen Fertigungsumgebungen verknüpfen. Zu diesem Zweck werden digitale Zwillinge entwickelt, um den gesamten Fertigungsprozess und alle seine Komponenten effizient zu steuern und Daten zu erfassen. Diese digitalen Zwillinge werden mit Mixed-Reality-Schnittstellen, Actuation und Tracking-Systemen verbunden, um Menschen und Maschinen während der Fertigung zu informieren und zu verfolgen. Die Forschungsergebnisse werden durch physikalische Experimente und vier Proof-of-Concept-Fallstudien erzielt, die verschiedene Aspekte der Mensch-Maschine-Zusammenarbeit in der Architektur und der digitalen Fertigung untersuchen. Durch die Lösung praktischer und methodischer Herausforderungen zeigt diese Arbeit, wie die Mensch-Maschine-Kollaboration eine schnellere und nachhaltigere Integration der digitalen Fertigung in der AEC ermöglicht. Darüber hinaus veranschaulicht diese Arbeit die ästhetischen und technologischen Vorteile solcher kollaborativen Systeme sowie ihr Potenzial, unser Repertoire an digitalen Fabrikationssystemen zu erweitern.

Keywords Mensch-Maschinen Kollaboration, erweiterte Realität, digitale Fertigung, computergestütztes Design, Roboterfertigung, feedback-basierte Fertigung, interaktive Fertigung

Contents

Abstract **iv**

Zusammenfassung **v**

Acknowledgements **vi**

Contents **viii**

1 Introduction **3**

1.1 Motivation . . . 3
1.2 Background . . . 8
1.2.1 Capabilities of humans and machines . . . 8
1.2.2 Human augmentation: the cyborg . . . 9
1.2.3 Machine extension: the synthesiser . . . 11
1.2.4 Aesthetic advantages of hybrid human-machine fabrication . . . 12
1.2.5 Technical advantages of human-machine feedback loops . . . 14
1.3 State of the Art . . . 16
1.3.1 Human as actuator: machine-assisted human fabrication . . . 16
1.3.2 Machine as actuator: human-instructed machine fabrication . . . 18
1.4 Problem statement . . . 21
1.5 Research questions . . . 23
1.6 Research objectives . . . 24
1.7 Structure of the dissertation . . . 25

2 Methodology **29**

2.1 Process digital twins . . . 31
2.2 Visual feedback systems . . . 31
2.3 Cooperative building workflows . . . 31
2.4 Interaction modalities . . . 32

3 Case studies **35**

3.1 Machine-assisted human fabrication . . . 39
3.1.1 Summary and contribution to thesis . . . 39
3.1.2 Paper A . . . 41
3.1.3 Credits and acknowledgments . . . 54
3.2 Human-instructed machine fabrication . . . 61
3.2.1 Summary and contribution to thesis . . . 61
3.2.2 Paper B . . . 63
3.2.3 Credits and acknowledgments . . . 89

3.3 Human-robot cooperation 95
3.3.1 Summary and contribution to thesis 95
3.3.2 Paper C 97
3.3.3 Credits and acknowledgments 115
3.4 Teleoperated human-human collaboration 121
3.4.1 Summary and contribution to thesis 121
3.4.2 Paper D 123
3.4.3 Credits and acknowledgments 133

4 Conclusion **137**
4.1 Summary 137
4.1.1 Summary of experiments 137
4.1.2 Summary of used visual augmentation systems 138
4.2 Contribution 140
4.2.1 Hybridising traditional craft with digital fabrication 140
4.2.2 Integration of human actions into process digital twins 141
4.2.3 Interactive computational models 142
4.2.4 Contribution of human-machine collaboration to architecture 142
4.3 Outlook 144
4.3.1 Tracking of humans, machines and objects 144
4.3.2 Augmented reality for process and machine parameters 144
4.3.3 Human-machine collaboration for larger-scale architectural implementation 146

Appendix **149**

A Human-machine setups **151**

B Degrees of Life **157**
B.1 Human-bacteria interaction in architectural space 157

C AR Bricklaying User Study **167**
C.1 Introduction 167
C.2 Method 168
C.2.1 Evaluation 169
C.3 Study 1 - Visualisation platform - procedure 169
C.3.1 Results 170
C.4 Study 2 - Learning curve 173
C.4.1 Results 173
C.4.2 Answers to the original questions 175
C.5 Conclusion 176

Bibliography **177**

List of Terms **195**

List of Figures **198**

List of Tables **202**


SIEMENS

Introduction | 1

1.1 Motivation

In the past two decades, digital fabrication in architecture, engineering and construction (AEC) has made significant advancements, introducing a variety of new design and fabrication opportunities for more complex, customised, and precise fabrication results [1–5]. Digital fabrication processes include, amongst others, complex timber construction [6], concrete 3D printing [7, 8], and autonomous brick assembly [9]. Most of these processes aim for full automation and require well-defined linear sequences of actions where the work environment, materials, and procedures are structured, unambiguous and predictable. Although these prerequisites are sometimes present, full automation does not fit every architectural fabrication procedure. Moreover, in many cases, full automation is neither economically nor technically feasible as it would require huge amounts of resources and research.

Examples of fabrication processes that are difficult to automate involve, for instance, complex material systems, such as plaster, mortar or clay. Complex materials are difficult to automate because their malleability is challenging to predict and simulate. The state of these materials changes from liquid to solid throughout the fabrication process depending on ambient temperature, material composition, and handling. Even with the most advanced digital modelling software, it is challenging to simulate and predict such a behaviour [10, 11]. Another example of a fabrication process that is hard to automate is on-site fabrication. Construction sites are dusty, noisy, subject to wind and weather and are unstructured. Building sites require constant human attention, even while using construction software, as the as-built state is often not sufficiently synchronised with the digital model. An example of the unstructured nature of construction sites is the constant relocation of building materials and construction workers by multiple contractors. Depending on the state of the construction, workers and materials are often relocated without a synchronised digital model.

Therefore, fabrication processes involving complex material systems and on-site fabrication require a digital fabrication workflow that offers flexibility for these unknown parameters. Current digital fabrication processes are not adaptive enough to facilitate such variable tolerances as they require global and precise measurements, and any deviation from the preprogrammed setup could lead to failure. Humans, unlike machines, can easily incorporate variable tolerances due to their efficient and intuitive context awareness. They can adapt a fabrication process on-the-fly to include process changes or material deviations. Even though we recognise these advantages of human skill, digital fabrication processes often lack the adaptability to include humans in the control logic of digital processes even if they foresee or detect machine or material failures ahead of time. Therefore, one possible solution to facilitate digital fabrication for complex fabrication processes is to combine human skill and knowledge with machine capabilities. These collaborative human-machine workflows have the potential to leverage the distinct strengths of human cognitive abilities, tacit knowledge, and dexterity with the precision, efficiency, and speed of machines. The combination can increase the robustness and autonomy of digital fabrication processes and, with that, facilitate broader adoption of digital fabrication [12].

Such human-machine collaboration (HMC) offers a variety of technical, aesthetic and economic advantages, advocating greater social sustainability in digital fabrication processes. These advantages are strongly linked to the physical participation of humans during construction. Research, especially in the field of human-computer interaction (HCI), focuses on the importance of physical participation during fabrication seen in processes such as interactive fabrication [13, 14] and digital embodiment [15], linking the physical action and cognition with the design process [16, 17]. These concepts emphasise that the direct engagement of architects and craftspeople with the prototype can be a cognitive resource throughout the process [18]. Moreover, human participation in digital fabrication can further promote social sustainability, as craftspeople do not only act as supervisors but also participate in value creation and production planning and are involved as decision-makers and specialists [19]. These new tasks for humans in digital fabrication bring an upgrading of qualifications [20] that could reduce the division of labour and address labour shortages. It could create a work organisation structure characterised by high flexibility and structural openness, supporting a more socially sustainable adoption of robotic technologies [21]. The technical advantages of human-machine collaboration include increased productivity and adaptability, as the qualities of manual fabrication are merged with those of machine production. The economic advantages are related to the wider adoption of digital fabrication processes in AEC. Full automation carries exponentially high costs and requires a significant investment of resources and research, which makes full automation often not economically viable.

Successful HMC systems can be found in other disciplines, such as medical robotics. The *Da Vinci Surgical System* [22] is designed to facilitate complex operations using a minimally invasive approach. The robotic surgery is controlled and navigated by a surgeon that uses a console to handle three to four interactive robotic arms equipped with scalpels or scissors. The skills of the trained surgeon are transferred to the robotic arm, which enhances the surgeon's dexterity and intuition with precision and camera vision. Masakazu Ejiri, a pioneer of early robotics at the Hitachi Laboratory in Japan, describes this vision of the future of robotics as follows:

"*The final goal should not be an automatic surgery machine, but a machine with the capability to help a surgeon as a skilled assistant*" [23].

Even though the *Da Vinci Surgical System* is an excellent example of HMC, it is still not a truly complementary workflow. For it to be considered truly complementary [24], the robot must have the ability to make autonomous decisions, adapt to changing conditions, and still allow for human intervention when necessary. Currently, the system's technology and capabilities do not allow for this level of integration.

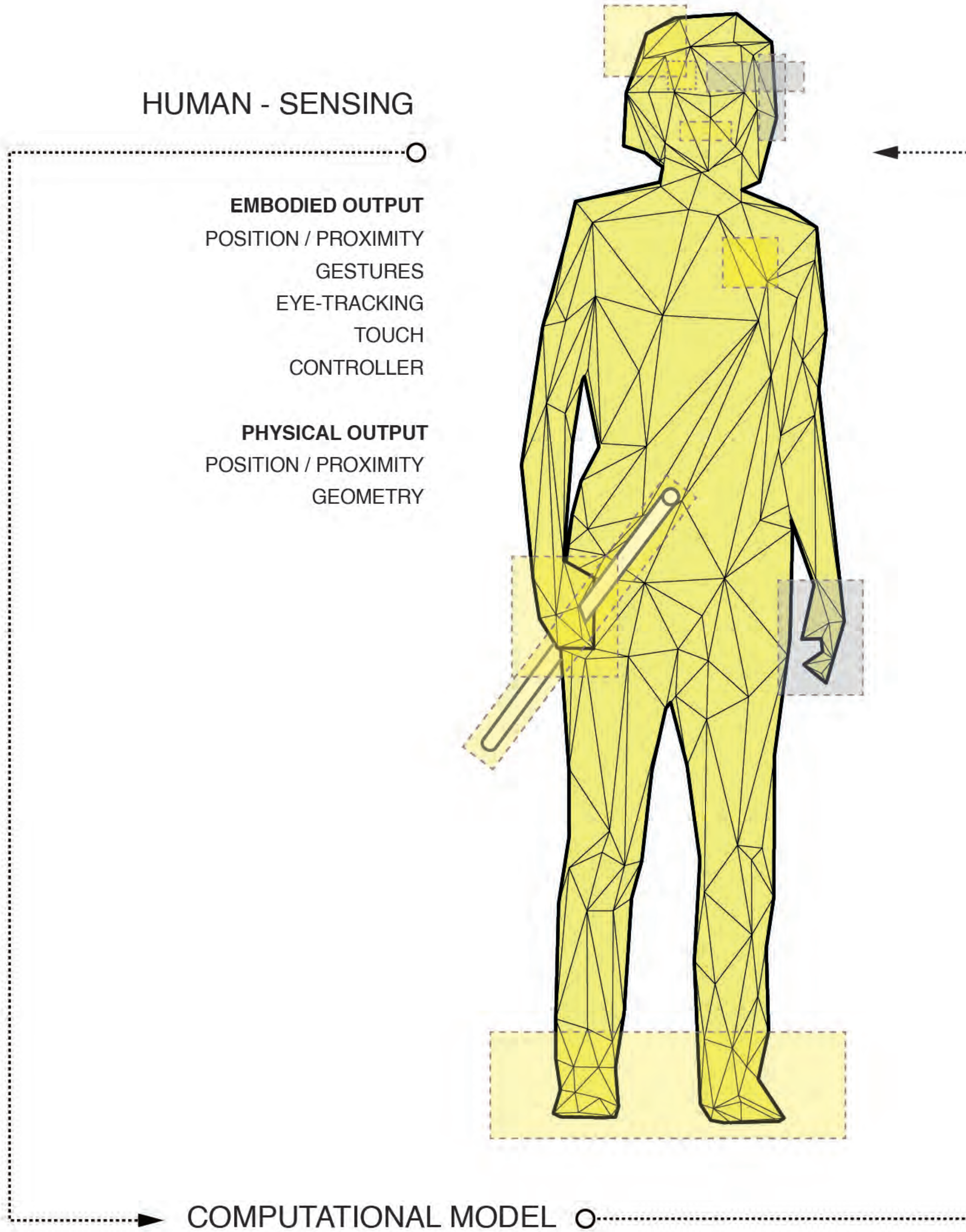
There are several valuable lessons to be learned from the *Da Vinci Surgical System* when it comes to HMC in architecture, such as the significance of real-time feedback and procedure-specific visual or haptic interfaces. It is a good example of how HMC helps minimise human error by automating repetitive or difficult tasks and allows humans to focus on more creative and strategic tasks. Compared to surgical robotics, digital fabrication faces domain-specific challenges that require specific HMC scenarios. These challenges are related to the requirements of the different craft applications and their needed precision, as well as the economy and scale of AEC. An example of such a domain-specific requirement is the human-to-machine ratio. The *Da Vinci Surgical System* operates with a 1:1 ratio of human to machine, which is suitable for surgeries but not ideal for AEC. In AEC, a system that links one human with multiple machines would be more beneficial, as it would increase efficiency and productivity. Another domain-specific requirement for on-site fabrication is the sheer scale of building sites. To cover such a large scale, the HMC setup needs to either be mobile or the machine must have a large workspace or reach.

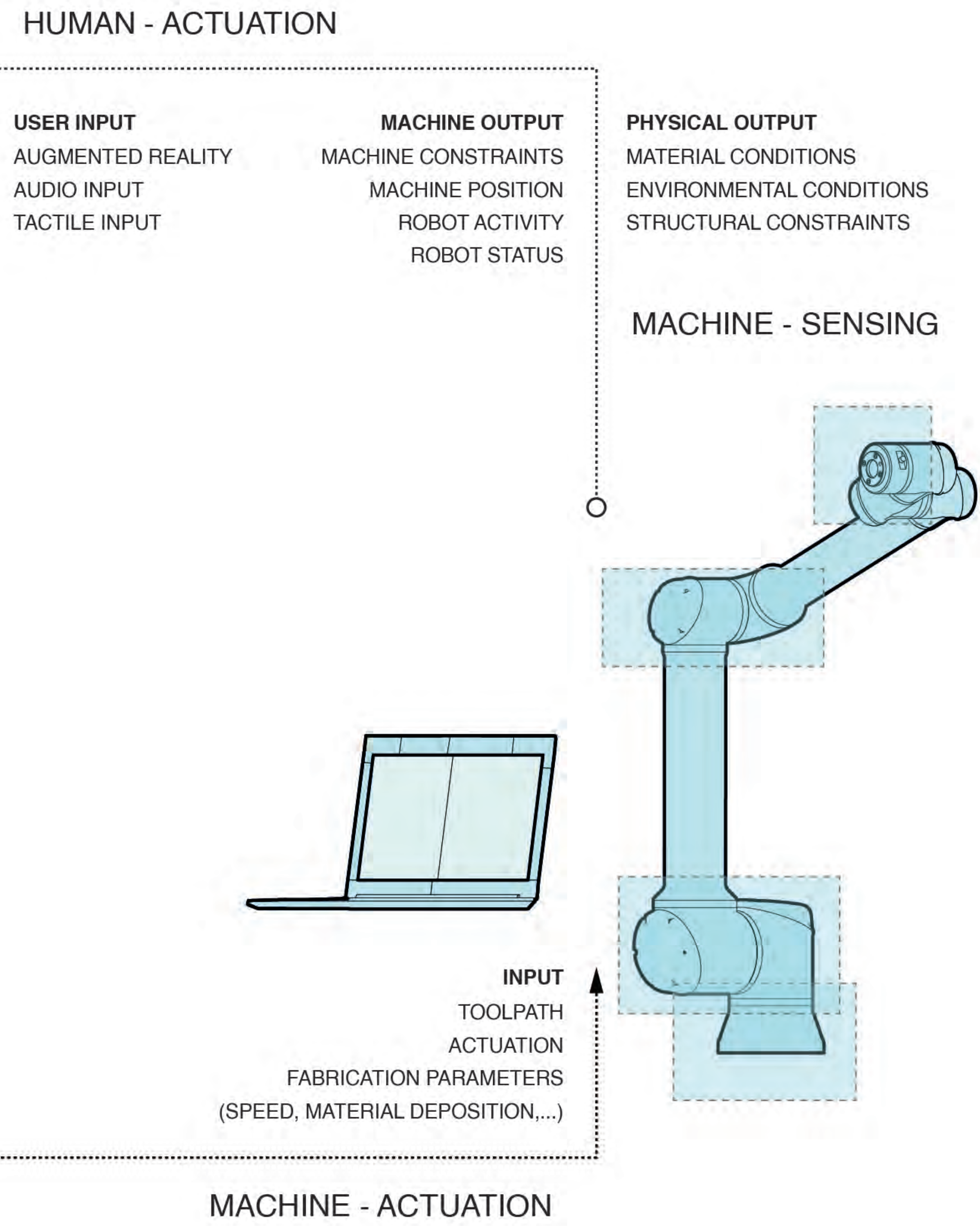
Besides all the advantages that HMC brings, research in this field is still in its infancy, impeding a wider adoption and integration of digital and robotic fabrication into AEC.

Therefore, this research addresses this opportunity by examining how to leverage the development of cooperative and semi-autonomous digital fabrication processes exploring the added value of human actions and decision-making in digital fabrication. This research focuses on hybridising traditional manual workflows with digital fabrication and developing a balanced human-machine collaboration system for digital design-to-production workflows. This thesis presents adaptive digital fabrication processes capable of handling unforeseen events and changing parameters to include human actions in digital fabrication. Such adaptive processes consist of a digital-physical environment in which robots and humans can operate together at the same time. These digital-physical environments aim to facilitate seamless communication and data exchange between humans and machines, enabling them to cooperate on building tasks. These digital-physical environments use digital twins to synchronise the digital with the physical reality, incorporating the entire manufacturing process. Further, the digital twin is linked with extended reality (XR)[1] interfaces that inform humans about design and fabrication-related boundary conditions. Depending on the specific fabrication scenario, different actuators – the humans or the robots – can be instructed by these digital twins. A tracking system coupled with these digital twins registers human actions and includes them in the digital model.

Throughout this doctoral research, methods to build this adaptive digital fabrication process are tested, challenged, and evaluated. The research results are obtained through physical experiments and four proof-of-concept case studies. The case studies investigate how otherwise impossible tasks can be accomplished through the combination of human cognitive abilities, dexterity, and tacit knowledge with the precision and efficiency of machine agents. All case studies explore different fabrication scenarios, in which either the human (Paper A, Paper D), the machine (Paper B), or both, human and machine, (Paper C) are the actuators. Furthermore, this thesis explores HMC for on-site (Paper A, Paper B, Paper C) and remote collaboration (Paper D).

[1] Extended reality is an overarching term to refer to augmented reality (AR), mixed reality (MR) and virtual reality (VR). The technology is intended to combine or mirror the physical world with a "digital twin world" that is able to interact with each other.


HUMAN - SENSING
EMBODIED OUTPUT
POSITION / PROXIMITY
GESTURES
EYE-TRACKING
TOUCH
CONTROLLER
PHYSICAL OUTPUT
POSITION / PROXIMITY
GEOMETRY
COMPUTATIONAL MODEL


HUMAN - ACTUATION
USER INPUT
AUGMENTED REALITY
AUDIO INPUT
TACTILE INPUT
MACHINE OUTPUT
MACHINE CONSTRAINTS
MACHINE POSITION
ROBOT ACTIVITY
ROBOT STATUS
PHYSICAL OUTPUT
MATERIAL CONDITIONS
ENVIRONMENTAL CONDITIONS
STRUCTURAL CONSTRAINTS
MACHINE - SENSING
INPUT
TOOLPATH
ACTUATION
FABRICATION PARAMETERS
(SPEED, MATERIAL DEPOSITION,...)
MACHINE - ACTUATION

1.2 Background

The scope of this section is to investigate the unique qualities of humans and machines and related theoretical and technical concepts. Concepts such as cyborgs and synthesisers are introduced, as this research employs humans as well as machines as fabricating agents. The section on cyborgs (see 1.2.2) describes how human actions can be instructed, guided or disrupted through machine input and corporeal augmentation. The section on synthesisers (see 1.2.3) describes a workflow in which machines are instructed by analogue human input. This section is followed by the aesthetic advantages of human-machine collaboration and the technical advantages of adaptive digital fabrication.

1.2.1 Capabilities of humans and machines

To create intelligent and viable collaborative human-machine processes, tasks must be distributed according to the capabilities of each agent - human and machine (Fig. 1.1, Fig. 1.2). In this, it is essential to understand what makes each agent unique based on physical and cognitive skills [25].

Cognitive skills can be split into two complementary systems, explicit and tacit knowledge [26]. Explicit knowledge is used for codified information, such as mathematical operations, calculation processes, or precise measurement procedures. It is objective, follows logical reasoning and rules and can be easily communicated and transferred. Furthermore, it can be recorded and stored in physical and electronic form to be shared with others. Tacit knowledge is a skill, idea, or creativity developed over time through experience and is hard to verbalise and share [27]. It includes activities such as riding a bike, cooking, or crafts and often requires one-to-one interaction and teaching. Tacit knowledge continuously looks for cause and effect, focusing on complex pattern recognition. Explicit knowledge is effortful for humans but easy to transfer to machines as it follows a rule-based logic. In contrast, tacit knowledge, effortless for humans, is challenging to store and translate to machines. Humans can acquire explicit knowledge but are more efficient at intuitive and context-based cognitive processes.

In addition to accessing knowledge, humans and machines also perceive and sense the environment differently. Machines use data collected through their sensors to perceive the environment. Humans acquire knowledge through their environment using tacit and embodied cognition, emphasising the importance of an agent's physical body in perceiving the environment [28–31]. The psychologist James Gibson [32] describes embodied cognition as *"the sensibility of the individual to the world adjacent to his body by the use of his body"*. Gibson thus emphasises that not all cognitive processes are purely logical, but that metabolic sensory and motor system are fundamentally integrated into cognitive processing.

The physical skills of humans include dexterity and manual skill, enabling intricate and delicate movements. The human body is flexible, and it can access hard-to-reach places and utilise multiple tools. In addition, humans can intuitively change their physical interaction in response to material behaviour and adjust the pressure and angle of tools accordingly. On the other hand, machines can produce tirelessly, repeat movements with millimetre precision and lift heavy loads. However, the reach of machines, and especially robots, is limited to their working area, position and orientation (pose) and also depends on the robot's

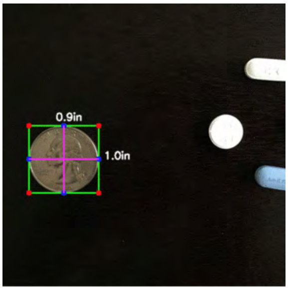
(a) Embodied cognition: humans adapt designs according to material behavior © royalzig [33]

(b) Tacit knowledge: humans work with malleable materials such as clay © Shimizu Genji [34]

(c) Dexterity: humans can produce intricate weaving patterns and geometries © Namita Kulkarni [35]

Figure 1.1: Examples of embodied cognition, tacit knowledge and dexterity of humans

(a) Reproducibility: Repetition of recorded motions © Giulio Brugnaro [36]



(b) Precision: Machine vision for object detection and size estimation © Adrian Rosebrock [37]

(c) Strength: Heavy and precise lifting of elements © Gramazio Kohler Research [38]

Figure 1.2: Examples of reproducibility, precision and physical strength of machines

tool (end-effector). In addition, motion planning to create collision-free paths in the robot's workspace requires a considerable amount of computing power.

To combine the cognitive and physical strengths of humans and machines in the best possible way, distinct human-machine feedback loops are necessary. In AEC, the design of these feedback loops closely aligns with the requirements of fabrication tasks and determines whether the human, the machine, or both predominately fabricate as actuators in a construction process. Successful implementations of these collaborative human-machine processes require the development of human augmentation and machine extension systems.

1.2.2 Human augmentation: the cyborg

Physical and cognitive augmentation helps humans to perform physical or mental actions with the help of machines and devices that are integrated into our bodies and extend the limits of our natural abilities. Human augmentation is a constructed synthetic extension of the biological body [39]. The augmentation of the human body with machine elements is reminiscent of concepts described as a *cybernetic organism* by Manfred Clynes and Nathan S.

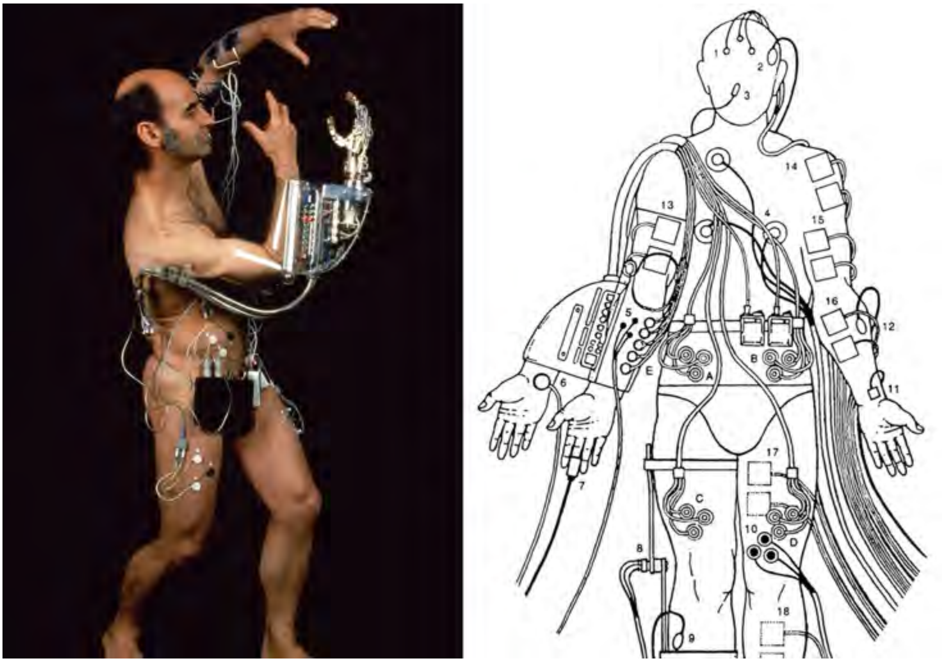


Figure 1.3: Stelarc's *Third Hand* is an art piece where electrical signals of other muscle groups, such as the abdominal and leg muscles, control the motions of the third artificial hand. © Simon Hunter

Kline in 1960 [40], which is an organism with both organic and biomechatronic body parts, whose functions have been improved due to the incorporation of artificial components and feedback-driven technology into its body. Shinya Tsukamoto describes such a cybernetic being in the 1989 cyberpunk thriller *Tetsuo*. Iron Man, the film's protagonist, depicts the body as a battlefield and a monster of flesh and metal in all its brutality. The film is obsessed with the seemingly opposing poles of human and machine, desire and pain, and biological and mechanical aesthetics [41].

In contemporary bio-art, the topic of human augmentation has been taken up by artists like Stelarc, whose work focuses on extending the human body's capabilities with robotics or other embodied technological devices. He looks at human augmentation in relation to the physical location of the machine. This machine can either be on, in, or around the human body. In his project, the *Third Hand* (1980), he attaches technology directly to the human body. In *The Stomach Sculpture* (1993), he inserts technology into the body. In Stellarc's performance in *Fractal Flesh* (1995), he connects the body to the internet and allows people to activate and control it remotely (Fig. 1.3). The artist defines it as a *"[..] displacing of motions from one net-connected physical body to another"* [42].

Marco Donnarumma investigates similar topics in his performance *CORPUS NIL* (2016), demonstrating how machines and intelligent algorithms could *"contaminate human bodily experience"* [43]. In this piece, the machine is attached directly to the human body and influences its movement, disrupting perception and motor skills. Research in this domain is not just part of the bio-art and sci-fi culture but can also be found in industry and as commercial products. An example of an early commercial visual augmentation is the *Google Glass* launched in 2012. This brand of smart glasses was sold and developed by *Google* with the mission of supporting ubiquitous computing [44]. It was one of the first AR[2] glasses available on the market, displayed information to the wearer using a heads-up display, and allowed interaction via voice commands. Current trends in AR and VR[3] hardware show that human visual and cognitive augmentation continues with devices such as *HoloLens*, *MagicLeap*, and *Meta Quest* that are sold hundreds of thousands of times since their launch. Other examples of commercial physical human augmentations are exoskeletons and prostheses, enabling humans to perform physically straining work while protecting their health.

1.2.3 Machine extension: the synthesiser

"These machines are responsive. They communicate. They're warm. They talk back." [45]

Combining analogue human input and machine output is a common practice in various creative disciplines, such as digital art and electronic music. This combination requires an act of translation from human input to data that a machine can process. Progressive and inspiring pioneers in electronic music, such as Luigi Russolo, John Cage, Karlheinz Stockhausen, and Wendy Carlos, show impressive examples of such acts of translation. An electronic example of such a process is the music and composition of Karlheinz Stockhausen. He introduced aleatory techniques[4] into serial composition[5]. A great example is his piece *Mikrophonie 1*, a piece for tam-tam[6], two microphones, two filters, and controllers, which consists of 33 unit pieces or moments. In *Mikrophonie 1*, two percussionists play the large tam-tam, while at the same time, another pair of musicians intuitively uses hand-held microphones to amplify subtle details and noises, inflecting the sound through quick motions. The last two performers, seated in the audience, apply resonant bandpass filters[7] to the microphone outputs and distribute the resulting sounds to a quadraphonic speaker system. This combination and set of logical rules and creative input creates truly unique pieces. Another example is the noise-generating device *Intonarumori* by the Italian futurist Luigi Russolo. With the *Intonarumori*, the musician's virtuosity shifted from finger technique to the art of selection, blending, and playing of noise sounds. Thus the focus also changes from the final musical product to the process of making music, as the device itself, the *Intonarumori*, becomes very much part of the produced sound piece. Even though the tool dramatically influences the final musical outcome, the authorship of the music piece still lies with the musician that plays the *Intonarumori*.

A commercially available product that uses analogue human input and machine output is the synthesiser. Wendy Carlos, an American musician and composer best known for her electronic music and film scores, helped develop the *Moog synthesiser* (Fig. 1.4). It was one of the earliest and most famous synthesisers created by Robert Moog. The synthesiser was the first commercially available tool that integrated the logic of translating analogue human input into controlled output with a set of logical rules and an interactive interface. This collaboration between the musician and the synthesiser led to a result in which the quality of the outcome

[2] Augmented reality is an interactive experience that overlays the physical world and computer-generated content.
[3] Virtual reality is an entirely simulated experience giving users an immersive feel of a virtual world.
[4] Aleatoric techniques are techniques that incorporate targeted randomness into the design process.
[5] Serial composition is a method of musical composition that uses a series of rhythms, pitches, dynamics, or other musical elements. An example of serialism is Arnold Schoenberg's twelve-tone technique. Schoenberg arranges the 12 notes of the chromatic scale in his twelve-tone technique into a series to form a unified basis for melody, harmony, structural progressions, and compositional variations.
[6] A tam-tam is a percussion instrument (flat gong) struck with a mallet covered with felt.
[7] Resonant bandpass filters pass frequencies in a specific range and attenuate other frequencies.

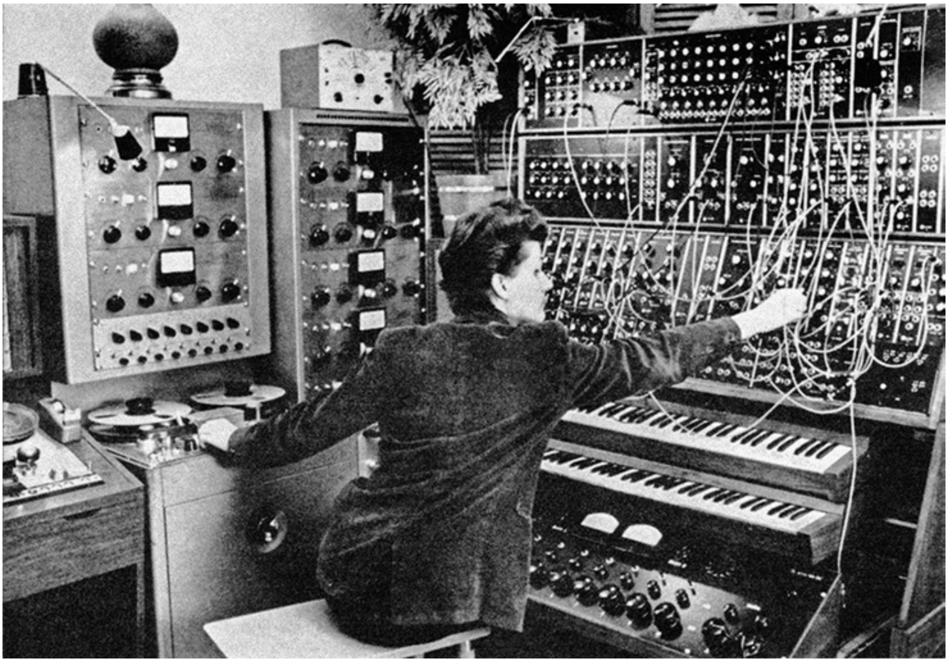


Figure 1.4: Wendy Carlos at her Moog Electronic Music Synthesiser (1969). Left is an 8-track recorder that tapes directly from the Synthesiser's output, and above the Synthesiser keyboards are the circuits, which can be interconnected to generate tones with desired qualities. [46]

still depended on the musician's judgment and actions, similar to the *Intonarumori*. At the same time, the musician's input was limited to fitting machine constraints. A vital component of the synthesiser is the user interface to manipulate input data. This interface can be multi-sensorial, ranging from eye-tracking [47], tactile [48] to gesture-based input [49].

Both concepts, cyborg and synthesiser, introduce different human-machine feedback loops and actuator systems. In the first example - the cyborg - the human is the actuator, and the machine assists. In the second example - the synthesiser - it is the reverse. The machine produces output as an actuator, and the human provides input. These concepts from bio-art, digital art, and electronic music are inspiring, and the field of architecture and digital fabrication can greatly benefit from their aesthetic and technical advantages.

1.2.4 Aesthetic advantages of hybrid human-machine fabrication

The goal of this thesis is to apply human-machine feedback loops, as described in the previous sections, to architectural design and fabrication. A balanced human-machine collaboration workflow aims to extend traditional workflows of digital fabrication and computational design. In the English Arts and Crafts Movement, the architect Hermann Muthesius and Frank Lloyd Wright strongly argued for the collaboration and interaction of humans and machines [50]. They believed that the opposition between craft and factory production was imaginary and that the artist should work with the machine, not against it. Instead of two competitors, machines should be conceived of as extensions of the craftsperson, a partner with whom humans work closely together [51]. Human-machine collaboration in AEC could promote such synergy, articulated through a combination of aesthetic attributes from human-made and machine-made fabrication methods.

Human-made in this context implies not only handcrafted pieces but also processes that are not fully automated and where the physical outcome still depends on the human craftsperson who controls and executes the fabrication.

Machine aesthetics are crucially different from the feel of human-made objects[8]. The accuracy of a machine and reproducibility of its products are essential advantages, entailing a saving of manual labour and time. For this purpose, the craftsperson programs a machine and sets all parameters, and the machine henceforth manufactures the same object repeatedly in mass production. Therefore, objects manufactured solely by machines exhibit the remarkable yet expected characteristics of the perfectly same identity, a precision that no human could reproduce by hand. This reproducibility ensures that no errors occur due to human inattention or clumsiness, but it also prevents creative surprises and discoveries during the production of the objects. In addition, mass production is not always suitable, especially in the construction industry, as objects may need to be adapted to individual building situations.

In *The Nature and Art of Workmanship*, David Pye offers two concepts to describe craft, industrial manufacturing and workmanship [52]: the *workmanship of risk* and the *workmanship of certainty*.

In *workmanship of certainty*, the quality and aesthetic of the outcome are already predefined before the production starts. By changing risk processes to certainty, machinery can increase productivity as the dexterity and care required to form the product are reduced.

In comparison, manual fabrication produces a *workmanship of risk*, where the quality of the outcome still depends on the maker's judgment, decisions, and care during the process, even when machines and devices are used. The intricate hand-carved caves of *Ellora* and the *Taj Mahal* are examples of the aesthetic qualities of the *workmanship of risk*, where the dexterity and craft of humans formed interlaced ornaments and details throughout the construction. Ra Paulette's bedecked caves are a contemporary example of handcrafted architecture, showcasing the carver's emotional expression through their intuitive carving style [53]. The intricate designs in the caves are not limited to just geometry but are an embodiment of the carver's feelings and experiences as they sculpt without following a strict plan. The craftsperson might have been tired, inspired, excited, or distracted for a short time, transforming perfectly straight cuts into new expressive articulations of built emotion. Another example of *workmanship of risk* in the domain of arts and crafts are the wooden *Krampus* masks from Tyrol, Austria. These masks are a great example of how craftspeople incorporate their tacit knowledge of the material and adjust the design on-the-fly to account for the material's behaviour and imperfections. A wooden knot from a broken or cut branch becomes, during fabrication, a crooked nose or a slightly distorted face (Fig. 1.5). These on-the-fly adjustments enhance the distinctive aesthetic of these masks.

Handcrafted objects and spaces have their own distinct aesthetics, but their production is risk-prone, unrepeatable and expensive. Conversely, machine production provides secure production which is precise and repeatable but does not offer adaptive processes or the inclusion

[8] Although this thesis distinguishes between the aesthetics of human and machine-made objects, the author acknowledges that recent advances in machine learning may make it more difficult to determine such differences on visual and tactile levels. Even though the trend of imitating handcrafted objects through machine production is progressing, the author suspects that the socio-cultural significance of human-made objects may be preserved.

Figure 1.5: Tyrolian Krampus mask by Franz Oberschneider © Wanderhotels

of tacit human knowledge. A synergy between manual fabrication and machine production could compensate for the risks and disadvantages of both, providing a new *workmanship of synthesis*. Such a *workmanship of synthesis* could enhance manual human fabrication with digital technologies, changing the way we design and fabricate with machines.

1.2.5 Technical advantages of human-machine feedback loops

Most design-to-fabrication workflows in digital fabrication are linear and non-adaptive due to the explicit nature of machine instructions. In such workflows, the design must be planned, tested, and sequenced before fabrication begins, thus physically and temporally separating the design and fabrication phases. The design is saved to a file, transferred to a machine, and finally produced as a physical form. Each time the design has to be changed, the designer or architect must start from the beginning and follow the design-to-fabrication workflow in a linear sequence. Such linear workflows are overly complex, require numerous separate steps and can lead to communication and execution problems that can increase manufacturing time and cost. Fully predefined design-to-fabrication workflows not only slow down the design-to-fabrication workflow but also limit the degree of decision-making during fabrication. Once the file is sent to the machine, humans can not intuitively interact with the process, even if they identify material defects or machine failures. They cannot dynamically adjust plans, correct errors or change parameters on-the-fly such as geometry, tool angle, or pressure. Besides preventing design adaptation, non-adaptive digital fabrication also prevents creative expression. In the art and craft movement, linear workflows separate the artisan from the physical prototype and inhibit any potential creative expression that might arise from interaction with the material.

On the other hand, craft practices (craftsmanship and arts and craft) are adaptive and flexible enough to include the craftsperson's actions in the process by not entirely limiting the path of execution [54]. A craftsperson reaches a specific goal while accepting the constraints and limitations of the machine and the material. Ultimately, craftspeople can adjust plans on-the-fly, make design adjustments, or counterbalance mistakes. To incorporate this adaptive concept into computational models, Knight and Stiny present a method to include the temporality of craft into the computational process through *making grammars* [55]. This approach segmented the spatial and temporal aspects of craft by codifying to create a more adaptive computational workflow.

Besides offering adaptive workflows, craft practices also support tacit and embodied knowledge, as craft is a haptic activity. Craftspeople use their hands to make sense of the material and their environment, transforming the world into an environment with salience, meaning, and value [56]. In contrast, digital workflows are rarely adaptive enough to integrate tacit knowledge and embodied cognition. To include these forms of knowledge in digital fabrication processes, novel adaptive digital-physical environments are required that combine digital twins, visual feedback systems and tracking systems. Such environments enable new possibilities of interplay between the body and digitally produced objects, defining the domain of *digital craft* and the notion of the *digital handmade* [57].

Digital craft enables craftspeople to change and adapt the design and physical outcome on-the-fly, merging the conventional design and fabrication space. Such a convergence of the design and fabrication space has already been tested in concepts such as *personal fabrication* [58], allowing end-users to manufacture and design within the boundaries of the domestic home. In such fabrication scenarios, machines and people share the same physical workspace, and computational systems integrate domain knowledge, such as structural, material, or machine simulations, to achieve functional and controlled results.

1.3 State of the Art

The following sections describe how this research builds on existing work by examining human-machine collaboration in digital fabrication, focusing on the human or the machine as the actuator.

1.3.1 Human as actuator: machine-assisted human fabrication

Machine-assisted human fabrication describes a system where humans fabricate by hand and are instructed and assisted by a machine. The difference from traditional manual manufacturing is that this process is digitally informed and enables humans to manufacture geometrically complex objects without the use of templates or paper plans. This process enables a hands-on digital fabrication experience by informing the craftsperson about design outlines and constraints. This information is communicated via an interface, enabling a direct connection between a digital model and a human performing manual tasks. The interface can be haptic [59, 60], visual [61], or audible [62]. To instruct humans throughout fabrication, these workflows use physical and cognitive augmentation to correct or enhance human movements or improve cognitive abilities.

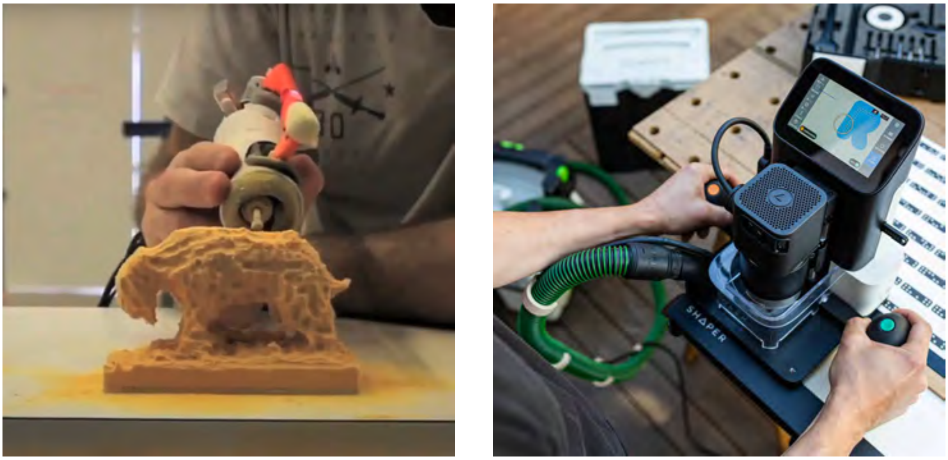
Physical augmentation enables humans to manually fabricate millimetre-precise objects and place them accurately in 3D space. An example of such a physical enhancement is *FreeD* [63], a hand-held, digitally-controlled milling device to enable humans to produce complex carving tasks (Fig. 1.6a). The device does not directly control human movements but regulates the speed of the spindle of the hand milling machine, depending on a digital model. If the hand movements intersect with the digital model, the device shuts down the spindle entirely to avoid damage to the physical artefact. *FreeD* aims to preserve the expressiveness and uniqueness of manual carving while ensuring accuracy in recreating a digital model.

Shapertool is another example of a machine that is correcting the humans physical movements [64]. It allows humans to mill wood with machine precision by providing real-time machine adjustments to human hand movements (Fig. 1.6b). The device uses a marker system to re-orient itself to the workpiece and visually instructs humans where to cut to follow a predefined design. To achieve high precision, the position of the spindle adapts to the human's movements and ensures precise cuts.

Adroid [65] enables humans to borrow precision and accuracy from a robotic arm while using hand-held tools. The tools are mounted on a robot, and a person can hold and move the tools directly. The system tracks the human's movement and applied forces, and the robot moves in response, selectively restricting certain motions.

FreeD, *Shapertool* and *Adroid* are examples of projects that show how manual craft combined with correction mechanisms of a machine can enable handcrafting with machine precision. These systems demonstrate the potential of *machine-assisted human fabrication* by aiming to produce identical physical copies of predefined digital models. These projects, however, do not support interactive design workflows to create 3D models from scratch while complying with machine and material constraints.

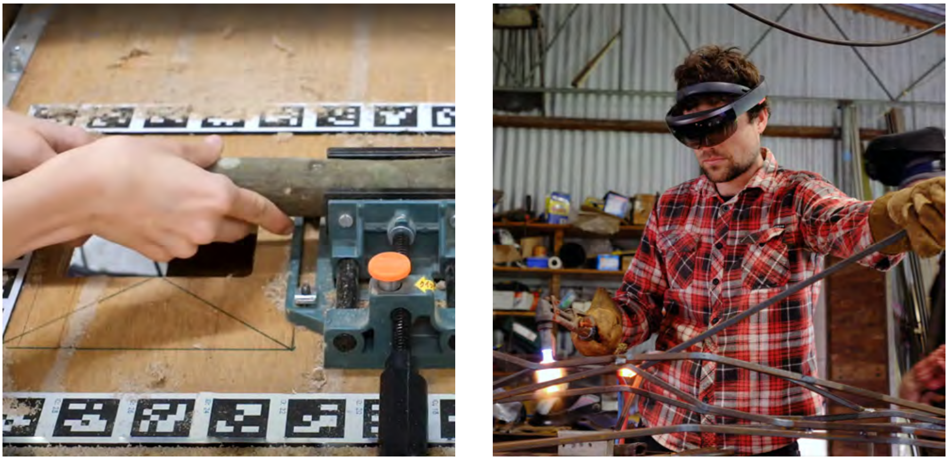
Cognitive augmentation supports humans in complex, abstract or logical applications. An example of human cognitive augmentation is the research presented by Larsson et al. [62].



(a) *FreeD* is a hand-held digital milling device assisting a manual milling process [63]

(b) *Shapertool* is a manually controlled CNC router to mill wood precisely and intuitively [66]

Figure 1.6: Examples of physical augmentation for more precise manual fabrication



(a) Larsson et al. [62] introduce a cognitive augmentation to instruct humans on how to mill custom joints.

(b) *Fologram* provides AR assistance to instruct craftspeople during fabrication such as welding or bending of steel [67]

Figure 1.7: Examples of human cognitive augmentation to support complex manual fabrication

The project uses an audio and visual interface to instruct humans on how to mill custom joints (Fig. 1.7a). In this research, various natural wood branches with diverse shapes are used. The augmented guidance system is necessary to maintain precision while placing and orienting tree branches on a CNC machine. Afterwards, these milled pieces can be manually assembled without screws or adhesives.

Another excellent example of cognitive enhancement is augmented reality (AR). AR is an interactive experience that overlays the physical world with computer-generated content [68], enabling humans to interact with digital content and receive information. AR technologies for human augmentation have been used for over three decades in diverse domains such as HCI and HMC. AR technology was introduced only recently to AEC as AR hardware and software libraries have become increasingly more affordable and available. The overlaying of digital data over the physical world has opened new paths for a great variety of fabrication procedures in AEC [61], providing a safe, quick and more intuitive way to manually fabricate geometrically complex objects [69]. AR can visually augment humans in the manual assembly of elements [70–73], joining of elements [74], enable construction supervision [75], and remote communication [76]. AR supports fabrication tasks through different visualisation methods, such as projection AR, screen-based AR, or head-mounted displays (HMDs). Projection AR can augment the building site and the machine environment, while hand-held and head-mounted displays[9] provide a more mobile augmentation. One example of projection-based AR is the *Stik pavilion* (2014) by the Digital Fabrication Lab of the University of Tokyo [71]. Humans were equipped with a hand-held extrusion device that aggregated printed chopsticks solidified with wood glue. A projection mapping guided humans as to where to deposit the chopsticks. The company *Fologram* commercially exploited AR-guided assembly strategies using HMD and screen-based AR to instruct craftspeople and architects via visualisation of a 3D model (Fig. 1.7b). It is used for crafts such as steel bending or bricklaying and demonstrates how fabrication within a mixed reality (MR)[10] can enable skilled and unskilled construction teams to assemble complex structures quickly [77]. Another example using HMD is the project *CRoW* by ICD Stuttgart [78], offering process-specific robotic control in AR.

These projects demonstrate the potential of AR for manual fabrication, but they are lacking in important technological and conceptual areas. First, they focus only on the visualisation of a given 3D geometry and do not allow humans to adapt the design of a digital model on-the-fly. Further, most AR applications for AEC do not offer custom craft-specific user interfaces (UIs), even though off-the-shelf AR systems often include such functionality in their application programming interfaces (APIs) [79]. Second, they do not have sufficient localisation accuracy and can not establish a direct correlation between the digital building model and the physical reality with high accuracy.

1.3.2 Machine as actuator: human-instructed machine fabrication

Human-instructed machine fabrication describes a system where the human provides input, and the machine responds with physical feedback. Similar to interactive fabrication [59, 80], it allows for direct manipulation of a physical prototype during fabrication as human input is registered and interpreted in real-time [58]. In *human-instructed machine fabrication*, humans provide input to larger-scale machines, such as industrial robots or milling machines. During fabrication, the human may interactively alter the design output or adjust machine parameters on-the-fly to correct machine or material failures, enabling a semi-autonomous manufacturing process. Such a fabrication methodology allows craftspeople to use their intuition and react quickly to situations while at the same time producing precise and repeatable results. It combines the machine's capabilities, such as strength, precision, and efficiency, with human capabilities, such as creative input, fast reaction time to complex situations, and intuition. To

[9] Head-mounted display refers to a visual display system that is worn on the head or as a component of a helmet and has a small display optic in front of either one (monocular HMD) or both eyes (binocular HMD)

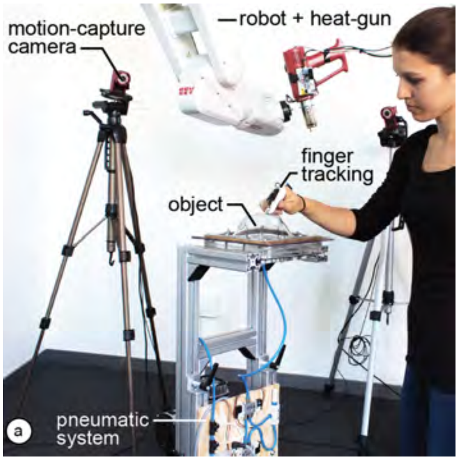
[10] Mixed reality describes the merging of the physical environment and computer-generated content. Physical and virtual objects can co-exist in mixed-reality environments and interact in real-time. Augmented reality and mixed reality are often used interchangeably.

(a) *Reform* incorporates digital and physical inputs to change the design of objects [81].

(b) *Endless wall* incorporates spatial input to manipulate the design of a brick wall [82].

Figure 1.8: Examples of interactive fabrication projects using physical objects and spatial input as a tangible UI

(a) *RoMa* is an example of a turn-taking processes [83].



(b) *FormFab* is an example of a continuous interactive process [14].

Figure 1.9: Examples of different interactive fabrication processes

facilitate *human-instructed machine fabrication*, it is necessary to track human actions and link them with a digital fabrication process.
To track human actions, physical objects or the human body can be registered, resulting in various types of information such as the pose and geometry of physical objects or the pose and physical state of the human body.

Several research studies explore interactive fabrication scenarios using work objects as a tangible UI to enable humans to intervene in digital fabrication creatively. For example, *ReForm* synchronises physical clay objects with a digital model via bidirectional fabrication. In doing so, *Reform* provides a more flexible design process incorporating digital and physical inputs, as a human can directly manipulate objects [81] (Fig. 1.8a). An example of direct manipulation within a spatial setting is the *Endless wall* by Gramazio Kohler Research [82] (Fig. 1.8b). It allows a human to draw chalk lines on the floor and use those to instruct a robot interactively on where to place bricks to build a wall. In this project, humans interact directly with their surroundings to design and fabricate physical objects. Another project that allows humans to intervene creatively in the fabrication process using a work object is *RoMa* (Fig. 1.9a). The setup of *RoMa* allows humans, equipped with an AR headset and an AR controller, to change and customise a 3D design throughout a robotic 3D printing process [83]. To customise the design, the human can interrupt the robot's printing process via a proxemics-inspired handshake mechanism. This interaction stops the robot from printing, and the human can then adjust the 3D model or add new elements using the AR controller. The 3D model is visually superimposed over the physical workpiece to perceive these design changes.

All previous examples that use work objects or spatial input as tangible UIs are turn-taking processes. These processes are sequential, which means that humans first perform a command, and then the system responds with physical feedback. Continuous interactive fabrication was realised in *FormFab* [14], which uses hand gestures as human input (Fig. 1.9b). In this research, humans can directly change the curvature of a thermoplastic sheet in real-time by instructing a robot with specific hand gestures. The human is equipped with a finger-tracking device, which registers finger location and pinch gestures. First, the human outlines an area on the workpiece they want to reshape. Then the robot warms up this area with a heat gun, and once the material is heated and compliant, the human activates a pneumatic system using a pinch gesture. The human controls the air pressure of the pneumatic system by increasing or decreasing the hand's distance to the workpiece and inflating or deflating the compliant area.

These examples highlight the potential of including human actions in digital fabrication. However, none of the mentioned projects apply useful constraints to guide human input, leading to potential material or machine failures. This lack of visual and audible feedback of machine and material constraints also increases the learning curve of humans as interaction occurs on a trial-and-error basis.

1.4 Problem statement

As shown in *Background* and *State of the Art* (section 1.2 and 1.3), collaborative human-machine processes offer new opportunities for digital fabrication in AEC by including humans as part of the control logic in digital fabrication processes. These opportunities include technical advantages, such as greater robustness and adaptability, aesthetic advantages, such as the merging of craft with automation, and greater social sustainability, combining skilled human labour with digital fabrication. However, to implement and realise collaborative human-machine processes in AEC, a multitude of domain-specific conceptual and technical challenges must be considered. These key challenges address the development of adaptive digital fabrication processes and include the following:

- **Process digital twin:** developing a feedback-based framework that combines physical and digital workspaces.
- **Visual feedback system:** development of visual feedback systems to enable cooperative building workflows.
- **Cooperative building workflows:** defining task distribution in adaptive digital workflows for two actuators - humans and machines
- **Interaction modalities:** understanding how we enable diverse interaction modalities by tracking human intentions and actions.

The following sections discuss each category and its relevance to the thesis.

Adaptive digital fabrication: Most digital fabrication processes aim for full automation but still require human involvement. However, these processes are not adaptive enough to incorporate human physical actions into the digital control logic. This lack of adaptability and the separation between the digital and physical workspace limits the robustness of digital fabrication processes. Furthermore, it hinders the applicability of digital fabrication for difficult-to-automate manufacturing processes, such as on-site fabrication or fabrication with more complex material systems. More adaptive digital fabrication processes can support feedback-based fabrication, including humans in digital fabrication and connecting the digital and physical workspaces. To facilitate adaptive digital fabrication, it is necessary to develop process digital twins incorporating human and machine input and output. The task distribution between those actuators has to be addressed through computationally controlled task distribution and diverse feedback systems. To include human actions, diverse tracking systems have to be investigated.

Process digital twin: Current digital manufacturing processes are feed-forward processes that strongly separate the digital model and the physical fabrication process. Human-in-the-loop processes require feedback-based processes that merge the digital and physical workspace. For this, a process digital twin[11] is necessary [84, 85]. The process digital twin encompasses entire production environments, incorporating human actions, environmental data, and machine control by capturing data in near real-time. The process digital twin acts as a virtual representation of all physical and digital entities and provides the means for monitoring and controlling the agents' behaviours and interactions within the digital-physical environment. It also includes a virtual representation of the entire construction environment.

[11] Building upon the capabilities of the product digital twin, the process digital twin enables humans to work in both virtual and physical models utilising immersive technologies.

Visual feedback system: Current digital fabrication processes offer limited UI customisation capabilities, inhibiting cooperative building workflows for automated processes in construction. Visual feedback systems, such as XR systems, link a physical workspace to a digital twin and have the potential to instruct humans in real time about fabrication tasks and processes. These systems allow multiple stakeholders to immerse themselves in the same digital twin simultaneously and remotely to facilitate collaborative work. Further, XR feedback systems can visualise and access data from the entire manufacturing process and its components and devices to enable intelligent task distribution.

Cooperative building workflows: Human-machine collaboration offers the possibility to distribute tasks between two different actuators – humans and machines. Whether the human, the machine, or both fabricate depends on the manufacturing scenario and its requirements, e.g. how much dexterity is required, how heavy the individual elements are and what the accessibility is. The spatial proximity and different tasks allocated to humans and machines determine whether the relationship between a human and a machine is defined as *co-existence*, *interaction*, *cooperation*, or *collaboration* [86] (see Annex A). Spatial proximity defines the physical relationship between humans and machines in their shared workspace. This means that humans and machines are either physically separated through barriers like fences or can work in close proximity without any physical barriers. Task allocation indicates whether actions can be executed by both agents simultaneously or sequentially, with or without physical contact.

Most current digital fabrication procedures are based on *co-existence* or *interaction*. *Co-existence* is a process in which humans and machines share a physical workspace, but their work cells do not overlap. The agents never come into contact and do not simultaneously work on the same workpiece. *Interaction* describes a fabrication scenario in which both agents share the same work cell and are sequentially active. Despite sharing the same work cell, they do not have physical contact. A practical example is a craftsperson stocking material for the robot while the robot is inactive. Once the craftsperson leaves the work cell, the robot continues to fabricate.

Adaptive digital fabrication scenarios have to potential to extend *co-existence* and *interaction* scenarios and facilitate *cooperation* and *collaboration* procedures. *Cooperation* describes a procedure where both agents work synchronously on the same element and workspace. An example is a robot that assembles elements while a human joins these elements at the same time. *Collaboration* is a workflow where humans and machines share the same workspace, have physical contact, and the machine responds in real-time to the movement of the human.

Interaction modalities: Real-time tracking is critical for incorporating human actions and intentions into a computational framework. Common digital fabrication processes do not provide human tracking capabilities and therefore do not allow human actions to become an essential part of the digital fabrication process.

1.5 Research questions

This thesis addresses the following research questions:

1. How can we implement human-machine collaboration sensibly in digital fabrication processes in AEC?

In AEC, there are domain-specific requirements for human-machine collaboration. These requirements are related to craft applications, the required precision of fabrication, the socio-cultural context of AEC, and the economy and scale of fabrication. In order to implement human-machine collaboration sensibly in AEC, this research aims to identify fabrication processes and material systems that would benefit from collaborative and hybrid human-machine systems. Therefore, this research seeks craft-specific augmentation solutions for existing construction trades to explore the role of tacit knowledge in computer-aided design and digital fabrication. For this, the research aims to develop more adaptive digital fabrication procedures that can include humans as part of the control logic.

2. How can we develop adaptive digital fabrication workflows to include human actions?

This thesis explores how to create shared digital-physical environments, including human actions in the digital fabrication process. This thesis investigates how to bridge the digital and physical space to enable adaptive digital fabrication workflows. For this purpose, the research investigates how to track human actions in real-time and link this data with a digital twin. Furthermore, this research investigates how digital twins, in combination with visual feedback systems, can instruct humans and machines.

3. Who is the potential stakeholder in such adaptive digital fabrication processes?

This thesis studies two possible stakeholders for human-machine collaboration in AEC. The first stakeholder is a craftsperson executing designs from an architect. This craftsperson might need to adapt the designs to site conditions or material variances, therefore requiring adaptive digital models that include such activities in the digital fabrication process. Second, this thesis speculates on a potential new stakeholder emerging from such processes in AEC. This stakeholder is a new digital art and craftsperson merging the aesthetics of machine production with manual fabrication. Therefore, this stakeholder requires novel digital design tools to adapt and design on-the-fly.

4. How can we augment the capabilities of a human without simply 'automating the human'?

Implementing human-machine collaboration in architectural fabrication means enabling the human instead of simply automating the human. Therefore, this research asks how to include human expertise in a digital fabrication procedure. This research investigates the role of humans in decision-making, supervision, and fabrication, as well as in error mitigation in moments of error occurrence.

Based on these questions, the following research objectives are outlined in the subsequent paragraphs.

1.6 Research objectives

This research proposes to investigate and establish novel forms of human-machine collaborations to explore the role of tacit knowledge in computational design and digital fabrication. It focuses on developing, testing, and evaluating multiple craft-specific human augmentations and UIs specific to a chosen fabrication process. By solving practical, methodological, and theoretical obstructions, the research aims to study the potential application of a human-machine collaborative system to perform adaptive digital fabrication tasks at an architectural scale. The research aims to develop different robust and economically feasible augmentation systems. These systems aim to combine the cognitive abilities, dexterity, and tacit knowledge of humans and the explicit knowledge, precision, and efficiency of machine agents to enable otherwise impossible or unsustainable tasks in digital fabrication on architecture.

Specific key objectives in the proposed development of the research framework are:

- Objective: The development of adaptive digital fabrication models to enable decision-making while collaborating with a machine during fabrication. (Paper A, Paper B, Paper C, Paper D)

  Rationale: Interactive fabrication systems require adaptive computational models that enable direct manipulation and non-linear workflows. Critical is the development of feedback-driven design processes that allow craftspeople to change design and fabrication parameters on-the-fly. This blending of design and fabrication space requires the development of an augmented environment and an augmented craftsperson. These augmentation systems must be able to track human actions in near real-time and provide a visual feedback system, such as AR interfaces.

- Objective: The investigation and development of fabrication-specific UIs and interactive instruction methods for diverse visual augmentation systems. (Paper A, Paper B, Paper C, Paper D)

  Rationale: This research focuses on applying XR interfaces in AEC for design and fabrication. Additionally, this research develops gamification strategies for craft-specific UIs adjusted to the specific requirements of the fabrication tasks. Different augmentation interfaces are tested and evaluated, such as on-body and on-environment augmentation. On-body augmentation includes phone-based AR (Paper C) and visualisation methods via a HMD (Paper D). On-environment visual augmentation utilises screen-based (Paper A) and projection-based augmentation (Paper B) to inform humans throughout the building process.

- Objective: The establishment and development of a continuous real-time flow of information between sensors and related computational models. (Paper A, Paper B, Paper C, Paper D)

  Rationale: Interactive and adaptive digital fabrication procedures require a scalable communication system connecting computational processes and multiple devices. These devices include visual feedback systems, such as UIs, human and machine sensing and actuation systems. A digital twin is used to enable near-real-time communication between all devices.

- Objective: The identification of suitable material systems for an adaptive digital fabrication process. (Paper A, Paper B, Paper C)

  Rationale: Not all material systems would profit from human-in-the-loop fabrication. This research investigates material systems that require human dexterity, such as malleable and complex material systems, i.e. mortar (Paper A) and plaster (Paper B), as well as intricate joint systems such as rope joints (Paper C). Furthermore, this research investigates these material systems at the building scale, employing different human-machine setups.

1.7 Structure of the dissertation

The subsequent chapters of the dissertation include *Methodology*, *Case studies*, and *Conclusion*.

Chapter 2

Methodology: This chapter explains the overarching empirical and experimental research methodology and the chosen research-relevant case studies. Furthermore, this chapter introduces four relevant research streams and work packages necessary to develop the case studies. These research streams include digital twins, visual feedback systems, cooperative building workflows, and interaction modalities.

Chapter 3

This chapter contains the key research papers and an introduction to how these papers fit into the general body of work. Below is a summary of the content of each paper.

Machine-assisted human fabrication: *Augmented Bricklaying* explores the manual construction of intricate brickwork through a context-aware AR system. The AR system uses a visual-inertial tracking system to augment humans cognitively, that is, a craft-specific UI instructs masons on how to place and orient bricks correctly in space. This research has demonstrated and validated the application of this visual guidance system for bricklayers in a real-scale building project.

Human-instructed machine fabrication: *Intuitive Robotic Plastering (IRoP)* enables architectural designers to engage intuitively with an in-situ robotic plastering process. The research combines interactive design tools, a projection-based AR system, and a robotic plastering process. The system utilises a controller-based interaction system to enable humans to interactively create articulated plasterwork in situ. The underlying computational pipeline translates human gestures into robotic motions while complying with machine and material constraints. The system was evaluated and validated by building a full-scale demonstrator.

Human-robot cooperation: *Tie a knot* expands on knowledge gained in *Augmented Bricklaying* and extends the dynamic optical guidance system with a bi-directional non-linear computational design logic. By doing so, the system creates a hybrid robotic and manual fabrication process that enables humans to change the design on-the-fly. It outlines the necessary system requirements of human-robot cooperative fabrication systems, such as shared workspaces, and develops a continuously interactive computational design model. The workflow and system were evaluated and validated by building a full-scale demonstrator.

Teleoperated human-human collaboration: *Extended Reality Collaboration (ERC)* is a mixed-reality immersive collaboration system that leverages the knowledge gained in *IRoP* and *Tie a knot*. *ERC* extends previous on-site systems with a bi-directional framework that connects two humans, one on-site and one off-site. Both humans mutually access a digital twin to design and fabricate collaboratively, which was experimentally evaluated and validated.

Chapter 4

Conclusion: This chapter summarises the research findings, discusses the contributions, and provides an outlook for the research. This section examines the impact of hybrid manual and machine fabrication, the importance of adaptability of digital processes and corresponding interactive computational models. In addition, this section examines how human-machine collaboration in digital fabrication can contribute to architecture. The Outlook section provides an overview of human-machine collaboration on larger architectural projects, developments needed in AR interfaces, as well as non-linear and interactive architectural fabrication.

Appendix:

The first four chapters are followed by an appendix that includes three chapters. The first chapter describes different human-machine setups (Appendix A). The second chapter covers aspects of human-machine interaction in a more artistic context shown in the project *Degrees of Life*. The project focuses on interactive human-machine-bacteria environments on an architectural scale. These interactive environments learn, grow, and decay in relation to human presence and behaviour. For this, human interaction was registered in real-time by multiple devices that recorded human actions (Appendix B). Finally, the third chapter includes the post-session usability study for bricklaying in AR (Appendix C). This user study focused on different visualisation platforms and learning curves based on the methods described in Paper A.

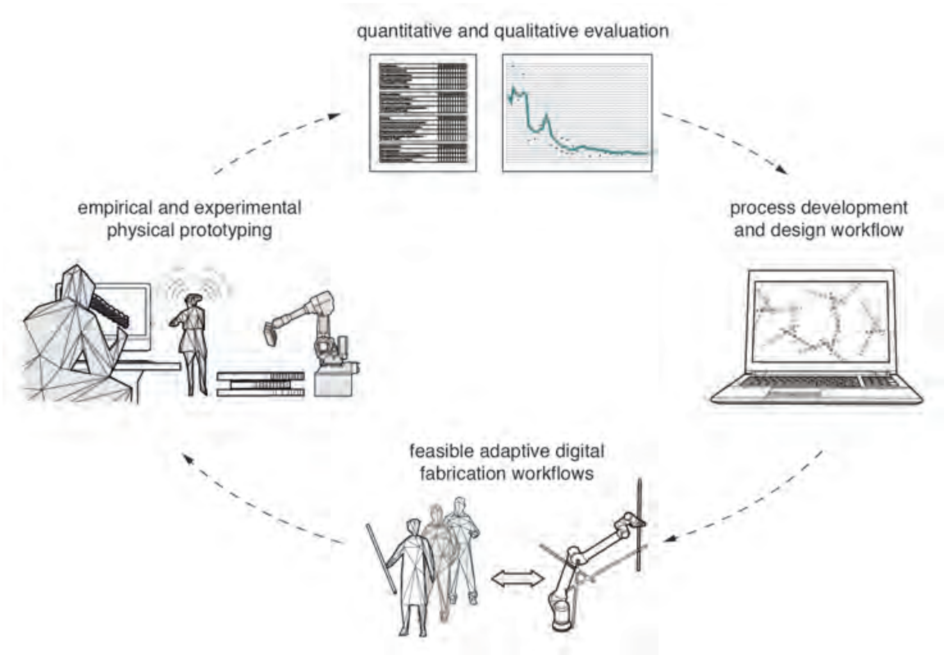


Figure 1.10: Diagram visualising the applied methodology.

2 Methodology

This research aims to expand the current limitations of HMC in the field of AEC by exploring the implementation of adaptive digital fabrication processes. The research utilises a *research through design* methodology [87], combining empirical and experimental methods, where the selected case studies serve as means to explore research questions, generate knowledge and validate the proposed methods (Fig. 1.10). This thesis combines process development to create feasible adaptive digital fabrication workflows with empirical and experimental physical prototyping to develop an in-depth understanding of the constraints and potentials of adaptive digital fabrication processes. To evaluate the process of making and its resulting objects [17, 87, 88], this thesis uses quantitative and qualitative evaluation methods. Qualitative studies investigate human behaviour and perception through user studies and the aesthetic potential of the produced prototypes. The quantitative analyses of this thesis focus on process parameters concerning building and tracking accuracy and assembly speed. Both quantitative and qualitative methods are chosen as the author of this thesis acknowledges that in the domain of HMC knowledge resides not only in the produced prototypes but also in the architects/craftspeople themselves and their process of making [89].

The case studies presented here utilise different craft and material systems to investigate the potential of adaptive digital fabrication, that is, bricklaying with mortar (Paper A), plastering (Paper B), and complex wood assembly with rope joints (Paper C), and are conducted with an interdisciplinary research team. For each case study, different XR interfaces are tested and evaluated, such as screen-based, phone-based, and projection-based AR, as well as AR with a HMD. All case studies are conducted in custom-developed digital-physical environments that link the physical and digital space with various sensors, interfaces, and actuators. This interplay between the physical and digital spaces is used to facilitate novel building processes and enable a wide range of investigations.

The four research streams throughout the thesis are linked to the problem statement (see section 1.4) and are investigated in all experimental studies (Fig. 2.1):

- **Digital twin:** the design and implementation of process digital twins synchronising digital and physical workspaces tailored to human-machine collaboration in AEC.
- **Visual feedback system:** the design and implementation of process-specific XR interfaces enabling both human-machine and human-robot collaboration.
- **Cooperative building workflows:** the design and implementation of dedicated cooperative workflows, where building tasks are allocated and distributed to humans, machines, and robots.
- **Interaction modalities:** the design and implementation of process-specific tracking routines, i.e., the tracking of direct human actions (human body tracking) or indirect human actions (object tracking).

These research streams are developed, evaluated and analysed quantitatively and qualitatively. The following sections describe these research streams' different development and evaluation criteria.

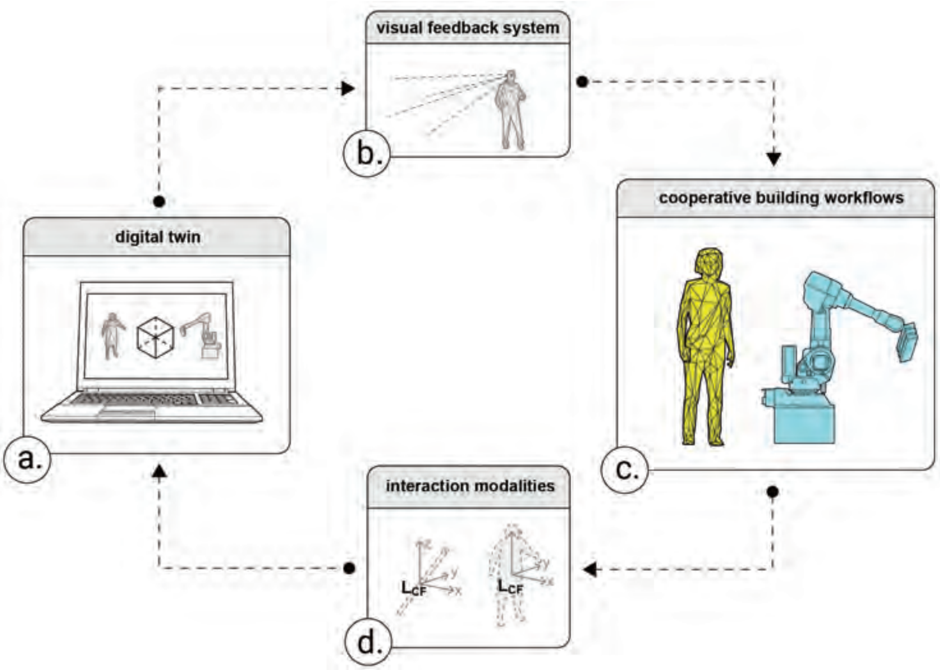


Figure 2.1: Diagram visualising the four research streams: (a) digital twin, (b) visual feedback system, (c) cooperative building workflows, (d) interaction modalities

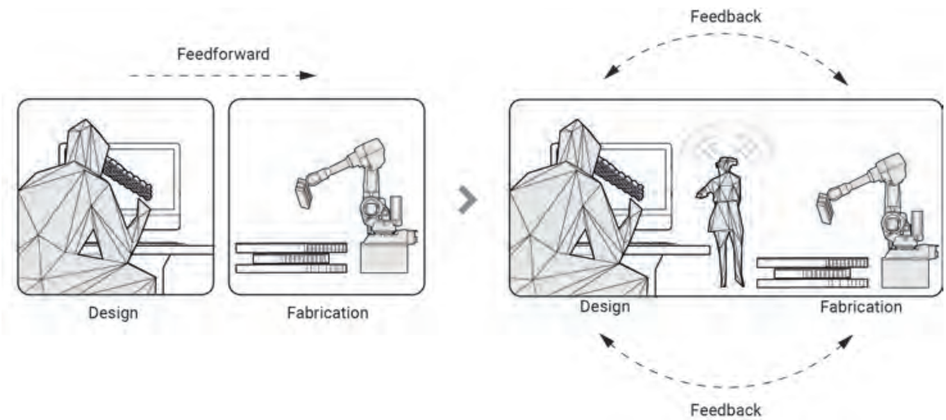


Figure 2.2: Process digital twins have the potential to synchronise the design and fabrication space.

2.1 Process digital twins

A process digital twin is used for synchronous communication to enable humans, robots and machines to operate together in digital-physical environments through a modular and scalable communication system (Fig. 2.2). The digital twin has to be made accessible for humans via a wide range of visualisation modalities of XR interfaces, through which humans can connect and visualise digital processes locally or remotely. Further, process digital twins enable craftspeople to work simultaneously on physical and virtual objects to induce and trigger changes in the design and building process. The case studies presented in this thesis define and calibrate the different functionalities required for such a digital twin, linking design and fabrication space. Paper A develops the core functionalities of a process digital twin, linking the as-built state with a digital model and user instructions. Paper B and Paper C explore process digital twins with interactive design functionalities to adapt the design on-the-fly throughout fabrication. Paper D extends this interactive design modality for on-site and remote users. The potentials of these different digital twins are evaluated and validated through quantitative and qualitative studies, physical object analysis, and user studies.

2.2 Visual feedback systems

Visual feedback systems such as XR interfaces enable architects and craftspeople to effectively and intuitively visualise digital process data during the fabrication procedure. This includes, for example, the design and fabrication space and related constraints that are directly overlaid onto the physical structure. To design intuitive interfaces, it is crucial to explore craft-specific tacit knowledge of the humans involved. The case studies test and evaluate different augmentation methods, such as on-body augmentation (wearable devices such as HMD, tablets, or phones) and on-environment augmentation (screen or projection based). Paper A and Paper B explore on-environment augmentation for co-located users, and Paper C and Paper D investigate on-body augmentation for co-located and remote users (Fig. 2.3). The four case studies are used to develop, test, and analyse a wide range of XR visual feedback systems and analyse their potential for different fabrication scenarios through user observation and user studies.

2.3 Cooperative building workflows

This research designs and implements process-specific collaborative workflows between humans and machines. For this purpose, this thesis investigates different human-machine configurations and their respective building task allocation and distribution. Building tasks are allocated to humans, machines or robots depending on the specific process requirements. This task allocation can either be flexible throughout the building process (Paper C, Paper D) or be predefined (Paper A, Paper B). The case studies serve to define, evaluate and calibrate the task distribution and the respective collaborative workflow. Paper A investigates manual fabrication assisted by machine systems to investigate handcrafted architectural structures with machine-like precision. Paper B explores the opposite task allocation and investigates robotic fabrication that includes intuitive human guidance. Paper C explores hybrid human-robot fabrication, merging manual and robotic fabrication procedures. Paper D studies a collaborative design and fabrication system for two physically separated humans for manual fabrication. The diverse case studies are used to test a variety of these different actuator workflows and systems and evaluate them quantitatively and qualitatively.

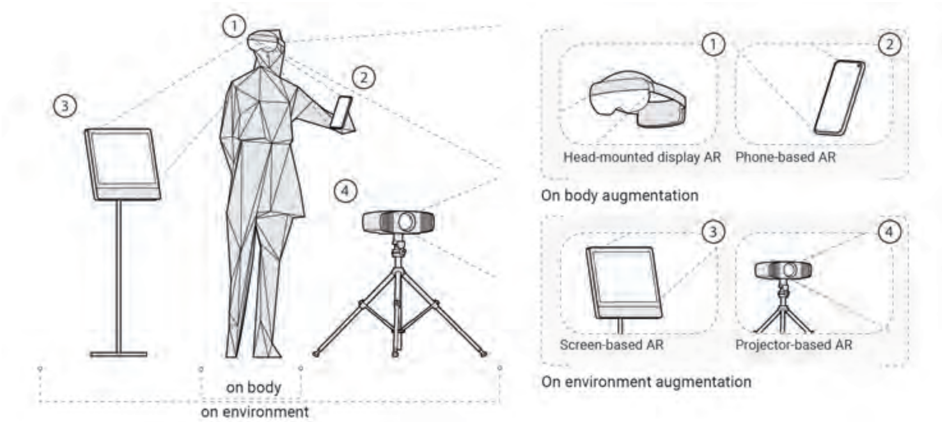


Figure 2.3: On-body and on-environment augmentation

2.4 Interaction modalities

To include humans in the digital fabrication workflow, this research establishes different interaction modalities that capture human actions and behaviour[1] and translate these actions into data that can be read by the machine. These interaction modalities are implemented into the digital twin and lay the basis for the design and fabrication framework. Human actions can be tracked directly via the human body or indirectly via objects in space. Different tracking systems are tested in the four case studies.

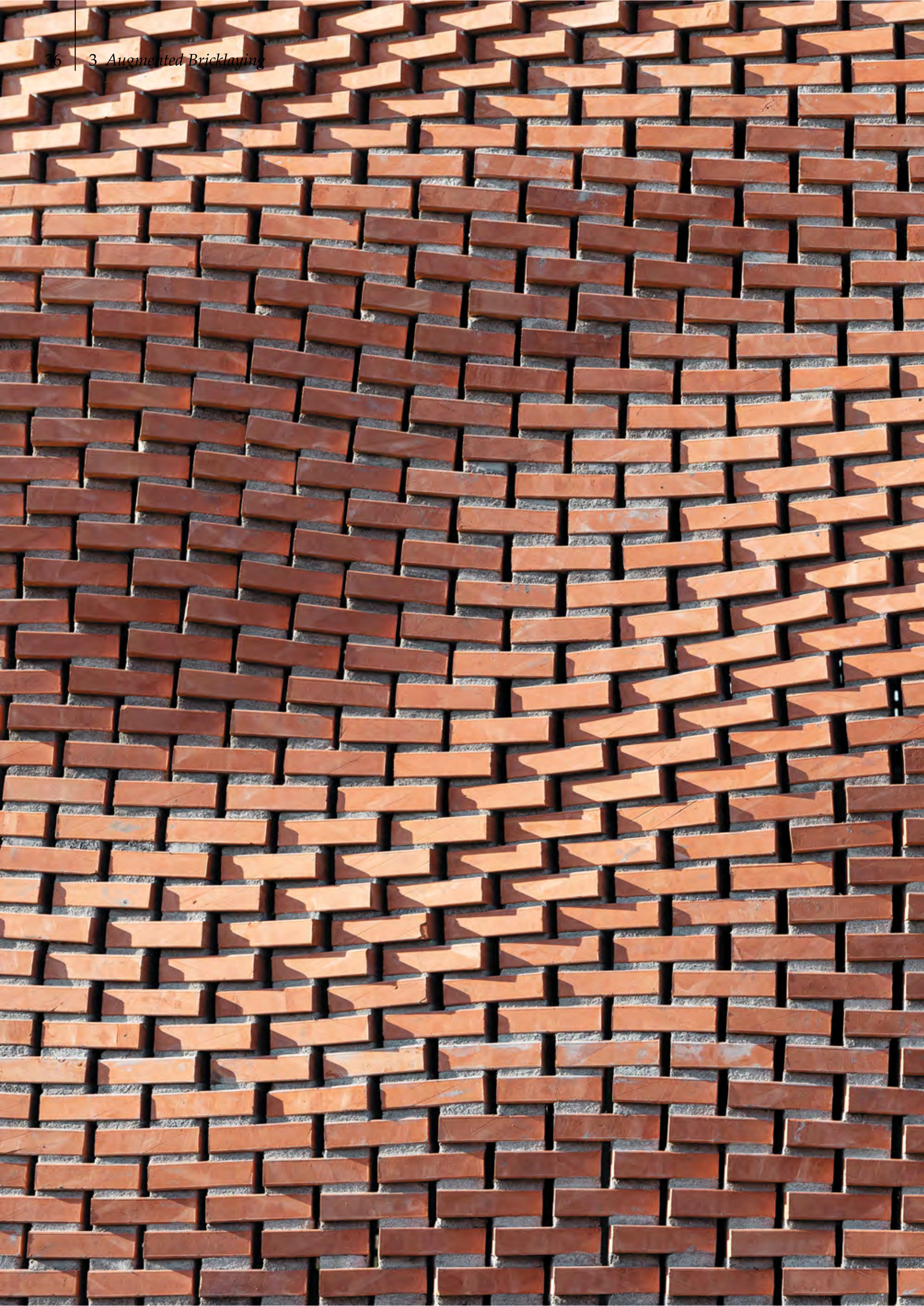
For body tracking, this thesis uses controller tracking (Paper B) and hand tracking (Paper D). To track objects in space, machine vision systems are employed, such as visual-inertial object tracking (Paper A) or manual probing with robots (Paper C). Tracking systems, in combination with context-aware and interactive computational models, enable diverse interaction modalities. The case studies serve to investigate, test, and evaluate the potential of various interaction modalities. Paper A investigates an interaction modality that provides access to a context-aware computational model. This is used to visually guide people during fabrication, as they can synchronise the digital twin in real time to the as-built state of the construction site. Paper B and Paper C explore audio-visual interaction modalities that enable humans to change the design interactively on-the-fly through body or object tracking. Paper D extends interaction modalities that provide access to context-aware and interactive computer models with collaborative capabilities for remote humans.

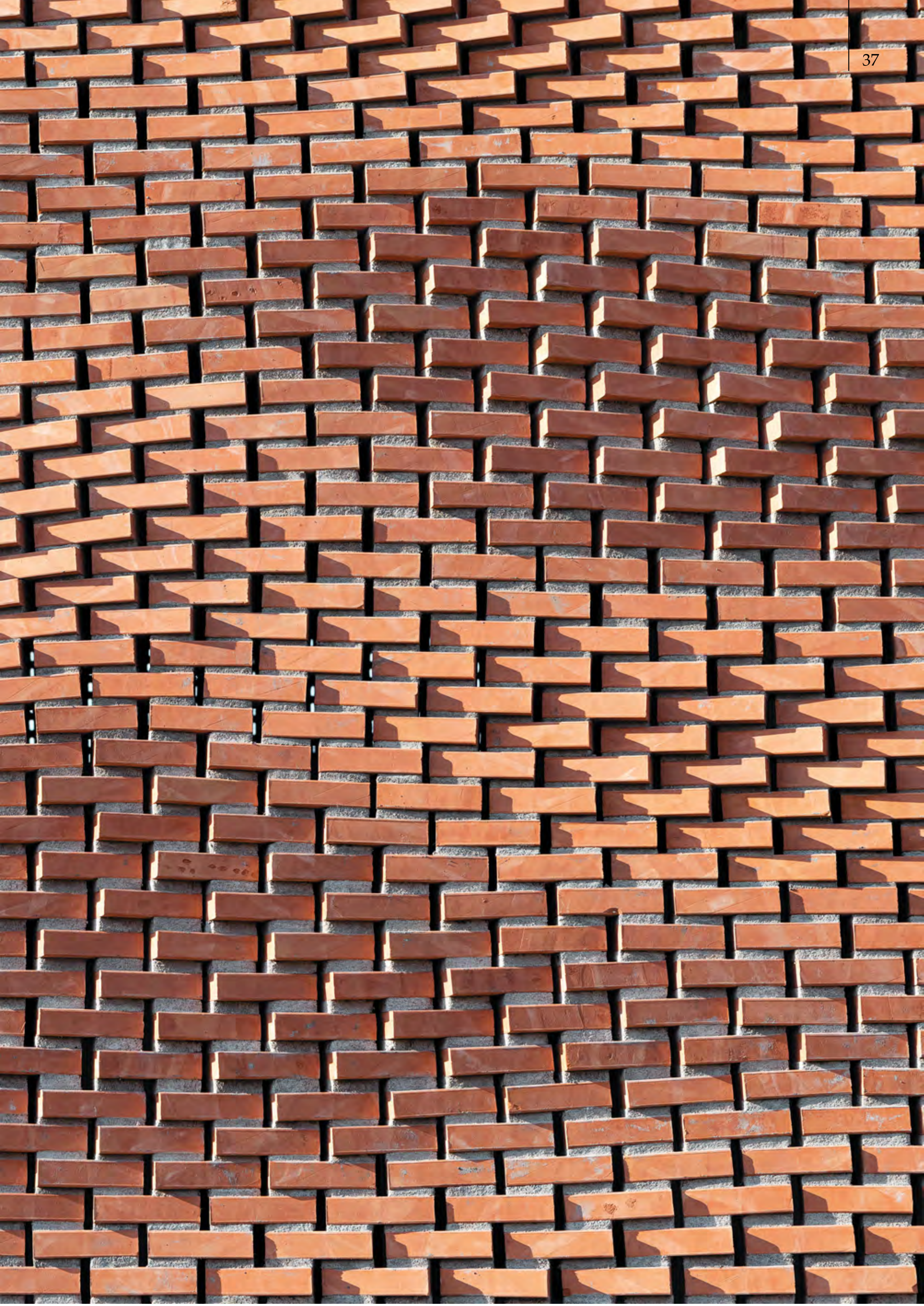
The four case studies are used to develop, test, and analyse a wide range of user inputs, various human interaction tracking systems, and interaction modalities ranging from simple user inputs[2] to complex user interactions[3].

[1] This thesis defines interaction as a conscious act, such as gestures or voice commands. Behaviour in this context is defined as unconscious interaction such as body language, presence or pupil diameter.
[2] Simple user inputs (Yes or No) are binary inputs that start or end a fabrication process or approve a fabrication phase.
[3] Complex user interactions require more detailed tracking as they contain more multi-layered information. An example

of complex user interaction is programming by demonstration, where the user tells the robot where to move by guiding it through a series of relevant configurations (position, orientation, and state of the gripper).

3 Case studies





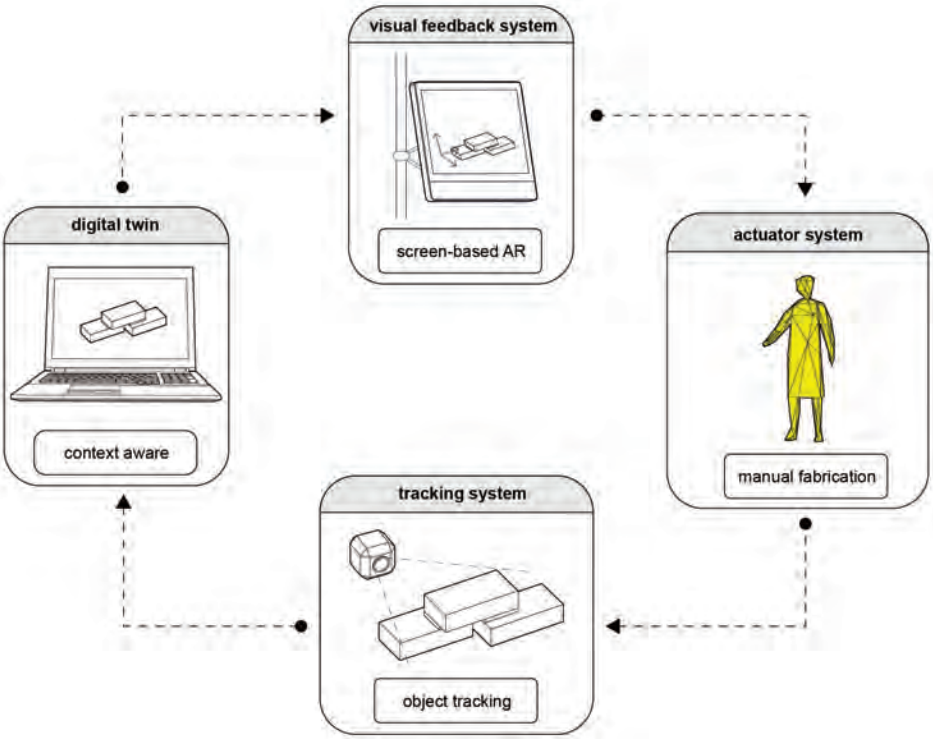


Figure 3.1: Diagram visualising the applied methodology for Augmented Bricklaying: (a) context-aware computational model, (b) screen-based AR, (c) manual fabrication, (d) object tracking

3.1 Machine-assisted human fabrication

3.1.1 Summary and contribution to thesis

This paper[1] contributes to the concept of *machine-instructed human fabrication* by exploring the manual assembly of complex brickwork assisted by a context-aware AR system. It introduces methods to combine human dexterity and crafts knowledge with the geometric complexity and precision of digital fabrication (Fig. 3.1). To achieve this objective, this paper showcases a digital twin that is informed by the current as-built state of the construction site. The as-built state is monitored by a visual-inertial object tracking system, which estimates the as-built locations of individual bricks, and compares them with their expected positions in the digital model. The digital twin is directly connected to a screen-based AR system. A custom-developed craft-specific AR user interface (UI) provides the masons with real-time information on how to assemble the bricks. This system eliminates the need for bricklayers to rely on physical templates while still utilising their expertise in handling mortar, thus both preserving and enhancing their craft.

[1] This version of the article has been accepted for publication, after peer review and is subject to Springer Nature's AM terms of use, but is not the Version of Record. The Version of Record is available online at: https://doi.org/10.1007/s41693-020-00035-8


voikiaσε...
S 81 ES
voikiaσε...
voikiaσε...

3.1.2 Augmented Bricklaying: Human-machine interaction for in-situ assembly of complex brickwork using object-aware augmented reality

Daniela Mitterberger[1], Kathrin Dörfler[1,2], Timothy Sandy[3], Foteini Salveridou[1], Marco Hutter[3], Fabio Gramazio[1], Matthias Kohler[1]

Abstract

Augmented bricklaying explores the manual construction of intricate brickwork through visual augmentation and applies and validates the concept in a real-scale building project-a fair-faced brickwork facade for a winery in Greece. As shown in previous research, robotic systems have proven to be very suitable for achieving various differentiated brickwork designs with high efficiency but show certain limitations, for example, in regard to spatial freedom or the usage of mortar on site. Hence, this research aims to show that through the use of a craft-specific augmented reality system, the same geometric complexity and precision seen in robotic fabrication can be achieved with an augmented manual process. Towards this aim, a custom-built augmented reality system for in-situ construction was established. This process allows bricklayers to not depend on physical templates, and it enables enhanced spatial freedom, preserving and capitalising on the bricklayer's craft of mortar handling. In extension to conventional holographic representations seen in current augmented reality fabrication processes that have limited context awareness and insufficient geometric feedback capabilities, this system is based on an object-based visual–inertial tracking method to achieve dynamic optical guidance for bricklayers with real-time tracking and highly precise 3D registration features in on-site conditions. By integrating findings from the field of human–computer interfaces and human–machine communication, this research establishes, explores and validates a human–computer interactive fabrication system in which explicit machine operations and implicit craftsmanship knowledge are combined. In addition to the overall concept, the method of implementation, and the description of the project application, this paper also quantifies process parameters of the applied augmented reality assembly method concerning building accuracy and assembly speed. In the outlook, this paper aims to outline future directions and potential application areas of object-aware augmented reality systems and their implications for architecture and digital fabrication.

Keywords Augmented reality fabrication, Mixed reality fabrication, Human-computer interaction, Human-machine collaboration

[1] Gramazio Kohler Research, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland
[2] TT Professur für Digitale Fabrikation, Fakultät für Architektur, Technische Universität München, Arcisstrasse 21, 80333 Munich, Germany
[3] Robotic Systems Lab, ETH Zürich, Leonhardstrasse 21, 8092 Zürich, Switzerland

Introduction

The high environmental impact of the construction sector and the perceived lack of increased productivity underscore the interest and investment in the development of digital fabrication technologies for the innovation of construction processes. Approaches to digital fabrication, in particular, combining methods of computer-aided design and robotic fabrication, have shown great potential for the integration of architecture and engineering design practices establishing a highly effective interplay between digital design and conventional construction processes [3, 90]. However, the challenge of digital fabrication on a building scale is not merely the full automation of single tasks. Recently, a stream of research has emerged in architecture, recognising the high diversity of tasks associated with the domain of architecture and construction [91]. This stream foresees a digital building construction methodology, where skilled workers and machines will share diverse tasks in the same work environment and collaborate towards common goals, combining the best of both their strengths and still fully exploiting a digital design-to-production workflow [20].

Collaborative human–machine systems are defined by a distribution of decision-making processes, combining the advantages of a machine with human knowledge, skills, and dexterity. Whereas humans have a fast ability to interact in the estimation of patterns and complex environments [92], machine logic exceeds human capacities with respect to precise calculations and data processing, for example, processing precise measurements resulting from machine vision). Hence, the concept of human–machine interaction is of increasing interest for the architecture, engineering and construction (AEC) industry as well as the academic community to achieve higher performance as well as enable socially sustainable semi-autonomous concepts and robotic processes [23].

Recent developments of such collaborative human–machine systems in architecture have begun to explore the potentials of augmented reality (AR) systems, focusing on manual fabrication and assembly tasks [72, 73, 93, 94] illustrating the potential to improve time efficiency and costs of on-site work tasks by up to 50% [95]. When using AR systems for guiding manual construction processes, one of the major drawbacks of current off-the-shelf AR systems (i.e., *HoloLens*, *MagicLeap*) is the insufficient accurate alignment of the digital model with the physical environment and an unsatisfying context awareness, i.e., for understanding the as-built condition in relation to the digital plans. To overcome the alignment limitations [96], researchers have thus proposed solutions that either use markers [77, 97], restrict the user to specific regions [98], or rely on Global Positioning Systems (GPS) [99]. However, these solutions still do not meet the requirements for building accuracy and lack options for measurements and process-specific feedback. Therefore, this paper proposes to use a custom-built AR system that applies a novel approach with markerless object detection for pose estimation [100]. This system provides the 3D registration of discrete objects together with highly accurate pose estimation, to visually guide humans executing manipulation procedures in real-time via a screen, promising to offer improvements in accuracy, feedback, and speed in comparison to off-the-shelf AR systems. By integrating findings from the field of human–computer interfaces and human–machine communication, this research establishes a craft-specific human–computer interactive fabrication system. This system aims to enable a highly dynamic and accurate AR-guided manual assembly process, in which a novel intent-based UI aims to combine explicit machine knowledge operations (i.e., the accurate 3D registration of bricks in real time) with implicit craftsmanship knowledge (i.e., the implicit

Figure 3.2: Katerini Winery (2019): biggest brick-structure constructed to date using augmented reality guidance

craft-specific knowledge as well as the dexterity needed for the proper handling of mortar). The augmented manual bricklaying has been applied and validated in a real-scale building project- a fair-faced brickwork facade for a winery in Greece in 2019. This project provided the opportunity to examine the implications, potentials, and challenges of applying such AR technology in a real-world construction scenario. The facade constructed of 13596 individual bricks is currently the biggest example of an on-site construction using a human–computer interactive system with an AR interface (Fig. 3.2).

The remainder of this paper is organised as follows: recent progress in AR fabrication is overviewed in section *Context*. Then, the interaction concept and methodology are outlined in section *Methods*. In section *Case study*, the developed concepts are applied to an augmented bricklaying scenario with human–computer interaction as a case study to present their practical relevance and implementation. Finally, the results and conclusion of this research are discussed in section *Results* and *Conclusion*.

Figure 3.3: Gantenbein winery facade (2006): fully robotically fabricated winery

Context

Projects such as the Gantenbein winery (Fig. 3.3) in 2006 paved the way towards enabling robotic fabrication to bridge the virtual and the physical realm weaving digital-design data into material building processes [101]. Despite the progress made since then in robotic fabrication, there remains a lack of transferability of in-situ robotic processes to real-world construction scenarios. An example of such are unstructured work environments such as construction sites, which still require human dexterity and knowledge to respond successfully and intuitively to material inconsistencies and complex changing environmental conditions.

Moreover, the setup costs, logistics, and necessary hardware, infrastructure, and technical know-how needed are barriers to implement robotic construction directly on the construction site successfully. While research has shown the potentials of using context-aware mobile robots for in-situ fabrication [102, 103], recent technological advancements in the domains of human–machine interaction and AR point towards an alternate yet synergistic strategy for digitalised building construction in a complex on-site context. It is now possible to equip construction workers and craftspeople with an ecology of tools, in particular, sensors and AR interfaces, to entirely fabricate in-situ, establishing a direct link between the digital design environment and a physical process, achieving a precision close to industrial robots with an entirely different technological approach.

The possibilities to use AR as a guide for craftspeople in the manual manufacturing process [69] have been shown recently by a growing number of research endeavours. One seminal project in the field was the *Stik pavilion* (2014) by the Digital Fabrication Lab of the University of Tokyo using AR technologies to guide human actions via projection-based mapping to inform builders about a designated building area [71]. Another projection-based AR project used to visualise potential material behaviour during the fabrication process is the project *Augmented materiality* [104] by Greyshed. A more recent example is the *Collaborative Robotic Workbench CRoW* by ICD Stuttgart [78], which combines a KUKA LBR IIwa robotic arm with an AR headset using AR as a process-specific robotic control layer. AR-guided assembly strategies have later been commercially exploited by the company Fologram. Fologram uses AR headset technology to allow operators to see instructions for manual assembly via a virtual holographic 3D model in space. With Fologram's approach and projects, they demonstrate how fabrication within a mixed reality environment can enable assisted unskilled construction teams to assemble complex structures in a relatively short amount of time [105, 106].

This commercially available system uses holographic outlines for spatially visualising geometry and promises to be easy to use. While this growing number of examples shows the enormous potential of such AR fabrication, all of the systems discussed show significant technological and conceptual gaps. Most importantly, this lack includes limited context awareness with no feedback, insufficient localisation accuracy to guide construction tasks, as well as the inability to register and measure the as-built structure with sub-centimetre accuracy. Additionally, a custom craft-specific UI for fabrication is rarely developed, even though most off-the-shelve augmented systems include the possibilities for such functionalities in their application programming interfaces (API) [79].

Methods

AR-guided assembly system setup

Augmented bricklaying explores the construction of a complex geometrically differentiated fare-faced brick facade through an intent-based augmentation system. The AR setup consists of a tracking and visual guiding system, combining an object-aware tracking procedure with a craft-specific UI. The tracking system enables the registration of discrete objects, in this particular case, bricks, with high precision in 3D space. For this, it uses edge-detection to incrementally track and estimate the location of the objects (for technical details and implementation, refer to [100]). Therefore, in extension to recently shown AR fabrication systems, the digital model can not only be projected as a hologram, as, i.e., seen in *Holographic construction* [106], but the as-built data of registered members of a structure being built can be directly registered and fed back to the digital model. Due to this highly precise object tracking and registration system, errors and deviations between the as-planned and the as-built data can be estimated in real time, and the dynamically adapted instructions can be visually communicated directly via the custom UI to the bricklayers using the system. Initially, the system was intended to be a one-person wearable AR system, but due to technical difficulties evoked by the substantial movement of a bricklayer, and the partial obscuring of the camera image by hands, this workflow had to be reconsidered.

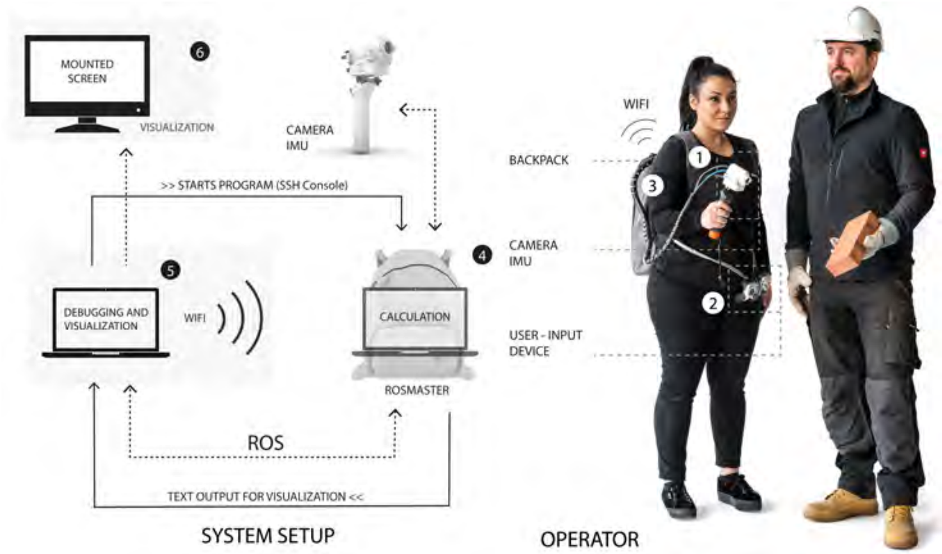


Figure 3.4: Custom-built AR setup: operator, bricklayer, handheld camera and IMU (1), portable sensory-input device (2), WIFI connection (3), calculation laptop (4), debugging and visualisation laptop (5), mounted screen (6)

Therefore, the system was extended to a two-person process, a bricklayer and an operator. The bricklayer is responsible for laying mortar and bricks. The operator carries and uses the AR system to direct the bricklayer. Both share a movable screen as a visualisation platform and communicate throughout the process. To place each brick in the 3D-complex masonry facade correctly, the bricklayer needs to understand the 3D position (position and rotation) of each brick in relation to its neighbouring bricks. Therefore, the operator is equipped with a handheld camera and an inertial measurement unit (IMU) (Fig. 3.4: 1), a so-called "eye-in-hand" system [107], for dynamic determination of user position (Fig. 3.4: 1). Furthermore, the operator carries a portable joystick used as a sensory-input device (Fig. 3.4: 2). The functionalities exposed through a joystick user-input device allow the operator to accept an already placed brick, reverse one brick, or delete an already accepted brick. Two portable laptops (Fig. 3.4: 4,5) support the AR system, whereas the operator carries the calculation laptop in a backpack. It is connected to the camera and IMU and communicates via Ethernet through ROS [108] with the second laptop, which is solely used for visualisation (Fig. 3.4: 5). These two processes (calculation and visualisation) are split to avoid delay in processing as well as to provide a cable-free portable laptop to allow the operator to move as freely as possible. The local metadata from the digital model is correctly anchored in space via object detection and overlaid with the camera image stream. This combination of virtual and real stimuli is visualised in-situ on the 27" mounted screen (Fig. 3.4: 6). To dynamically sense and measure the 3D position and rotation of the bricks, the AR system uses edge-detection to incrementally track and estimate the location of features of the masonry structure. The system additionally tracks larger objects on the work site; in this case, the concrete frame and vertical struts, which serve as global reference geometry and ensure the avoidance of error accumulation and that the wall maintains sufficient alignment with the existing building structure over the course of construction (Fig. 3.9). The system depends on the dimensions of these global objects of reference to be precisely measured and digitised before construction (Fig. 3.9).

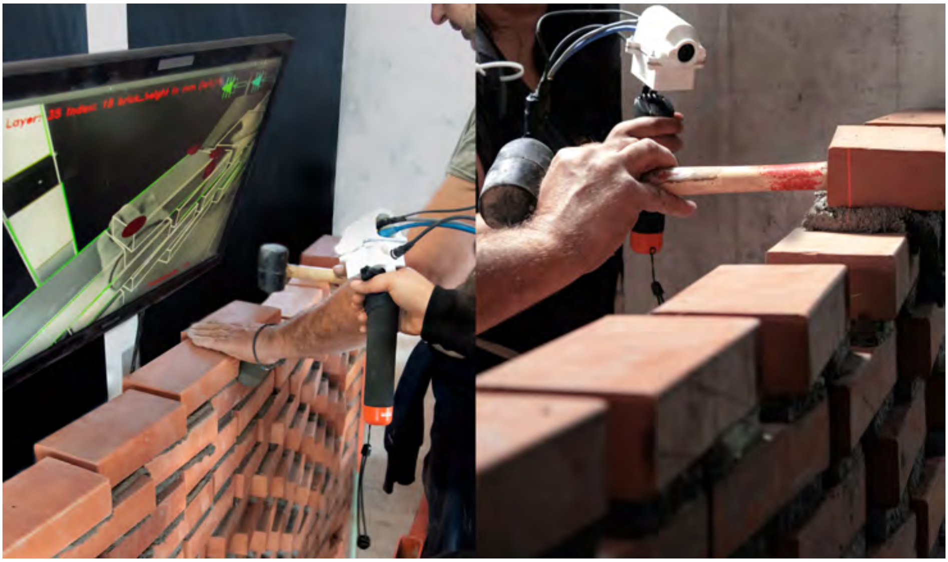


Figure 3.5: Full setup in operation: The bricklayer adjusts the bricks whilst the operator registers the current brick in relation to the neighbouring bricks and global objects of reference (concrete frame, struts)

Craft-specific user interface (UI)

The development and design of a bespoke craft-specific UI was crucial to the successful application of the AR system in building the facade. Augmented bricklaying is divided into three temporal differentiated main task sequences for bricklayers to follow. This visual feedback system guides the bricklayer and operator by providing visual instructions for laying bricks in their correct relative locations with high geometric precision to the tracked structure as defined by the computational model in real time. The UI design uses gamification elements in the interface design, which are derived from craft-specific gestures familiar to the bricklayer. Traditionally, bricklayers adjust bricks not via free-hand rotation but by tapping them with their trowels in x/y/z-plane to reorient them.

Therefore, the most crucial information for a bricklayer is the horizontal and vertical location of the hit, as well as the strength of the tap. This information is visualised by vertical and horizontal arrows, in which the arrow's size is directly linked to the required tapping strength (Fig. 3.5). The exact position of the arrows results from the visual–inertial object-tracking algorithm, whereas the length of the arrow indicates the strength of the tap, resulting from the difference between the target position and the estimated pose position. The design included the differentiation of the brick courses with varying mortar heights and alternating rotations of the individual bricks. Additional icons convey to the operator how much mortar should be used for the next brick by showing one of three types of abstracted trowels (S, M, L) (Fig. 3.6).

As the wall is perforated, the interface indicates the left and right mortar amount. The bricklayer learned over time how much mortar corresponded to each icon and intuitively chose the correct amount of mortar per brick. The temporal sequence of augmented masonry tasks was split into three main steps. First, the bricklayer was instructed about the approximate amount

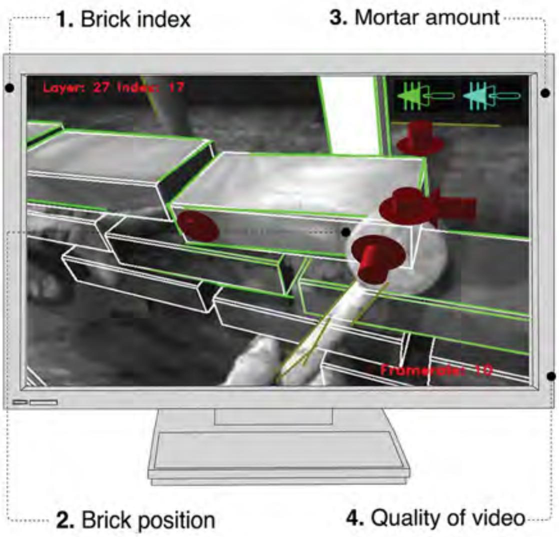


Figure 3.6: Craft-specific UI: arrows indicate location and strength of the knocking to reposition the bricks (2). Bricks are indicated according to layer and brick-index per layer (1). Symbols show the mortar amount per brick (3). Frame rate is indicated in the corner of the screen, informing the operator about light conditions (4)

of mortar per brick, indicated with an abstract trowel from full to empty. Second, similar to the main type of feedback in conventional AR systems, the bricklayer is shown a red outline of the desired position of the brick. This outline gives the bricklayer a fast understanding of the rough placement and rotation of the element. When the brick is approximately placed, the operator accepts the position via manual sensory input, and the interface switches to fine adjustments. In this stage, arrows appear, and the bricklayer uses the trowel to hit on the positions indicated by red arrows with the strength indicated until they vanish. The arrows vanish if an accuracy between the estimated and desired brick 3-D pose is 4 mm or lower. A lower error acceptance (<2 mm) was tested, but the system's sensitivity, in combination with material viscosity and human dexterity, led to a long execution time, as bricklayers spend too much time trying to adjust the bricks till the arrows vanished.

Therefore, 4 mm proved to be the ideal ratio. Every brick was indicated with an index number to allow the bricklayer to self-control during the process and to avoid skipping bricks within one row. To bring this technology from the lab onto the construction site, several different visualisation setups were initially explored and compared, utilising screens, tablets (openCV and OpenGL), and head-mounted augmented reality device (HMD-AR) (*Magic Leap*). For the specific case study (outdoor, bright), a screen-based system proved to be the most efficient visualisation platform, as the permanent display offered the possibility to communicate between craftspeople and even to other non-AR audiences. The brick wall was designed in Rhinoceros with a Python-based script using Grasshopper and COMPAS [109]. The position of each brick, as well as the global reference geometry, was saved via a text file which was read by the system. This file represented the connection between the digital design and the tracking system storing the sequence of each brick as well as their desired target position.

Additionally, this text file could store supplementary information for each brick, which was

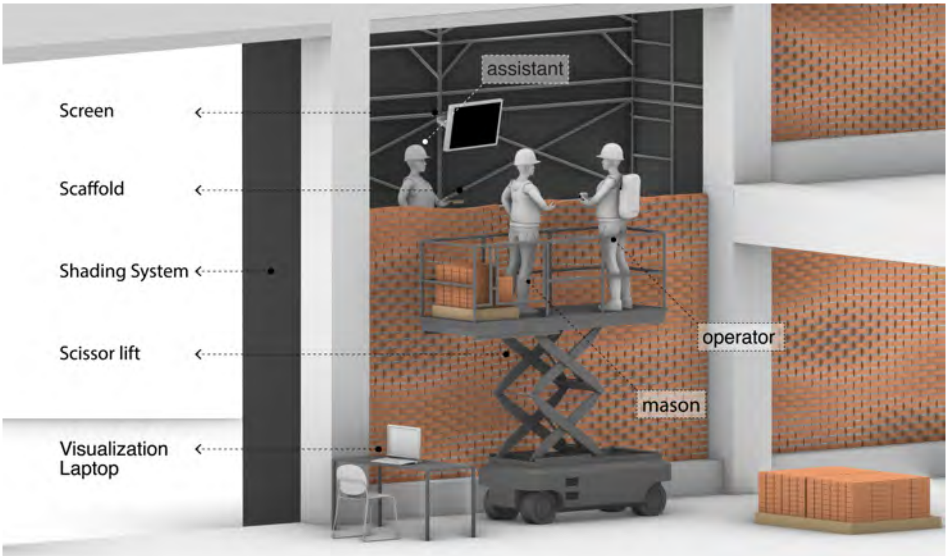


Figure 3.7: Diagram and pictures of the on-site setup

then visualised during the augmented bricklaying process. This information included changes in brick geometry (half or full brick), mortar amount, index and row number. Throughout the building process, the list of additional information changed according to needs.

Case study

The final implementation of the proposed system was used to build a double fair-faced geometrically differentiated permeable masonry façade for the Kitrus vinery in Katerini/Greece. The structure included eight infill masonry facade elements of 5 by 5m and three small-scale facade elements of $5x3$ m resulting in a total of 245^2 of brick façade (Fig. 3.8). Overall, a total of 13596 handmade bricks were used. To highlight the malleability of mortar and the flexibility gained by the AR fabrication system, the design exploited a differentiation of brick courses and varying mortar height (5mm to 30mm) using a time-based Perlin noise field. The rotation of the individual bricks was related to the amount of the underlying mortar ($-20°$ degree to $+20°$ degree rotation). The gap between the individual bricks was used to allow ventilation and light into the building and ranges from between 22 and 24 mm. The structural support system of the fair-faced non-load-bearing façade consists of four horizontal bars and custom-made metal blades cut, inserted and glued into the brick wall on-site.

On-site deployment

During the construction period, two teams were operating two individual AR systems. Each team consisted of three workers: one bricklayer, one assistant, and one system operator (Fig. 3.7). The division of tasks was separated, whereas the bricklayer and the operator placed the individual bricks and operated the system, the henchman meanwhile cleaned the mortar joints and fulfilled side tasks such as mortar preparation. The screen was placed on an adjustable monitor arm and displayed virtual and real stimuli. Due to the height of the walls,

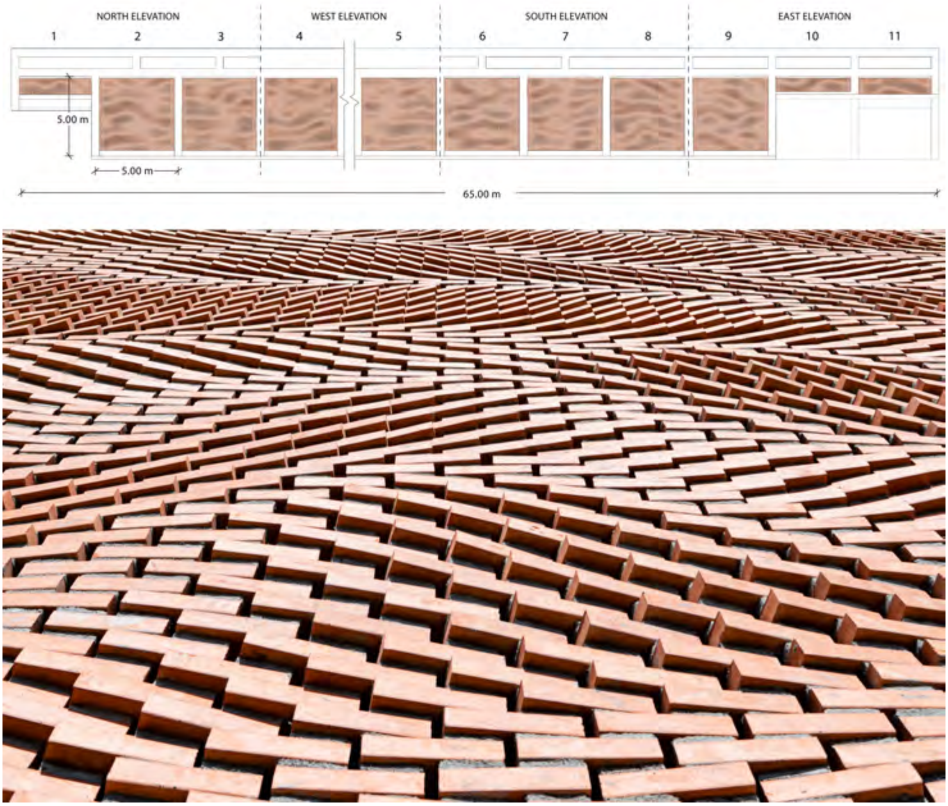


Figure 3.8: Design articulation of Kitrus winery

the bricklayer and operator were stationed on a scissor lift, emphasising the importance of an untethered approach. The front of the building was covered by a black, translucent shading system to avoid hard shadows on the bricks, which potentially could lead to tracking errors. The infill brick walls were circumscribed by a concrete framework (Fig. 3.8), whereas the pillars were used as previously described global objects of reference for the tracking to minimise the accumulation of errors (Fig. 3.9).

Results

The construction period spanned over three months, experiencing extreme Mediterranean climates ranging from summer to winter outdoor conditions. The typical building speed for fair-faced brickwork is 1 min/brick for two bricklayers. The average time per brick after a learning and adjustment period with the custom AR system was measured at 3 min/brick, which equals three times the amount of straight fair-faced brick masonry without rotation or vertical movement. The precision of the brick wall resulted in ± 5 mm local precision and ± 1 cm precision in an overall span of 5×5 meters per facade element. These numbers are supported by the precise local connection points of each brick wall to the concrete frame (Fig. 3.9).

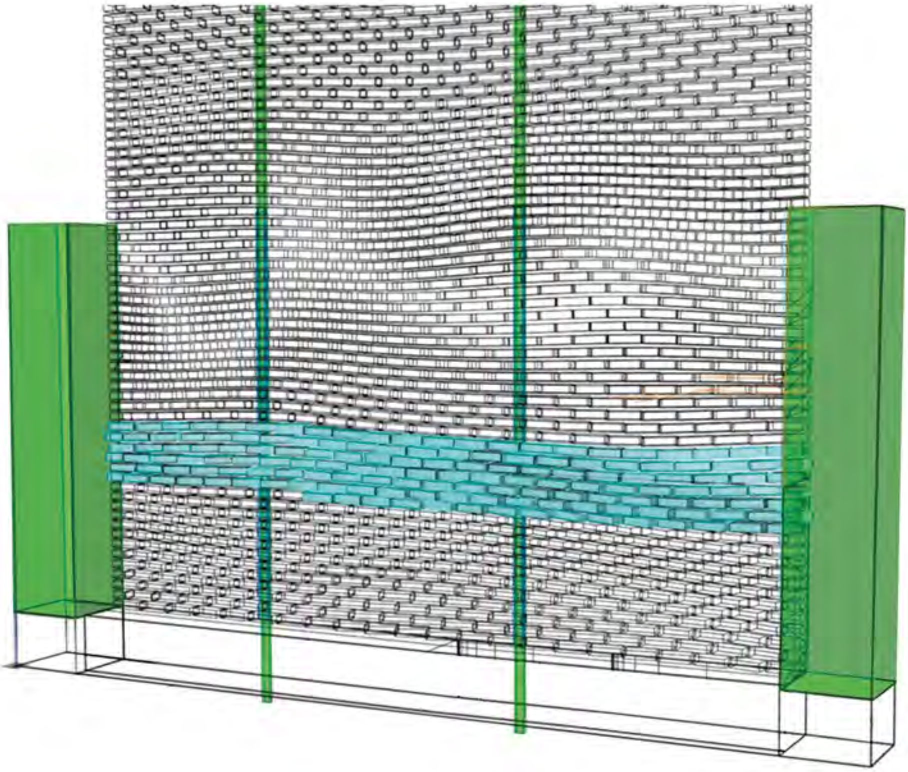


Figure 3.9: Global objects of reference (green) need to be precisely measured and digitised beforehand

The custom UI was analysed via a post-session usability study[2], and it proved to be very well received by the bricklayers. To analyse the user's perception, we chose a self-reported metrics questionnaire for post-task rating analysis. Additionally, to a paper form questionnaire, respondents were observed and recorded during task completion to gather additional information. To avoid social desirability bias, the survey was taken anonymously and in solitude. The outcome of the questionnaire showed that novice users without assistance had a significantly worse experience of the system. Moreover, users with assistance reported that it required less training compared to non-assisted users. Another key finding is the fact that the interface was perceived similarly by every group. The conducted study showed that novices require a short period of assisted introduction to the procedure to use the latter successfully. Nevertheless, the user's performance increased noticeably over time (Fig. 3.10), regardless of the visualisation platform or the assistance given. Unassisted novices, therefore, cannot use the system, as the number of errors made is too high. However, given that the user's performance increased steeply over time, they became competent to use the system alone after

[2] The user's performance was evaluated through observations of their behaviour and voiced opinions during the task, as well as the use of self-reported metrics in paper form after task completion. After task completion, the users were asked to fill out a paper questionnaire following the Questionnaire for User Interface Satisfaction (*QUIS*) model [110]. *QUIS* measures the overall perceived usability after the completion of a session. It consisted of 14 questions in which users would rate their level of agreement with statements using a 10-point Likert-type scale. Two teams were evaluated: first, four construction workers using the system for a few months and second, and four novices without prior experience.

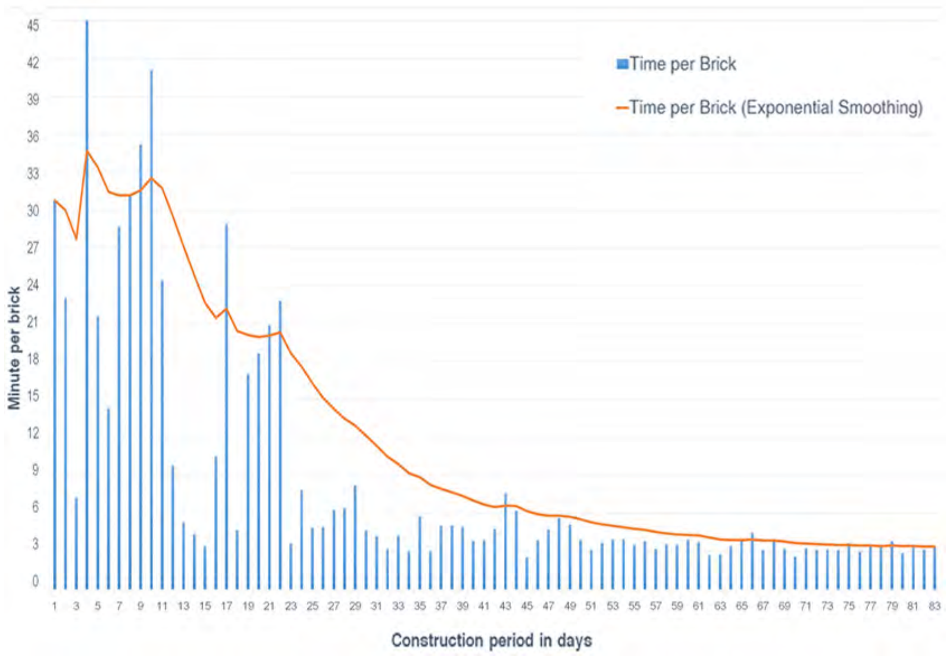


Figure 3.10: User performance analysis and learning curve

a training period with an assistant. The "eye-in-hand" system, the handheld camera system, needed some learning time as the optical axis of the camera points into a different viewing direction and sometimes leads to a potentially awkward translation of view direction. This fact indicates the potential advantage of head-mounted or phone displays. Nevertheless, after a learning period, the operator learns to use the system intuitively. The tracking system is stable for outdoor conditions and can be supported by the installation and registration of landmarks (concrete frame, vertical posts) to stabilise the system. Light conditions were another crucial parameter for the success of the system, as direct sunlight can produce very sharp shadow lines disturbing the distinct detection of bricks. Shading the sun with a black textile prevented this, but as the object-based visual–inertial tracking is continuously developed, one can foresee that this problem will be solved in future releases.

Conclusion

This paper outlines and discusses the novel UI tailored to the masonry craft and the overall system design and integration into the building site's layout and workflow. This technology has been tested in regard to accuracy (Fig. 3.9), indoor/outdoor conditions, and validated in terms of applicability, accuracy, and usability under outdoor conditions and on a large scale. The design explored the differentiation of brick courses with varying mortar heights and alternating rotations of the individual bricks (Fig. 3.11). Investigated through a large-scale demonstrator (Fig. 3.12), this paper presents different strategies for preserving consistent process improvements through AR for in-situ assembly in the domain of building accuracy and assembly speed. For future development, the object detection algorithm could be included in off-the-shelf (HMD) as an app-based application, including both user-friendliness of HMD and context awareness of such tracking systems. In this case, if multiple craftspeople are working on a piece, a shared workspace would be necessary as communication is of utter importance on a construction site. Another future development would be the combination of the AR bricklaying processes with robotic fabrication, whereas a sensible task distribution between the craftspeople and the robot has to be developed. Significantly, the project extends digitalisation to conditions and building scenarios that would resist a fully automated robotic process. Such an approach is particularly relevant to construction scenarios ill-equipped with the necessary infrastructure to support an on-site robotic process or in material processes that benefit from tacit knowledge and craftsmanship or scalar restrictions, which are easier to overcome in an AR manual fabrication process. Another important quality of such an approach is social sustainability, the effective integration of traditional craftsmanship with digital fabrication processes. This approach is not to be understood in opposition to on-site robotic production but rather as a complementary and synergistic approach, which would be used selectively and strategically to more fully extend the potentials, application scenarios and thus the impact of digital construction.

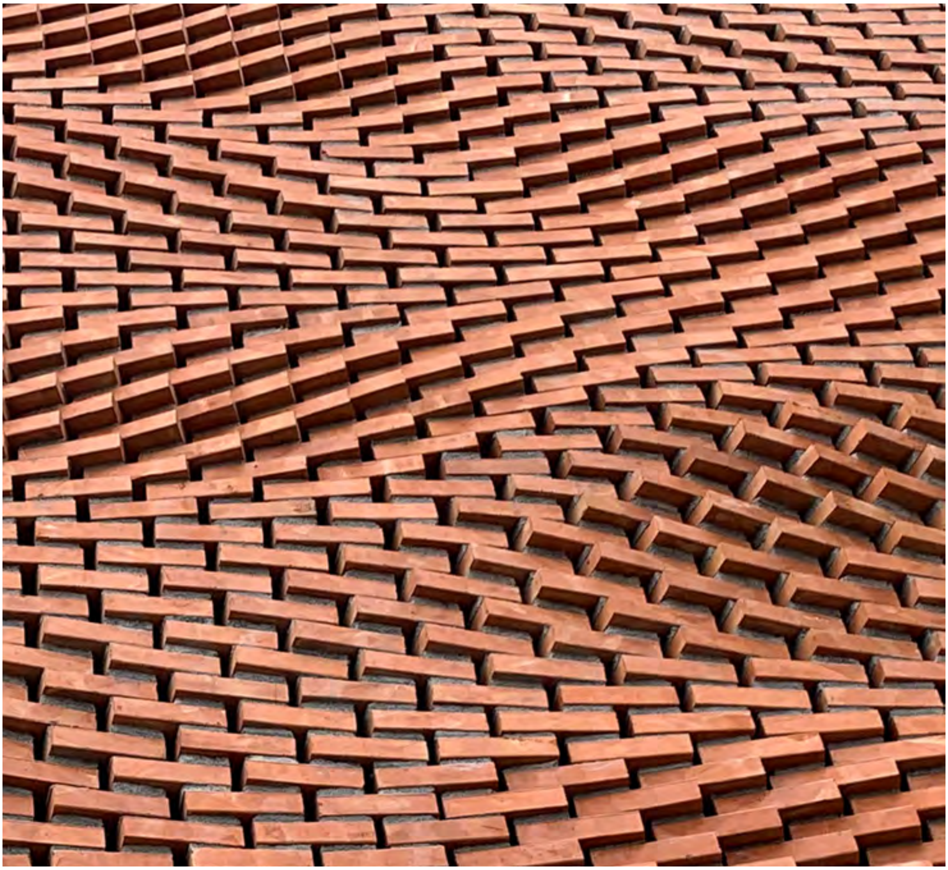


Figure 3.11: Kitrus winery façade: The individual rotation of each brick correlates to the amount of mortar underneath

3.1.3 Credits and acknowledgments

Author's contribution:

From 2018 to 2019, the author of this thesis undertook the conception, development, testing, and validation of the *machine-assisted human fabrication* workflow. Additionally, the author defined the workflow setup and implemented several visual feedback systems and AR UIs. The workflow setup included the integration of a visual-inertial object tracking system into the architectural design and planning environment, linking it with a digital twin able to register human actions via object tracking. In addition, the workflow required developing a set of computational tools to enable an integrated design and fabrication process for augmented bricklaying. The workflow included the generation of brick-wall assembly sequences for the custom-built AR system for in-situ fabrication and the implementation of a high-level communication system for the sensor system. Furthermore, the author of this thesis designed and developed a bespoke craft-specific AR-UI, linking it with the visual-inertial object tracking system.

Finally, the author conceived and implemented the architectural application scenario and physical prototypes presented in this thesis. To analyse the workflow via quantitative and qualitative methods, the author carried out user studies and a user performance analysis to evaluate the precision of the process, the user experience, and the learning curve of the masons.

Collaboration:

The sensing solution of the visual-inertial object tracking was developed by Dr. Timothy Sandy at the Agile & Dexterous Robotics Lab (ADRL), led by Prof. Dr Marco Hutter [100]. The building project and the research presented in this paper were developed under the supervision of Dr. Kathrin Dörfler (Gramazio Kohler Research). Foteini Salveridou (Gramazio Kohler Research) assisted with the on-site fabrication.

Authors contributions to the paper:

The contributions of each author in this paper are described using the Contributor Role Taxonomy [111].

Daniela Mitterberger Conceptualisation, Methodology, Software, Validation, Data curation, Formal analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Project administration

Kathrin Dörfler Conceptualisation, Methodology, Software, Validation, Investigation, Writing – Original Draft, Writing – Review and Editing, Supervision, Project administration

Timothy Sandy Methodology, Software, Validation, Investigation, Data curation, Formal analysis, Writing – Review and Editing

Foteini Salveridou Investigation

Figure 3.12: The design of the semi-transparent façade reflects the idea of a constantly changing pattern resembling the shimmering light of liquid

Marco Hutter Conceptualisation, Supervision, Writing – Review and Editing, Funding acquisition

Fabio Gramazio Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Matthias Kohler Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Acknowledgements:

This paper and the research were supported by the extensive contribution of fellow researchers of Gramazio Kohler Research, Lukas Stadelmann, Fernando Cena and Selen Ercan, and the Robotic Systems Lab, Lefteris Kotsonis. We thank Lauren Vasey (ETH Zurich) for editing and commenting on the manuscript. Tobias Bonwetsch of RobTechnologies accompanied the building project realisation. We would finally like to express our thanks to the project clients, the Kitrus winery, and the family Garypidis for their trust and support throughout the project. Additionally, we would like to thank Eleni Alexi and Dimitris Ntantamis for their tireless effort on-site throughout the process. Thanks to Luigi Sansonetti (ETH Zürich) for helping with the post-session usability study for bricklaying in AR, focusing on visualisation platforms and learning curve.

Figure 3.13: Design adjustments are made on-site to update the digital model to inform the AR interface.

Figure 3.14: Augmented Bricklaying setup with one operator and one mason.

Figure 3.15: Masons are evaluating the recently finished wall element.

Figure 3.16: The finished building has a changing shadow pattern on the facade depending on lighting conditions.


WÄLTI
BAUMASCHINEN AG


GÜDEL
SIEMENS
Adjust the position of the last Curve using the touchpad
26
27
25
28
20
28
20
23
29
21
30
30
31
39

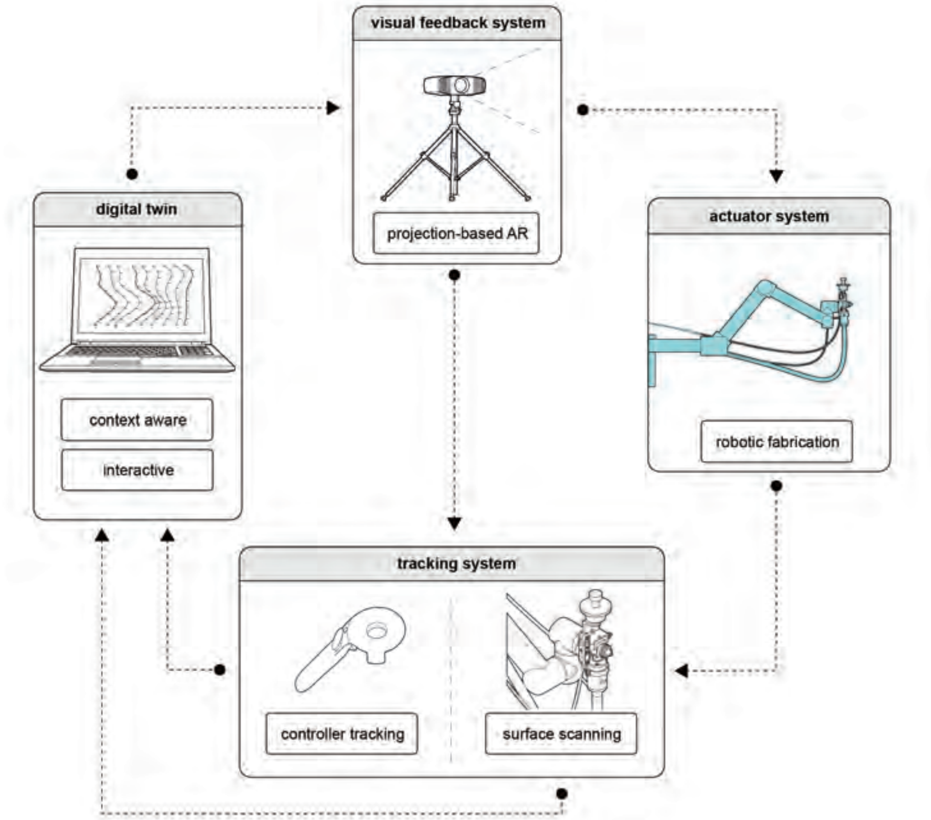


Figure 3.17: Diagram visualising the applied methodology for Interactive Robotic Plastering: (a) context-aware and interactive computational model, (b) projection-based AR, (c) robotic fabrication, (d) controller tracking and surface scanning

3.2 Human-instructed machine fabrication

3.2.1 Summary and contribution to thesis

This paper[3] contributes to expanding the concept of *human-assisted machine fabrication* by enabling humans to engage intuitively with an in-situ robotic plastering process. This paper introduces methods to include human tacit knowledge and creativity in a robotic plastering process. It does so via an iterative and interactive design feedback loop (Fig. 3.17). An audio-visual feedback system enables humans to create, preview, and adapt the design of a 3D plasterwork in-situ and from scratch. This system translates intuitive human instructions to robotic movements within the boundaries of machine and material constraints. To achieve this translation, the study utilises a digital twin, which is informed by the current as-built state of the prototype and adapts to human hand movements. The digital twin obtains information about human hand movements via controller tracking and the current state of the prototype via surface scanning. A projection-based AR system is connected to the digital twin, allowing humans to preview robotic spray paths before they are executed. Finally, after a design is approved by a human, it can be directly sent to the robot for fabrication.

[3] This version of the article has been accepted for publication, after peer review, but is not the Version of Record. The Version of Record is available online at: https://doi.org/10.1145/3491102.3501842

3.2.2 Interactive robotic plastering: Augmented Interactive Design and Fabrication for On-site Robotic Plastering

Daniela Mitterberger[1], Selen Ercan Jenny[1], Lauren Vasey[1], Foteini Salveridou[1], Ena Lloret-Fritschi[1], Petrus Aejmelaeus-Lindström[1], Fabio Gramazio[1], Matthias Kohler[1]

Abstract

This paper presents interactive robotic plastering (IRoP), a system enabling designers and skilled workers to engage intuitively with an in-situ robotic plastering process. The research combines three elements: interactive design tools, an augmented reality interface, and a robotic spraying system. Plastering is a complex process relying on tacit knowledge and craftsmanship, making it difficult to simulate and automate. However, our system utilises a controller-based interaction system to enable diverse users to interactively create articulated plasterwork in situ. A customisable computational toolset converts human intentions into robotic motions while respecting robotic and material constraints. To accomplish this, we developed both an interactive computational model to translate the data from a motion-tracking system into robotic trajectories using design and editing tools as well as an audio-visual guidance system for in-situ projection. We then conducted two user studies of designers and skilled workers who used *IRoP* to design and fabricate a full-scale demonstrator.

Keywords interactive fabrication, augmented reality, robot, digital fabrication

[1] Gramazio Kohler Research, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland

Introduction

In the past decade, robotic fabrication in architecture, engineering, and construction (AEC) has made remarkable advances, leading to significant improvements in the customisation of construction, production speed, and precision, as well as opening up new design opportunities [1–3, 5, 112]. However, most robotic construction processes are based on well-defined and linear sequences of actions where the work environment, materials, and processes are unambiguous and predictable.

Construction processes involving complex or soft material systems, such as concrete, plaster, or clay, face many challenges that make their automation difficult. An example of such a difficult-to-automate process is robotic plastering. The malleability of plaster is difficult to control, as it changes from a liquid to a solid state during processing. This change is influenced by several parameters, including ambient temperature, material composition, and spray parameters. Even with the most advanced digital modelling and rendering software, the behaviour of such a malleable material is difficult to simulate [10, 11, 113]. Moreover, advanced rendering and visualisation environments still fail to convey the same depth, texture, and sense of materiality that can be achieved through manual handling and tacit user interaction [114]. Yet, the application of robotic plastering could help to create more controllable, repeatable, and precise surfaces and would rely less on strenuous physical labour. Therefore, plastering is an excellent example of a construction trade that would greatly benefit from combining craft-specific knowledge, tacit interaction, and robotic fabrication to define novel design potentials and process innovations.

One potential solution to the difficulties posed by materials like plaster would be a balanced combination of human interaction with robotics and digital technology. Such collaborative systems could leverage the unique strengths of both machine precision and human tacit knowledge. The potential and need for such human-in-the-loop processes are clear, but so far, only a few studies [78, 79] have examined how to include humans in larger-scale robotic fabrication. Furthermore, human-in-the-loop processes in AEC are still perceived as a limitation rather than as a source of potential. There are several reasons for the scarcity of research on this topic in AEC. One of them is the lack of understanding of the complexity of bringing full automation into an unstructured environment like the construction site. Another reason is that industrial robots have only limited options for user interface (UI) customisation [115], which makes it challenging to develop customisable and intuitive craft-specific interfaces for robotic processes in construction. In summary, most research on robot manufacturing in architecture is aimed at full automation, which excludes any aesthetic and technical potential of human-in-the-loop manufacturing.

The aesthetic potential of such processes is strongly linked to the physical participation of the human during the fabrication process. Studies on the importance of physical participation in digital and robotic processes touch on concepts of interactive fabrication [13, 14] and digital embodiment [116], and emphasise the close connection between physical action and cognition in the design process [16, 17]. In particular, direct engagement with the material can serve as a fundamental cognitive resource for designers and skilled workers [18]. An interactive robotic fabrication workflow coupled with a customisable design interface could help designers and skilled workers intuitively learn and manipulate complex design and manufacturing processes. In addition, such tools could minimise the background knowledge needed to program such a robotic process.

This paper presents such a system for plastering, the Interactive Robotic Plastering system (*IRoP*), which enables users to engage intuitively with an in-situ robotic plastering process. The system combines a robotic spraying setup with a controller-based interaction system and an augmented reality (AR) interface. The proposed method utilises the controller's movements to program intricate robotic spray paths (robot trajectories), thus capitalising on the embodied knowledge of designers and skilled workers. The system developed here allows users to design complex digital models in minutes, rapidly generate multiple design alternatives, and instruct a robot by demonstration.

This research is developed for robotic and computational applications in AEC, which has stakeholders with a broad range of knowledge and skills. The target user group for this system includes both designers and skilled workers. We use the term skilled worker to refer to a craftsperson who has extensive plastering knowledge but limited robotic programming experience. The term designer includes individuals specialised in computation and the creative use of robotics for architecture fabrication with diverse levels of computational and robotic competence.

Specifically, the contributions of this paper are:

1. a novel method for on-site robotic plastering that uses programming by demonstration to define complex robotic trajectories (spray paths) and fabrication parameters. This method proposes a projection-based AR interface for taking design decisions and previewing their effects on-the-fly.
2. a full-scale demonstrator and user study conducted with 18 designers validating the hypothesis that enabling design decisions during fabrication can provide new opportunities for future crafting and, as presented in this paper, can lead to novel forms of creative expression.
3. a user-study with skilled workers demonstrating that this system can substantially simplify the programming of robotic fabrication and thus make robotic fabrication accessible for users with no or little prior knowledge of robotics. The results of this approach suggest that we can use controller tracking in combination with projection mapping as an interactive design tool for on-site robot manufacturing.

This paper is structured as follows: We begin by reviewing human-guided machine fabrication, robotic plastering, and projection-based AR. The method section then introduces the system architecture, presenting how the system works, the necessary hardware components, and a description of the software features. More specifically, we focus on the customisable computational toolset, the motion-tracking system, the set of design and editing tools that can remap user input to robotic spray paths, and the audio-visual guidance system for on-site projection. In *Experiments and results*, we present two experimental studies: one with designers and one with skilled workers. Study 1 shows how designers explored the design pipeline of *IRoP* and interactively designed and fabricated a large-scale architectural implementation. Study 2 evaluated the usability of *IRoP* by conducting a user study with skilled workers. In conclusion, we discuss our findings, limitations and potential future investigations.

Background

The following sections describe how our research builds upon existing work in exploring new modes of human-guided machine fabrication, robotic plastering, and projection-based AR.

Human-guided machine fabrication:

Human-guided machine fabrication in digital fabrication describes a system in which a user provides an input to the fabrication system and a machine responds with physical feedback, allowing for direct manipulation of a physical form during fabrication [13, 58]. The user's physical actions are sensed through an interactive interface and interpreted in real-time. This workflow allows for a semi-autonomous fabrication process, where the user can either physically handcraft with machine precision or interactively change the design outcome during fabrication.

Handcrafting with machine precision: A way to offer a hands-on fabrication experience is to use devices which correct users' physical movements by providing real-time feedback on design outlines and constraints. Projects such as *FreeD* [63], *Protopiper* [117], *Human-in-the-loop Fabrication of 3D Surfaces with Natural Tree Branches* [118], *Adroid* [65] and the *Shapertool* [64] show how the additional automated actuation and correction mechanisms of a tool can enable safer handcrafting with machine precision. However, these systems focus primarily on reproducing a digital model in physical space and do not support interactive design in 3D from scratch. Another limiting factor of those systems for architecture is that they are designed to manipulate objects on a relatively small scale.

Interactive fabrication:

Several systems explore interactive fabrication in which humans can intervene creatively in the digital design and fabrication process. For example, *ReForm* [81] shows how users can manually alter clay forms to influence the digital design process. *Spatial sketch* [119] allows users to sketch in 3D and to transform the digital sketch into real-world objects. Other systems also combine robotic fabrication and human interaction to fabricate larger-scale artefacts. *The Endless Wall* by Gramazio Kohler Research [82] allows a user to change the design of a robotically assembled brick wall by adjusting a line in situ. *RoMA* [83] allows users to interrupt a robotic printing process to adjust the design while fabricating. Finally, in the project *FormFab* [14], users can change the surface curvature of a plastic sheet in real-time using reversed vacuum-forming techniques. These systems enable the human to intervene creatively in the fabrication process, but they do not apply any constraints to the human input or provide information to the user about potential failure or the constraints of the machine, structure, or material. *RobotSculptor* [120] is an interactive robotic fabrication system that allows users to fabricate clay models using a robotic arm while providing design and fabrication constraints. This system enables creative expression through the user's definition of sculpting area, stroke direction, density, and tool selection. However, the user still interacts with a graphical UI, not with the workpiece itself, which leaves out the creative potential that a hybrid design and fabrication environment could offer.

Robotic Fabrication with soft materials:

Robotic fabrication processes with soft materials often require human interaction and supervision to validate results and facilitate automation. Projects such as *Meshmould* [121] and *Soil 3D-printing* [122] combine a robotic process with manual fabrication steps, while *Smart Dynamic Casting*[123], *Shotcrete 3D Printing* [124], and research in 3D concrete printing such as [125] use sensory feedback to inform users about material performance. All these processes require human participation in the robotic process for either material deposition, quality control, or finishing. However, they do not explore human interaction for providing feedback on potential structural or material failures and do not enable direct process intervention.

Creative programming by demonstration:

To allow human-guided machine fabrication through direct tacit interaction, this research focuses on programming by demonstration (PbD). PbD is an end-user development technique for teaching a computer or a robot new behaviours and tasks [126]. Instead of conventional machine command programming utilising CAD software, the user directly demonstrates the desired motion trajectory through actions. This demonstration can happen through vision [127–129], data gloves [130], controllers [131], or kinesthetic teaching (i.e., by manually guiding the robot's arms through the motion) [132]. Such systems shift the programming power from the professional programmer to the end-user but focus mostly on pure guidance for automation processes. Projects such as *Adaptive Robotic Carving* [36] and *Seeing is Doing* [133] show how PbD can allow skilled workers with limited programming skills to transfer their techniques and knowledge to the machine. However, these systems do not allow users to interactively fabricate or design on-the-fly. In contrast, *IRoP* focuses on controller-based PbD to instruct a plastering robot based on user interaction, and thus it has the potential to enable designers and skilled workers to interact with computationally difficult technology.

Robotic plastering

Plaster is typically used for interiors, ceilings, walls, or on facades. It has diverse roles ranging from protecting the building structure to improving the acoustic performance of spaces by making use of the three-dimensionality of the material. The latter inherently includes visual and ornamental qualities. When generating ornaments with plaster, traditionally, customised tools or running moulds are used [134]. Early research on automation in the 1990s [135–137], and several contemporary academic research projects and start-ups have been exploring the robotic application of plaster. Such processes target the reduction of the dependence on manual labour addressing to automate a standardised plastering process [138, 139]. Furthermore, there has been research on robotic plastering, which focuses on exploring material formation, ranging from smooth to articulated surfaces [140]. These systems show the potential of creating novel forms of plasterwork through robotic plastering. However, none of the previous examples have implemented an interactive fabrication system or allowed a plasterer to interact directly with a robot in a shared workspace. Furthermore, they lack real-time feedback during the fabrication process that could alert the user of material and structural failures.

In this paper, we will use the process of *Robotic Plaster Spraying*(*RPS*), which creates plasterwork through an adaptive thin-layer printing technique. This technique involves spraying multiple, millimetre-thin layers of plaster on existing building elements in order to incrementally build up volumetric formations (Fig. 3.18, right [141]). A typical manual plastering process consists of (1) manual spraying of the material (2) and smoothing, levelling or shaping with additional

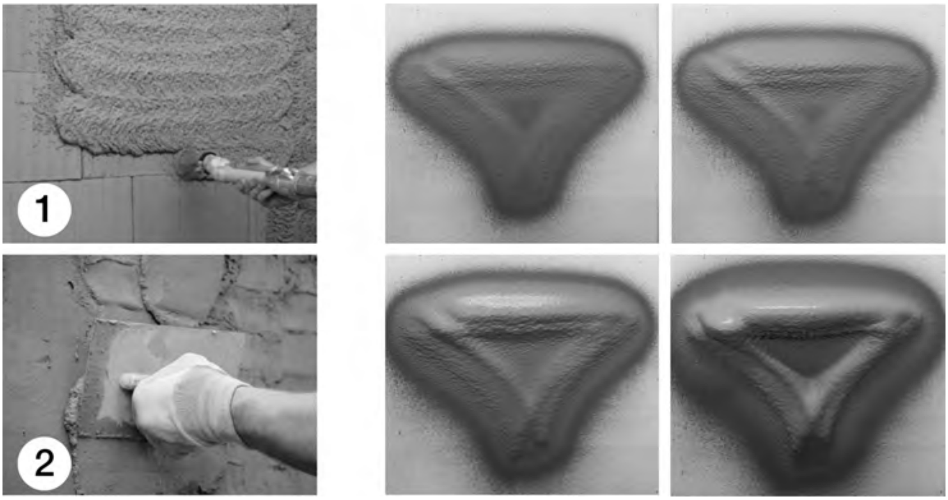


Figure 3.18: Left: (1) Manual spraying of the material (2) and smoothing, levelling or shaping with additional tools. Right: Robotic Plaster Spraying, an adaptive thin-layer printing technique, builds a volumetric formation without any additional formwork or support structures.

tools (Fig. 3.18, left [142]). In comparison to the manual spraying of plaster, robotic plaster spraying combines the spraying and shaping of the material in one process step, which makes it a repeatable and scalable process. This is achieved by digitally controlling specific fabrication parameters, such as the robotic arm's distance, angle, and speed. Furthermore, *RPS* allows for adaptive process control by using sensory feedback. Such a robotic plastering process shows the potential of making plastering efficient for standard and non-standard construction by promising up to 50% material savings. Moreover, the process can create complex volumetric plasterwork without the need for any additional formwork or support structures.

Our goal in the presented work is to combine the process of *Robotic Plaster Spraying* with an interactive fabrication system using a projection based AR system enabling users to intuitively program a robot by demonstration using real-time feedback.

Projection-based augmented reality:

Recent advances in immersive and augmented technologies allow users to receive fabrication-related information on-site, introducing novel forms of interaction between the physical and the digital realm for fabrication and construction. The overlay of the actual physical environment with computer-generated images is known as augmented reality (AR). AR systems usually accomplish this combination of the real and virtual world via optical or video technologies, which carry both advantages and disadvantages [143]. Video technologies usually overlay a live video onto the physical world, most commonly on display, or a mobile device such as a tablet or smartphone [99, 144, 145]. The overlayed graphics are updated continuously to appear to be inserted into the real world.

This approach has the disadvantage that it might divert attention away from the site condition as the user focuses on watching the screen or mobile phone display. Optical systems, such as head-mounted displays (HMD), address this shortcoming but require very expensive and sensitive equipment that is not ideal for unstructured environments, rough handling, dirt, and dust of a construction site [73, 105]. An alternative approach to achieve direct viewing of digital content in the physical world is to use projection-based AR. Research exploring projection mapping ranges from small-scale projection [146] to room-size projection mapping [71]. Several examples show how large-scale projections can cover entire surfaces and rooms [147–149].

Some researchers have explored using a motorised platform to re-orient a single projector and camera to view arbitrary locations throughout a room and to avoid being limited by the field of view of a single projector [150–153]. Pevzner et al. [154] focus on wall plastering, discussing how projection and scanning technology could provide workers with real-time information and feedback on the quality and accuracy of wall plastering. *IRoP* takes this approach of room size projection mapping for human instruction of complex materials further and links it with an interactive design system for large-scale robotic fabrication.

Interactive robotic plastering

The research presented in section *Background (Creative programming by demonstration)* highlights how programming by demonstration can be used to explore interactive design and engage users creatively in the fabrication process. However, state-of-the-art human-guided machine fabrication systems described in *Background (Human-guided machine fabrication)* either reproduce a digital model in physical space or implement open-ended systems with minimal constraints. *IRoP* aims to combine such an interactive design system with robotic plastering to translate human intentions into robotic motions via programming by demonstration. While most systems rely on predefined 3D models, *IRoP* uses data from users combined with robotic and material constraints to design 3D models from scratch. As such, this system capitalises on the intuition of the human user while still leveraging the power of machine precision and computational iteration. The method of this research can be largely defined as Research through Design [87] involving two user groups: designers and skilled workers. The research findings emerged through physical experimentation.

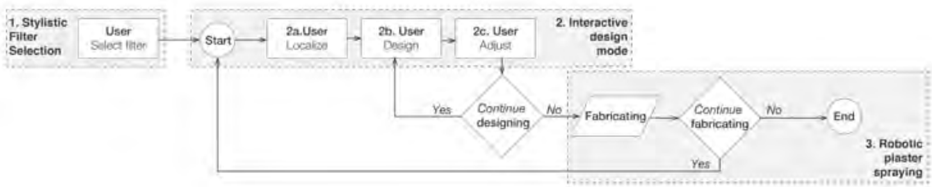


Figure 3.19: The design and fabrication workflow designed around three key modes.

System walkthrough

IRoP is designed around three different key modes that assist a user in interactively designing a plastered surface and output the necessary robotic spray paths, starting with *1. Stylistic filter selection*, *2. Interactive design mode* and *3. Robotic plaster spraying* (Fig. 3.19). After selecting a stylistic filter, users can use the computational model in the interactive design mode, which includes three steps: *Localize, Design* and *Adjust*. During the interactive mode, the user is instructed by an audio-visual guidance system. Figure 3.20 shows the hardware components

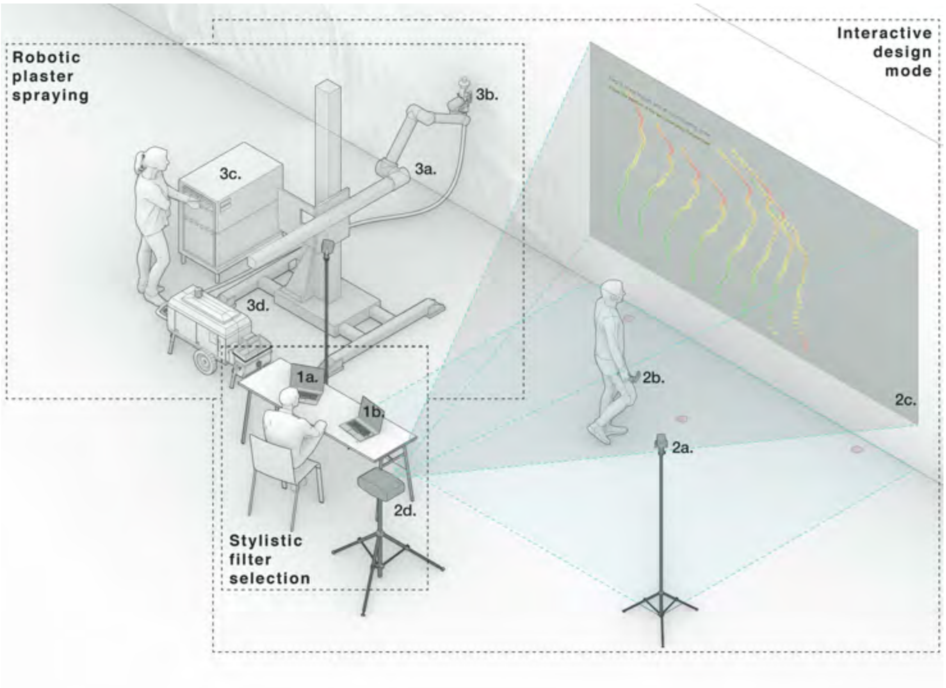


Figure 3.20: System architecture: computational setup (1a, b), the user interaction-tracking system with projection mapping (2a-d), robotic fabrication setup (3a-d)

of *IRoP* starting with the computational setup, the user interaction-tracking system with projection mapping, and the robotic fabrication setup.

Furthermore, the graphic shows that the user and the robotic arm are situated next to each other, where the 3D design is first interactively designed and then fabricated. To illustrate a typical interaction using the *IRoP* system, we consider the case of a designer fabricating a custom interior plaster element from scratch as shown in Figure 3.21. The user follows a routine of alternating between interactive design and fabrication sessions.

Selection of a stylistic filter (Fig. 3.21: A): Before the start of an interactive design session, the user can choose different stylistic mapping methods, which we refer to as stylistic filters. The term filter is chosen in reference to image-filters [155] used in digital image processing and graphical software such as Photoshop[4]. These filters describe a technique to alter the characteristics of 2D or 3D images by changing the colours of the pixels as well as adding a variety of special effects.

In *IRoP*, a similar logic is applied to translate and remap analogue human input into a robotic output such that it complies with material and machine constraints. These constraints include parameters such as maximum joint accelerations, robotic reachability, and other locally manipulated process parameters. The underlying computational model of the filters is based on the idea of a synthesiser, where the analogue input of the user, such as controller position and orientation, can be adjusted and transformed according to a set of different aesthetics and

[4] Adobe Photoshop is a raster graphics editor developed and published by Adobe Inc.

styles. Different filters result in different plaster surfaces, allowing users to choose how their input is stylised. Furthermore, users can extend the skeleton of the interactive computational model by creating custom filters to adjust for different requirements. The resulting robotic spray paths and additional important fabrication data are visualised as line drawings on the wall in real-time via an audio-visual guidance system (see Fig. 3.22).

Localize (Fig. 3.21:B): After selecting a filter, the user first localises the motion tracking system by registering the controller position at pre-measured area points in the physical space.

Design (Fig. 3.21: C): In the *design* step, the user can record the position of the handheld device by pressing the trigger on the controller. Depending on the filter system chosen, these positions can then be used to create geometry (points, curves), manipulate a surface, or generate a pattern. In the example shown in Figure 3.21: C, the positions of the handheld device were used to create points and interpolated curves to design the plaster surface. As the user selected the "tween" filter, the system offsets the hand-drawn guide curves in real-time by making the distance between the curves smaller or bigger. Using the same interaction steps, the user adds more lines to fill the wall segment.

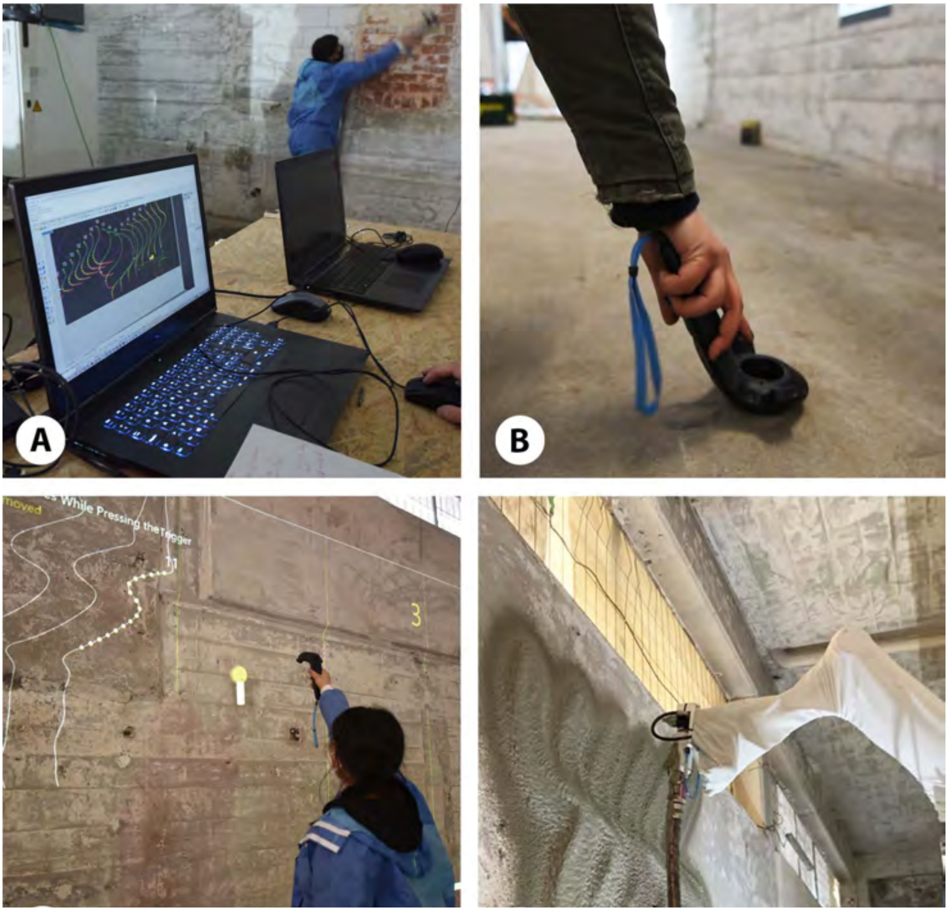


Figure 3.21: (A) Selection of filter (B) localisation (C) designing, adjusting the design (D) robotic spraying.

Adjust (Fig. 3.21: C): Since the user is drawing in a 1:1 scale, the user can transform the design in the "adjustment step" by scaling, moving, and extending it. This feature allows the user to reach areas that otherwise could not be reached, such as ceilings and high wall areas.

Robotic Plaster Spraying (Fig. 3.21: D): In the last step, the user approves the design outcome and exports the spray paths (robot trajectories) to start the robotic spraying process. The robot trajectories are simulated before they are executed, thus allowing the user to preview a safe and feasible robot motion within the work envelope. Next, the user mixes the plaster, and when the wet material is ready to be sprayed, it is fed into the pumping and spraying system. The user starts the spraying process by sending the robot trajectories to the robot controller for execution, which drives the material flow (spraying) and pumping. After finishing a sprayed segment, the user either continues fabricating or ends the process. If the user decides to continue fabricating, the system advances to the scanning step, which adapts the robot trajectories. To acquire the geometry of the current state of a target surface, an *Intel RealSense Depth Camera D455*, mounted on the pneumatic spray gun, is used. The robot trajectories are adapted after each spraying iteration by projecting them onto the current state of the target surface. This results in an adjustment of the desired spraying distance and angle.

The next sections describe the hardware and software components of the system in more detail.

System Setup

The system architecture, as displayed in Figure 3.20, consists of three main parts: (1) computational setup, (2) the user interaction tracking system with projection mapping, and (3) the robotic fabrication setup.

User interaction-tracking system: For the user interaction tracking system, we used an *HTC VIVE* with two base stations (lighthouses) (Fig. 3.22: 2a), one controller (Fig. 3.22: 2b), and two computers. Computer A (Fig. 3.22: 1a) is used to render the visualisation and run the customisable interactive computational model. Computer B (Fig. 3.22: 1b) is used to send and receive the sensor data. We chose the *HTC VIVE* tracking setup, as the precision for indoor tracking is under 5mm, and the system costs less than custom-built setups.

Projection mapping: An angled adjustable projector (Fig. 3.22: 2d) was used as an augmented interactive interface. We used a standard projector with 2000 lumen, which was fixed on a tripod and projected frontally onto the wall (Fig. 3.20: 2c). The position of the projector was registered in the digital model and was used as a camera position for projection.

Robotic plaster spraying setup: The overall robotic fabrication setup includes a 6-DoF, collaborative robotic arm (*UR10*) (Fig. 3.22: 3a), a pneumatic (plastering) spray gun (Fig. 3.22: 3b), an *Intel RealSense Depth Camera D455*, a *Collomatic Collomix XM2* mixer, a modified *PFT Swing L* pump (Fig. 3.22: 3d), and a *Kaeser SXC* series compressed air system. The material used is a base coat, lime-cement plaster that is fed into the pneumatic spray gun by the pumping system, which is driven by the *UR10* robot controller. The robot is mounted on two external axes (Fig. 3.22: 3c) that extend the working space of the *UR10*. For the global localisation of the external axis tower in a room, we use a total station.

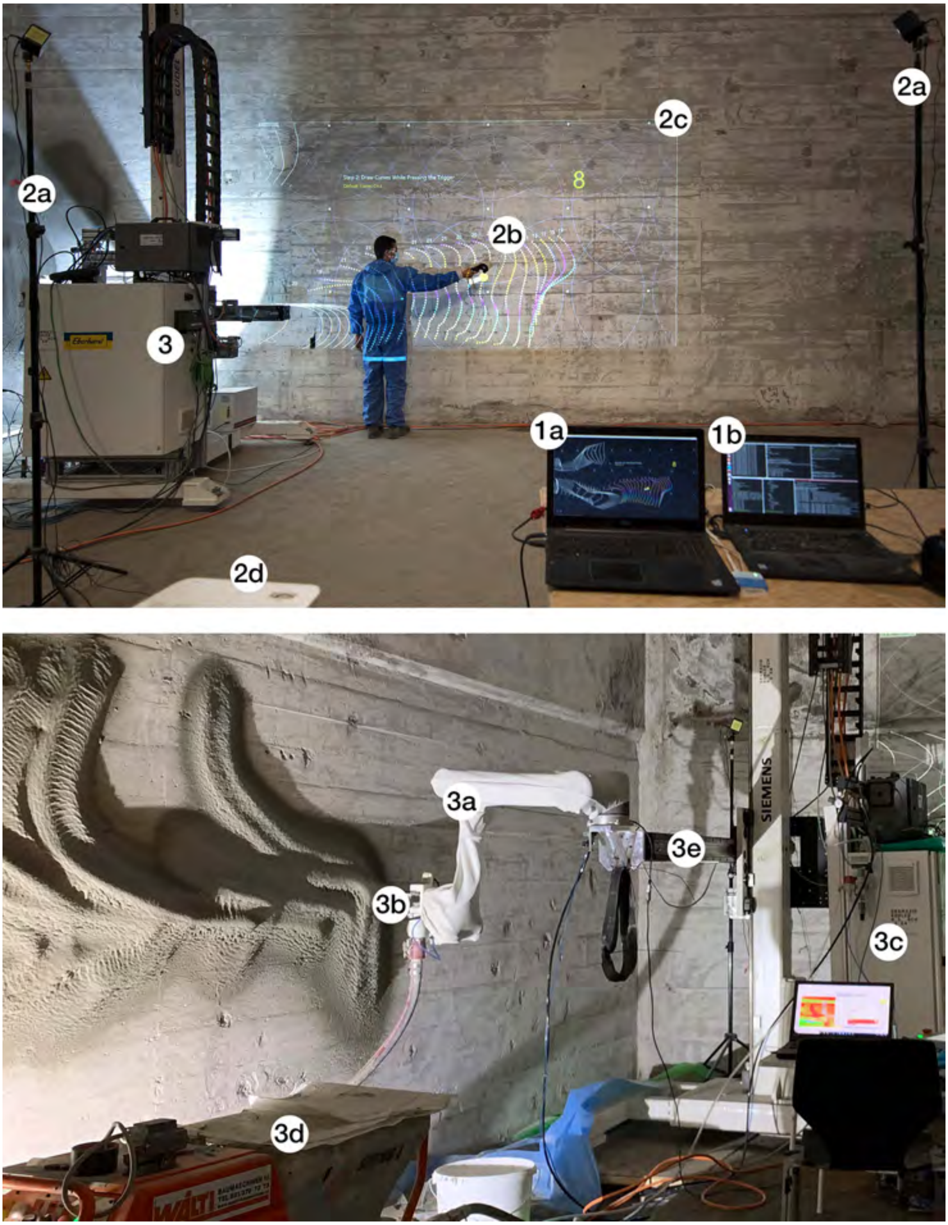


Figure 3.22: User interaction-tracking system including visualisation computer (1a), *ROS* master (1b), *VIVE* tracking system (2a), controller (2b), projection mapping (2c), projector (2d); Right: Robotic fabrication setup including *UR10* robotic arm (3a), spray gun (3b), controller box (3c), pump (3d), external axis (3e).

Interactive computational model:

At the core of the interactive computational model is the (1) tracking of user input, (2) remapping of the analogue human input to robotic output, and (3) generating of trajectories for the robotic arm. The computational framework is set up in *Python* and *Grasshopper*[5], and the visualisation happens in the 3D modelling software *Rhinoceros*[6]

Tracking of user input: A necessary component for the user interaction-tracking system described in *Interactive robotic plastering (System setup)* is a scalable, near real-time communication system for connecting multiple devices and back-end computational processes, which in this case was achieved utilising a *ROS* publish-and-subscribe architecture and the rosbridge package [156]. The interactive computational model receives as an input the *HTC VIVE* controller 6-DoF location and orientation as well as the button and trackpad information of the controller. To access the *HTC VIVE* localisation on *ROS*, we used the *OpenVR SDK* and a *ROS* package for publishing device locations using *Robosavy*. The *ROS* node interfaces with the *OpenVR SDK* to obtain the position of each device.

The user starts recording the tracking by pressing the trigger on the controller, which stores the position and rotation of the controller as frames defined by an origin point and two orthonormal base vectors. Depending on the chosen filter system, these frames can then be used in different ways.

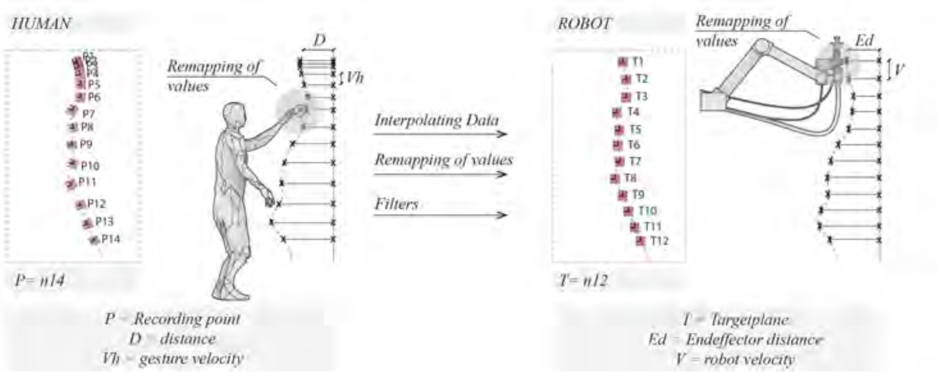


Figure 3.23: Translation of human input to robotic trajectories via interpolation and remapping of gesture input data to fabrication output data: $P \to T$; $D \to E_d$; $V_h \to V$

Remapping of human input to robotic trajectories: At the beginning of the process, the user could choose different filter systems to translate the human input into different robot outputs. In the computational model, the unaltered recorded controller poses (position and orientation) are stored as a list of frames (origin point, x-axis, y-axis) in a `filter_base` class. The `filter_base` class first transforms and scales these recorded frames from the VIVE coordinate system to the model coordinate system. Second, it trims the beginning and end of each frame list to filter out noise. Custom filters are methods in the `filters` class that remap spatial human inputs to machine outputs (Fig. 3.23). Different filters allow the user to either specify a more direct robotic action or create more generative designs driven by user input.

[5] Grasshopper is a visual programming language and environment that runs within the software *Rhinoceros*
[6] Rhinoceros is a 3D computer graphics and computer-aided design (CAD) software developed by McNeel and Associates

Table 3.1: Table showing the key remapping parameters

Abbreviation	Explanation	Unit
P	Hand position in space	-
D	Hand distance to target surface	mm
V_h	Gesture velocity	m/s
T	Robot target planes	-
E_d	End-effector distance to target surface	mm
V	Velocity of the trajectory	m/s
L_n	Layer number	-
E_a	End-effector angle	-

The hand's position in space (P), hand distance to a target surface (D), and gesture velocity (V_h) are translated respectively to robot target planes (T), end-effector distance to a target surface (E_d), and velocity of the trajectory (V) (see Table 3.1). The distance and velocity values are remapped between tested key parameters that were defined using empirical testing. The hand distance D is remapped between 200mm and 500mm end-effector distance E_d. Therefore, the closer the user's hand is to the target surface, the smaller the distance of the end-effector to the target surface. This results in a unique rippling pattern for smaller distances as the air pressure from the nozzle of the pneumatic spray gun displaces the wet plaster resulting in a carving effect (see Fig. 3.24). Therefore, D also influences the height of plaster deposited for each layer. Furthermore, D also influences L_n, the number of layers that need to be sprayed to achieve a specific geometry or pattern. A parameter that influences the amount of material deposited is the gesture velocity value V_h, which translates to the velocity of the robot's trajectory (V). V_h is remapped between 0.1m/s to 1 m/s of V. High-velocity V_h values result in high V and therefore lead to less material being deposited on the surface. In return, this translates to thinner layers. The end-effector angle is linked to a global variable that is defined at the beginning of each spraying session.

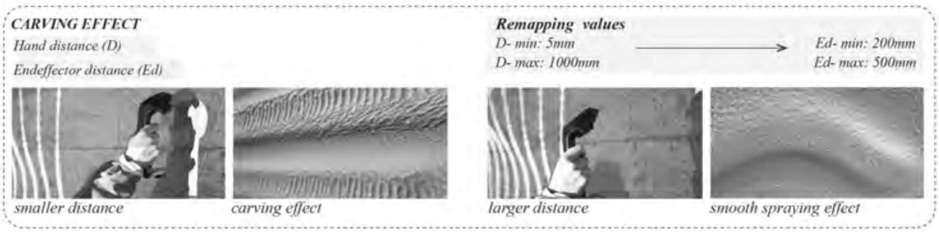


Figure 3.24: The remapping of the distance value D translates into specific plaster effects as a smaller D results in a smaller E_d leading to a carving effect.

Robot movement: Once the user decides on a design, it is stored in a JSON file format by pressing a button, which is followed by importing it into the fabrication module to be used by the robot to spray. The fabrication module we are using is built predominately within the open-source framework *COMPAS*[7]. This framework is also used for the simulation of the robot trajectories before execution.

[7] `https://github.com/compas-dev/compas`

Audio-visual guidance system:

IRoP provides an audio-visual guidance system to instruct the user while operating the interactive design mode. As described in the *System Walkthrough*, the interactive design mode has three different substeps with different functionalities: *(1) Localize*, *(2) Design*, and *(3) Adjust*. The audio-visual information changes when the user switches between substeps by pressing a predefined controller button. The UI for each substep has task-relevant information that is projected directly onto the building surface. All three different substeps (Fig. 3.25) have textual information in the upper left corner of the UI, instructing the user about the functionalities of the selected step.

IRoP provides the following interactive steps with distinct functionalities:

- Localisation step (Step 1) to localise the system
- Design step (Step 2) to design the robot trajectories and sprayed geometry
- Adjustment step (Step 3) to adjust the designed outcome

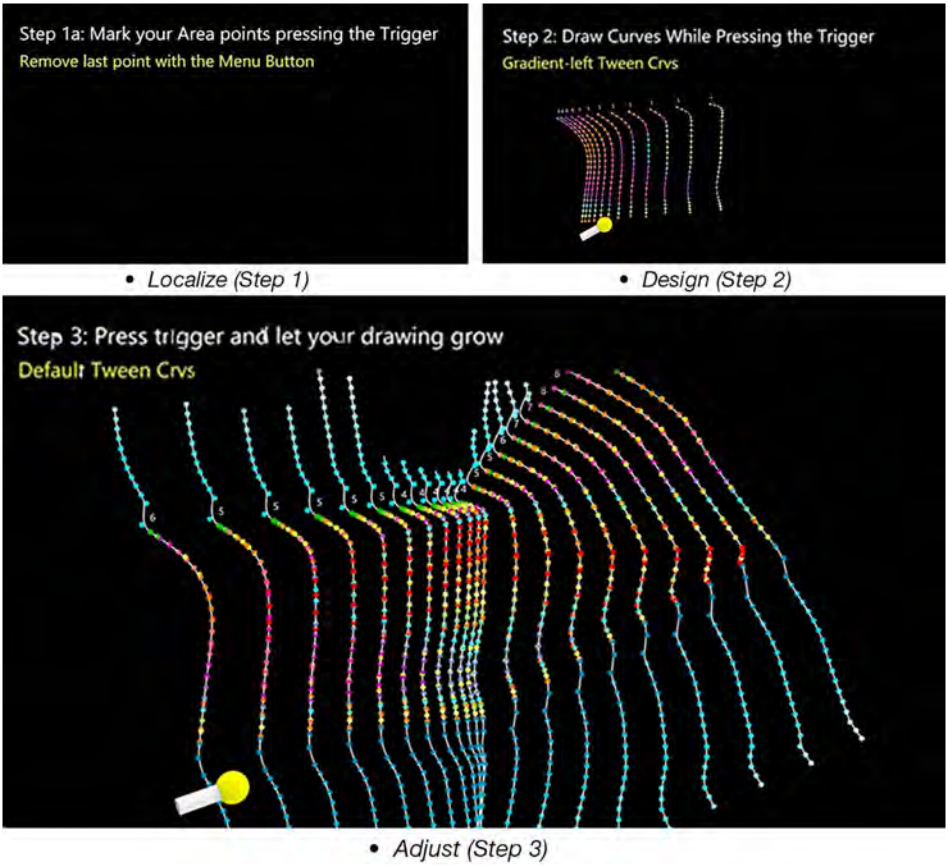


Figure 3.25: Screen recordings of the different interaction modes: Localize (Step 1); Design (Step 2); Adjust (Step 3).

Localisation step: In this step, the UI does not show any additional visual clues as the system is not yet localised. To instruct the user, we use tones to signal when the user records an area point as described in section *Interactive robotic plastering (Audio-visual guidance system)*.

Design step: An abstracted digital controller symbol shows the user the current position of the controller in space, allowing for a real-time experience. Projected fabrication constraints, such as the outlines of the robot reach from a stationary position (Fig. 3.26: 2), permit a more fabrication-informed design. Different gradient colours visualise the distance of frames to the wall surface, as the input is in 3D (Fig. 3.26: 3), ranging from purple dots, indicating a distance of 5cm, to white, which indicates more than 1m. The numbering describes the number of sprayed layers (Fig. 3.26: 4).

Adjustment step: The adjustment step shows users their extended or moved curves and the resulting updated design.

Audio-guidance: In many process steps, the user needs to direct visual attention to the construction site or the robotic manufacturing process. To overcome the limitations of purely visual cues, along with the visual interface, we developed audio guidance to signal certain events. Figure 3.27 shows the connection between the different interaction steps and the audio guidance. The audio guidance comes in the form of voice cues and tones. Voice cues alert the user to major events, such as the start of the system *("Welcome to the construction site")*, the localisation of the system *("Points are marked, projection is starting")* and the change between the different interaction steps *("You can start drawing", "Use the trackpad to reach higher", "Press trigger to let your drawing grow")*. Tones notify the user of special events within the substeps, for example, indicating that a position has been registered or has been successfully erased.

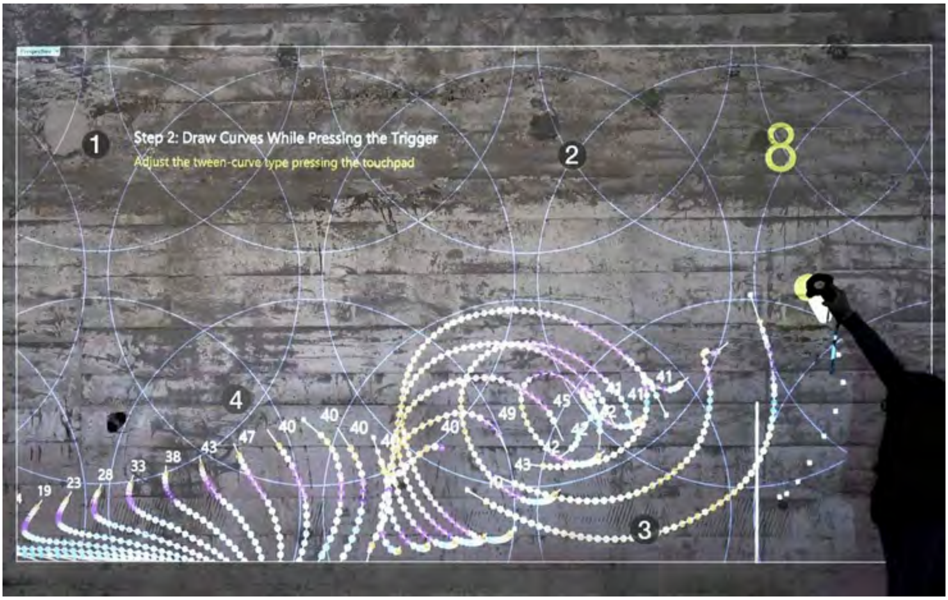


Figure 3.26: On-site projection mapping of Design step (Step 2): Interface shows fabrication parameters such as information on current (1) interaction mode, (2) robot reach from a stationary position, (3) distance of frames to the wall surface, and (4) the number of sprayed layers.

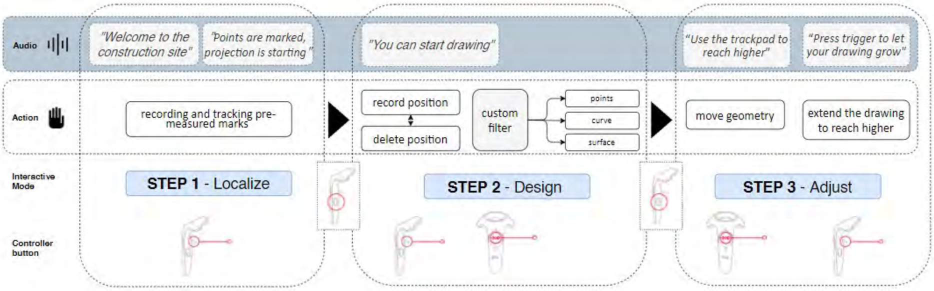


Figure 3.27: Audio-visual guided fabrication workflow.

Experiments and results

To validate the feasibility of the proposed method and to evaluate and clarify for real application of the interactive fabrication system, we focused on two experiments with different user groups: designers and skilled workers. The first group, the designers, tested the interactive design model by developing their own filter system and using the setup to build an articulated base-coat plasterwork. The skilled workers were five plasterers who tested the usability of the setup to evaluate it in a qualitative user study. In both cases, the experimental setup was used to evaluate the potential and disadvantages of an interactive fabrication system on a larger scale.

Study 1: Designer

We tested the system and procedure by fabricating a ~110 sqm interior wall design with robotic spraying over a period of 10 working days (Fig. 3.28). The system setup and procedure are described in section *Interactive robotic plastering (System Setup)*. Participants were 18 designers (Master students, PhD students and researchers) who are frequent users of digital design and robotic fabrication tools. Four of the 18 participants supervised the usage of the system and were more actively involved in the development of the AR-UI.

Phase 1: Filter development: First, participants developed their own filter system within the synthesiser design framework provided by *IRoP*. The filters implemented by the participants are shown in Figure 3.29 and included:

"Hand-drawing" filter: The user can draw in real scale the robotic 3-dimensional trajectories. The distance to a selected surface is translated into the number of sprayed layers for each trajectory.

"Pattern" filter: The user can translate the hand movements into small-scale patterns to populate a target surface. For this, different stroke and brush patterns were tested, such as circular, curve and hatch patterns.

"Tweening" filter: This filter is defined by user-drawn guide curves, which influence a linear pattern infill. The distance between the curves can be adjusted by the user, who chooses between equidistant interpolated, exponentially interpolated, and expressive interpolated curves.

Figure 3.28: Experimental setup showing the design and fabrication routine.

"Sculpting" filter: The sculpting filter allows the user to deform a digital mesh with hand movements. The robotic trajectories are then automatically generated by slicing the deformed mesh. Two types of spray paths were used - one for volume generation and one for texturing. The mesh was sliced vertically, so thicker volume resulted in slower robot movement.

"Agent-based-approach" filter: The user gives directionality and velocity as input to manipulate an agent-based system which fills a target surface. This approach limits user interaction time as the user's control of the design is limited, which at the same time enables efficient design on a large scale.

The participant's filter development proved to us that the system can be used by different designers to develop custom filters. These custom filters allow designers to quickly develop a multitude of geometric articulations. To test the overall workflow of interactive design and fabrication, the same designers were then asked in Phase 2 to use one of the filters to fabricate a custom, large-scale architectural implementation.

Phase 2: Full-scale Architectural implementation: For the full-scale architectural intervention, the designers chose the *tweening* filter as described in the previous section. Furthermore, participants chose the option to extend the curves using an agent-based approach to reach the ceiling. As described in section *Interactive robotic plastering (System walkthrough)*, design and fabrication phases alternated on-site. The participants decided to design collectively rather than choosing a single master drawer.

Localisation steps for full-scale implementation: The sensor systems of the interactive design system did not cover the entire room, and the robotic spraying system was not an autonomous mobile system. Therefore both systems had to be manually moved, localised and calibrated

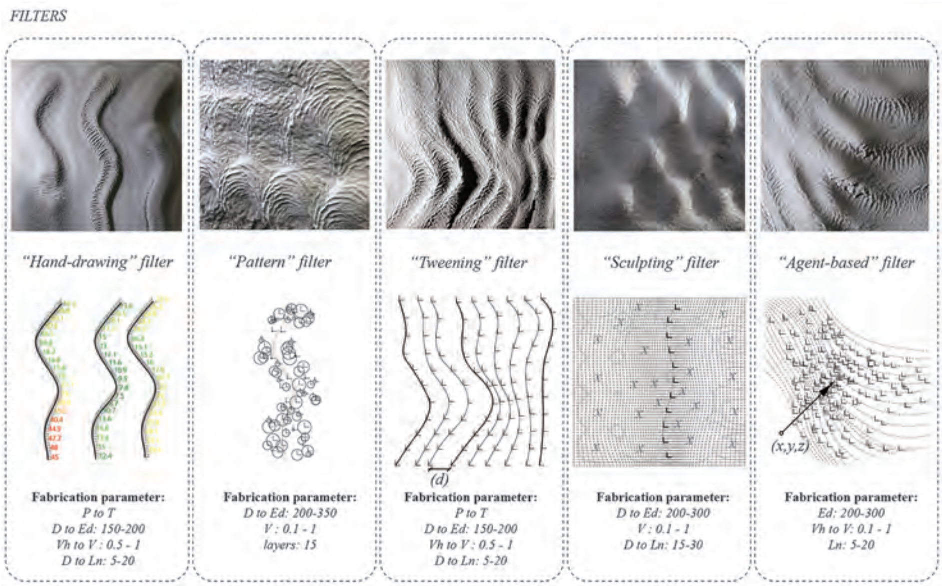


Figure 3.29: Different filter systems and their distinct translation of human input to machine output.

daily to cover the entire room. It was important to enable rapid and precise localisation to ensure a smooth and efficient working process.

Localisation of the Interactive tracking system: Participants localised the local (*VIVE*) coordinate system (LCS) for each wall element by recording and tracking pre-sprayed and pre-measured marks on the floor using Step 1 of the software (see Fig. 3.21: B). Once the input from LCS had been transformed to the global model coordinate system, the drawing procedure was the same as described in section *Interactive robotic plastering (System walkthrough)*. Participants repeated this process after finishing each wall element. Furthermore, we used the projector to validate correct localisation by aligning the digital twin of the space onto the physical space as described in section *Interactive robotic plastering (System setup)*.

Localisation of the robot: The first step in localising the robot was to set up the total station for defining a world coordinate system (*WCS*) by measuring any two of the ten fixed (pre-recorded) reference points on the walls of the room. After this, a reflector prism was mounted on the spray gun (on the robot arm). The position of the reflector prism was measured and recorded for three different points in space, corresponding to three different configurations of the robotic arm. The user chose the first point as the origin of the robot coordinate system *RCS*; the second point as the *X-Axis* of the *RCS*; and the third point as the *Y-Axis* of the *RCS*, defining a 3-point localisation method [157]. Then, in the digital building model, the origin of *RCS* stayed unchanged, and the rest of the geometries were transformed, thus transforming the robot trajectories from *WCS* to *RCS*.

The interior space (Fig. 3.30) was fabricated to facilitate an evaluation of our methods, specifically the instruction of robotic processes via interactive fabrication coupled with an open-ended design system.

User-study: Designer

To assess how designers perceived *IRoP*, we observed behaviour and opinions expressed during the fabrication period and developed a questionnaire following the Post-Study System Usability Questionnaire model (PSSUQ) [158] and extended it to include the following questions:

1. What do you think about the level of abstractness of the visualisation?
2. What do you think about the audio cues of the guidance system?

Additionally, the questionnaire offered a comment section for more open-ended notes by the participants.

The PSSUQ (Version 2) consists of 19 items using a 7-point Likert-type Scala. The PSSUQ score starts with 1 (strongly agree) and ends with 7 (strongly disagree). The lower the score, the better the performance and satisfaction. The evaluation of the PSSUQ can further be broken into four categories: Overall score, System Usefulness (SYSUSE), Information Quality (INFOQUAL) and Interface Quality (INTERQUAL). To avoid social desirability bias, the survey was conducted anonymously and in solitude, and before the task, participants were informed about the anonymity of the quiz. Furthermore, participants were instructed that the system and not their performance were under evaluation.

Figure 3.30: Interior space fabricated solely by using *IRoP*.

Observations: The most consistent findings involved the change of behaviour of the participants during the entire fabrication and design period, as well as the importance of audio signals. As the participants decided not to pick a master drawer, they used a voting system to define the "winning" design at the end of each section. This voting was first carried out verbally and then shifted to an online platform. We observed that users started to contextualise their design intent by reacting to already existing elements such as wall shapes, cantilevers, and windows. In addition to the abstract interface, we offered participants a visualisation software module to predict and preview their design outcomes. However, they soon stopped using the visualisation of the volumetric outcome due to the lack of real-time feedback, as the loading of the mesh was too computationally expensive.

User-study: The most apparent advantage of the system voiced by the participants was the ability to test the design on a 1:1 scale directly on the construction site. Participants found the system fun, easy to use and useful for design applications. One participant stated that the wall was treated as a canvas, which helped in the understanding of scale. The most criticised aspects of *IRoP* were the lack of comprehensible error messages and the missing help section.

Abstract augmented reality interface: The general feedback on the abstract visualisation was that it is perfect for a knowledgeable user but difficult for a novice. Participants learned to interpret the abstract visualisation and intuitively understood its relationship to the potential sprayed outcome. 5/18 participants voiced that they would also like to have a volumetric preview, as the results were in 3D but were visualised only in 2D.

Auditive signals: All participants reacted positively to the auditive signals. The users described the auditive signals as very useful, playful, and informative. One participant proposed using headphones instead of speakers.

Study 2: Skilled workers

The experimental setup above tested the implications of *IRoP* for the design and fabrication process, but several questions regarding *IRoP* from the perspective of the skilled worker were left unanswered. Therefore, we tested the usability and the user perception of the system and procedure by conducting a post-session usability study with five skilled workers over a trial period of 15 to 20min for each participant. The setup and procedure were the same as described in *Interactive robotic plastering (System setup*, and the skilled workers went through all steps of the interactive mode. Participants were five professional plasterers between the ages of 34 – 54, and none of the skilled workers had any previous knowledge of the system. User performance was studied similarly to the user-group designer via observation, as well as self-reported metrics completed in paper form after the session. Before the task, users were encouraged to think out loud and freely express their opinions and feelings about *IRoP*. This method provides very useful feedback [159], as users might point out flaws that were otherwise completely unknown to the testers and were thus not covered by the questionnaire.

The study aimed to answer the following questions:

1. Can the system be used by a novice?
2. Is the system useful for plasterers?
3. What do plasterers think of the system?
4. How much did the user's performance improve during the experiment?
5. How did the interface support interactive handling of the system?

Additionally, the questionnaire offered a comment section for more open-ended notes by the participants.

User-study: Plasterer: After the task completion, users were asked to fill out a paper questionnaire following the PSSUQ model (Fig. 3.31).

Overall system scored 2.3. Users were excited by the novelty of the system and its game-like features. The frustration level was described as very low, and the gamification elements of the interface were described as fun. Nevertheless, the controller's buttons were described as not sensitive enough for smooth interaction. In addition to the audio and visual interface, users would have liked to have additional tactile signals, such as vibration, to signalise specific aspects of the spraying result. Users proposed that the handle could haptically visualise the 3D movement and strength of spraying via vibration. Furthermore, users found the act of "drawing" to be very intuitive and easy to learn and use.

System Usefulness scored 2.2, and participants underlined the usefulness of the software as a method to attain the desired robotic spraying result easily.

Information Quality scored 2.8. Users would have liked to have a better explanation with legends and a dedicated help section for novices to understand the system without verbal instructions. Users also wanted error messages to be more explanatory.

Users were very content with the quality and looked of the interface, and thus *Information Quality* scored 1.9. Generally, users supported the idea of a pattern catalogue to choose from when designing. In addition to the provided filters, users mentioned that a filter to straighten hand-drawn lines and lock specific points of lines would enhance the drawing process. Furthermore, additional functionalities, such as clear regulation of the tween curves and the ability to delete individual curves, were requested.

User performance stayed consistent throughout the study as the skilled workers gained a quick understanding of the system. All participants said that the system can be used by novices.

Although the study only included five plasterers, the feedback was informative enough to strengthen the hypothesis that such a system appeals to plasterers and allows for an easy introduction to robotic fabrication processes on the construction site. Although Spool and Schroeder [160] recommend more than five participants, according to Virzi [161], five users are enough to detect 80 per cent of usability problems. Our results, therefore, suggest that such a system is of high interest to skilled workers for implementing robotic processes in their daily tasks. Additional studies should continue to explore different interfaces and user experiences.

Acquiescence bias

As the additional questions provided in the *PSSUQ* questionnaire for the skilled workers were formulated in a way that only allowed for a yes or no answer, the results may have been influenced by acquiescence bias. This response bias may have influenced the users to select a more favourable response option. Nevertheless, observing the participants and reading their open-ended comments, we received similar positive cues about system usability and usability for a novice. Therefore, we decided to include these answers in the results. We also found that more open-ended questions, such as the comment section, resulted in more insightful and revealing answers in this research stage.

Discussion on experiment results

This section discusses the results of all experiments conducted. The field study with designers and the qualitative user research with both designers and skilled workers helped to understand the potential and the qualities of *IRoP*. Our qualitative data helps to understand the motivations, thoughts, and attitudes of the two user groups. More generally, we have significant evidence that such an interactive fabrication system can be effective in architectural scale fabrication. In the following, we discuss and consider this evidence with respect to three key points: why the system was effective, whether it will be successful in real-world tasks with more functional criteria, and what the potential problems of interactive design during fabrication will be.

Effectiveness of IRoP: The system was well accepted in both studies because the user interaction was real-time, precise, and easy for novices to understand. The frustration level was low in both scenarios, and users experienced the interactive design interface as enjoyable. It is important to note that the system can adapt to fit the user's expertise. For example, a designer can customise different filters for the interactive design system and use the robotic spraying setup, and a skilled worker can use the system to program a robotic fabrication process using pre-designed filters. Another advantage is that robotic trajectories can be adjusted for specific special scenarios such as windows, corner situations and special surfaces, enabling users to perform non-standard and personalised fabrication tasks at an architectural scale. The system is intended to facilitate automated robotic processes by allowing a designer or skilled worker to switch between automatic and human-guided modes.

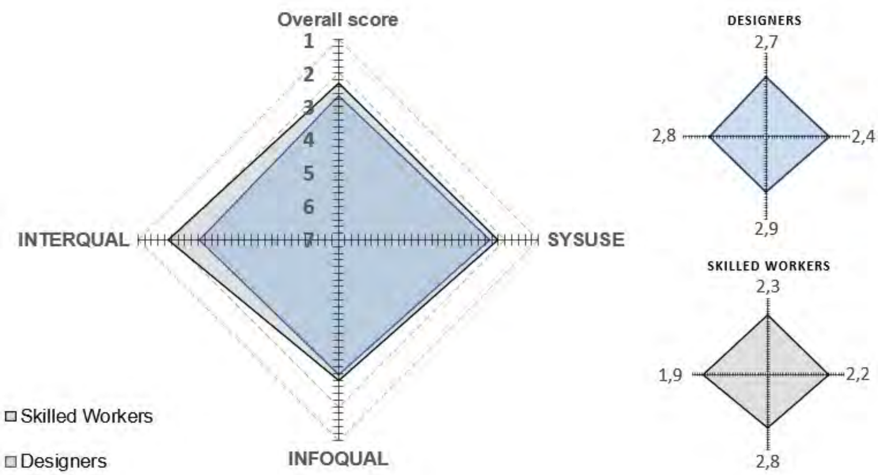


Figure 3.31: Results of user-study 1: designer and user-study 2: skilled worker.

Real-world application: To understand the real-world application of *IRoP*, we need to investigate whether the system can perform required fabrication tasks, utilise low-maintenance technologies, and be expandable to other materials and scenarios.

First, the task performed by the designers and skilled workers in these studies was a creative construction scenario with limited performance and functional requirements. To open the system to real-world applications, we need to extend the developed interactive functionalities of our system to include typical daily tasks of plasterers, e.g. optimised generation of trajectories for the production of flat surfaces for arbitrary and irregularly selected areas. A predictive toolset for the assessment of time and material consumption would be beneficial. Furthermore, the current robotic system can only be manually moved in space, and therefore the system has limited spatial freedom and increased downtime for robot re-positioning. At the same time, re-positioning of the robotic system introduces challenges in maintaining material continuity. A continuous fabrication workflow could be achieved by a mobile robotic setup, which comprises a robotic arm on a mobile platform similar to the *In-Situ Fabricator* [9] or to the setup of the construction robotics start-up *CyBe*. Even more continuity and scalability in a material deposition could be achieved by synchronising arm and base movements suggested by [142, 162, 163]. This approach could increase seamless continuity between plaster layers applied on larger surface areas. Furthermore, such a system could enable discrete and continuous fabrication during the continuous movement of the robotic system.

Second, low-maintenance technologies are essential for the use of such systems on the construction site. *IRoP* uses a setup (motion tracking system and projector), which supports easy integration, as these technologies are relatively inexpensive and accessible. The *UR* robot is a versatile collaborative industrial robot that allows users to work in proximity and is, therefore, suitable for human-in-the-loop processes and a wide range of applications.

Third, this paper focuses on plaster spraying, but *IRoP* is suitable for many complex material systems that require manual dexterity and direct observation and thus have a wide range of potential practical use cases.

Benefits of skilled workers using the system: *IRoP* allows users to instruct a robotic process using a handheld device in an interactive design system. With the handheld device, it is possible to capture micro-gestures, resulting in subtle differentiation between the sprayed plaster artefacts. Even though skilled workers are trained to apply plaster by hand, the required knowledge to direct the handheld device differs from their hand-plastering skills. Nevertheless, the system includes multiple steps that would benefit significantly from the plasterers' skills. Plasterers have a broad understanding of the material and the process, know how to monitor it, and have extensive knowledge of how to supervise quality control of finished plaster walls. Furthermore, plastering is a medium of artistic expression, and skilled workers may have a more nuanced understanding of what effects are possible with plaster. Therefore, even though *IRoP* does not fully translate their tactile knowledge into robotic processes, it still helps skilled workers to use their implicit knowledge to inform the robotic process.

The challenges of interactive design during fabrication in architecture: There are, of course, complications in overlapping the design process with the fabrication procedure, including questions regarding integration, authorship, and responsibility.

Typically, AEC uses a linear production workflow based on static systems, i.e., plan drawings executed before construction. This type of workflow enables a clear delineation of responsibility between project stakeholders and process stages. *IRoP* does not provide predefined plan drawings, as a result, emerges through the interactions of several individuals. In the case of an error, it would be challenging to establish culpability. In addition, construction processes have downstream dependencies. Predefined drawings allow third parties to prepare in advance. For an open-ended design process to be viable, an interactive digital model shared by all parties would be necessary. This networked computational model would need to be updated to the as-built design rather than the desired design. Finally, an interactive fabrication process requires new understandings of shared authorship, as the outcome results from human interaction in combination with developed digital tools and stylistic filters.

Limitations and future work

So far, we have tested and introduced five different custom filters. We plan to continue to study and develop those filters and extend them with different variations. Furthermore, different visualisation models should be tested, especially volume and mesh visualisations that render and update fast enough for real-time interaction.

Although our approach holds some promise, there are several limitations. First, even though skilled workers make design decisions on-site, designers do not usually design on the construction site. By extending the on-site interactive design with a teleoperated design system, we could further extend collaboration possibilities between skilled workers and off-site designers. Second, our robotic system is currently moved manually, and our tracking system has a limited reach of recording. This requires extensive localisation and calibration. Therefore, we will focus on including a fully mobile setup for plastering as well as a better motion-capturing setup with a broader reach. We are already looking into including motion capture technologies in tracking human gestures. Third, a custom-built handle which includes vibrating information would also support the visual and auditive interface. Finally, our projected AR system is limited by the field of view of the projector. We partially overcame this by introducing multiple static projectors, but this method increased the complexity of our system. To overcome such drawbacks of projected AR systems, we aim to test a mobile projector able to re-orient the projected image according to the new field of view. In this way, we furthermore address the challenge of combining a real-time prediction and visualisation tool with a mobile projector system.

Conclusion

We have developed a system that allows an in-situ robotic plastering process to be used intuitively. This is achieved by combining interactive design tools, an AR interface, and a robotic spraying system. The experimental setup was tested with two different user groups to show that this approach can substantially simplify the programming of robotic processes with complex material systems and capitalise on the intuitive potential of programming by demonstration.

For these groups, we have arrived at the following conclusions: The plastering process is typically challenging to simulate or pre-program, but *IRoP* enables designers to draft and fabricate articulated plasterwork in situ with a controller-based interaction system. Our system shows that it is possible to capture micro-gestures that result in custom effects. Furthermore, designers using traditional 3D modelling tools would have most likely not designed such robotic trajectories (see Fig. 3.32). Thus, such a system contributes to the unique aesthetic qualities of the design outcome, as illustrated in Figure 3.33. In addition, we demonstrated that fabrication without a master design but with the selection of specific filters allowed 18 designers to create a space with continuous and consistent aesthetics. In the full-scale architectural implementation, we also showed that *IRoP* was suitable for reacting to site conditions on-the-fly. For instance, the designers were able to react to existing elements in the space, such as an uneven surface, a corner, or edge situations. In conclusion, the large-scale prototype shows how such a new interactive design interface can provide new opportunities for future crafting, leading to novel forms of creative expression as designers interact on-site with complex material processes.

For skilled workers, the user-study validates that *IRoP* enables those with limited robotic programming and design experience to manipulate the complex design and robotic fabrication processes intuitively, particularly due to the gestural input. Thus, *IRoP* has demonstrated a high potential to lower the barriers for skilled workers to robotic fabrication technology and computational design.

As a general conclusion, *IRoP* demonstrates a great potential to be able to intuitively integrate challenging-to-automate processes in architecture, engineering, and construction and to capitalise on the tacit knowledge of humans. This was mainly thanks to the real-time feedback, which increased user control on-site, shifting the attention back to the human in automated robotic processes. Finally, the project shows that by implementing intelligent and collaborative human-machine workflows, we can support a socially sustainable integration of robotic construction processes and expand our repertoire of potential material systems.

Figure 3.32: Wall detail showing the aesthetic qualities of *IRoP*

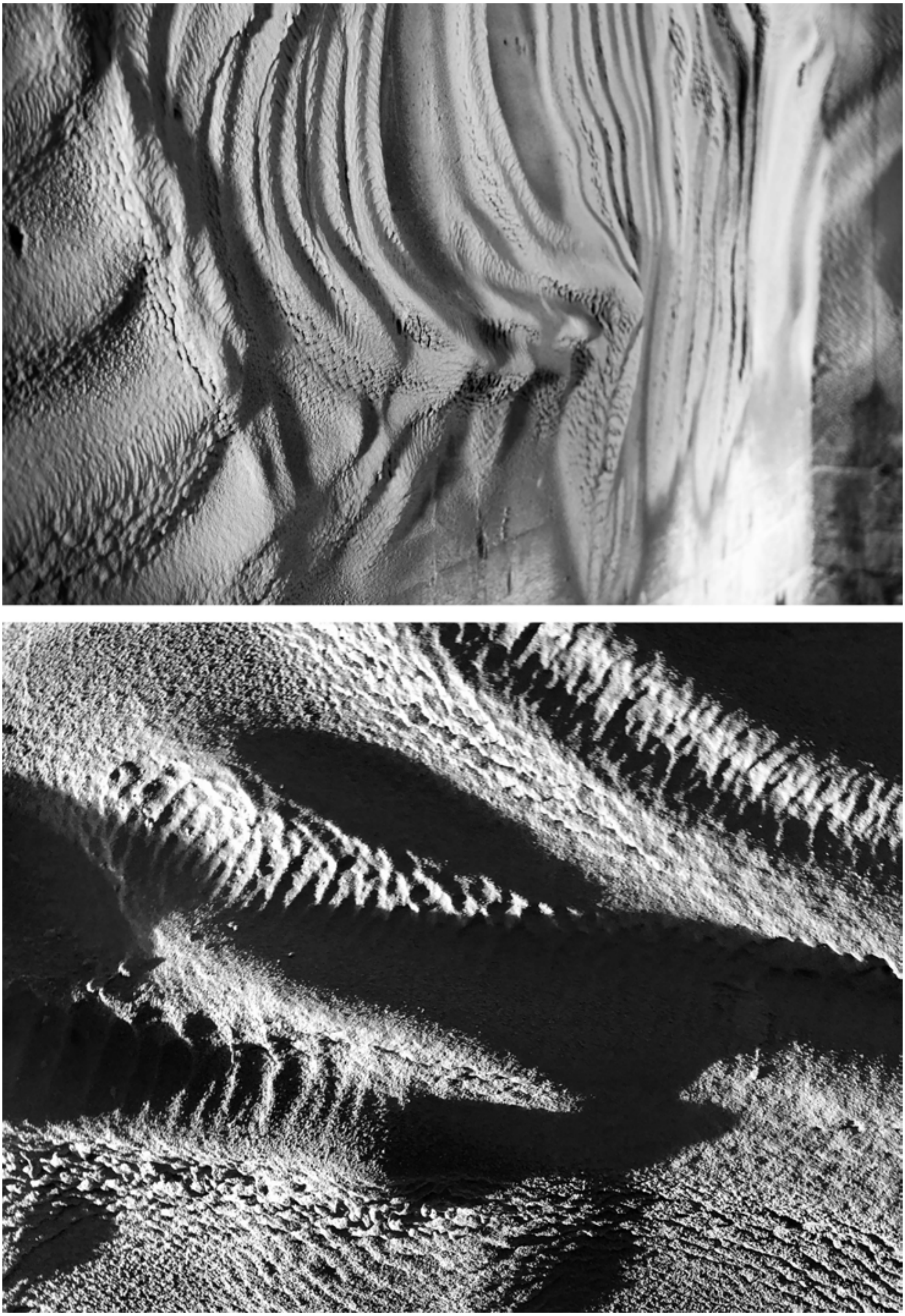


Figure 3.33: Details of the wall elements showcasing results of micro-gestures.

3.2.3 Credits and acknowledgments

Author's contribution:

From 2020 to 2021, the author of this thesis undertook the conception, development, testing, and validation of the human-assisted machine fabrication workflow. This included the integration of a robotic plaster spraying method into the human-assisted machine fabrication workflow within an architectural design and planning environment. The establishment of the adaptive digital fabrication workflow included the development of a digital twin comprising a computational fabrication model, a controller tracking setup, and a projection-based visual feedback system. The digital twin required the development of a design system to generate on-the-fly bespoke 3D designs of plaster walls. Human hand gestures generated the design model, which was then translated into robotic fabrication instructions. The visual feedback system included the design and development of a bespoke audio-visual UI for projection-based AR. The digital twin required implementing a high-level communication system for all sensor and actuator systems.

Finally, the author conceived and implemented the architectural application scenario and physical prototypes presented in this thesis to analyse the workflow and the prototype via quantitative and qualitative methods. For this, the author carried out user studies to analyse the user experience and evaluate the learning curve of plasterers and architects.

Collaboration:

Part of the research was executed within the framework of the postgraduate Master of Advanced Studies (MAS) program in Architecture and Digital Fabrication at ETH Zurich. Students of the MAS program participated in the research development and the execution of the final prototype. The robotic plaster spraying method was developed by Selen Ercan Jenny at Gramazio Kohler Research (GKR), led by Prof. Fabio Gramazio and Prof. Matthias Kohler [142]. It included the robotic plaster spraying hardware developments, localisation of the robot on site, and the method used to scan the sprayed surface. Selen Ercan Jenny, Eliott Sounigo and Ping-Hsun Tsai were part of the implementation and conception of the physical prototypes. Petrus Aejmelaeus-Lindström led the teaching of the MAS program and assisted in user study 1 (designers).

Authors contributions to the paper:

The contributions of each author in this paper are described using the Contributor Role Taxonomy [111].

Daniela Mitterberger Conceptualisation, Methodology, Software, Validation, Data Curation, Formal analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Project administration

Selen Ercan Jenny Conceptualisation, Methodology, Software, Validation, Data Curation, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Project administration

Lauren Vasey Conceptualisation, Methodology, Writing – Review and Editing, Supervision

Ena Lloret-Fritschi Conceptualisation, Methodology, Investigation, Writing – Original Draft, Writing – Review and Editing, Supervision, Project administration

Petrus Aejmelaeus-Lindström Conceptualisation, Investigation, Formal analysis, Writing – Review and Editing, Project administration

Fabio Gramazio Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Matthias Kohler Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Acknowledgements:

This research was partially supported by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement no. 51NF40-141853) and by the HILTI group. The authors acknowledge the students of the MAS ETH in Architecture and Digital Fabrication program, Evgenia Angelaki, Liya Sunny Anthraper, Pascal Bach, Yen-Fen Chan, Wei-Ting Chen, Wei Chengyuan, Ilaria Giacomini, Simon Griffioen, Guillaume Jami, Eleni Kitani, Artemis Maneka, Beril Önalan, Foteini Salveridou, Priyank Soni, Ko Tsuruta, Carlos Wilkening. The authors would like to thank Eliott Sounigo, Ping-Hsun Tsai, and David Jenny for their tutoring contribution. Philippe Fleischmann, Andreas Reusser, Tobias Hartmann, and Michael Lyrenmann are acknowledged for their technical support. Eberhard Unternehmungen and Giovanni Russo AG are acknowledged for their logistic and technical support and sponsorship.

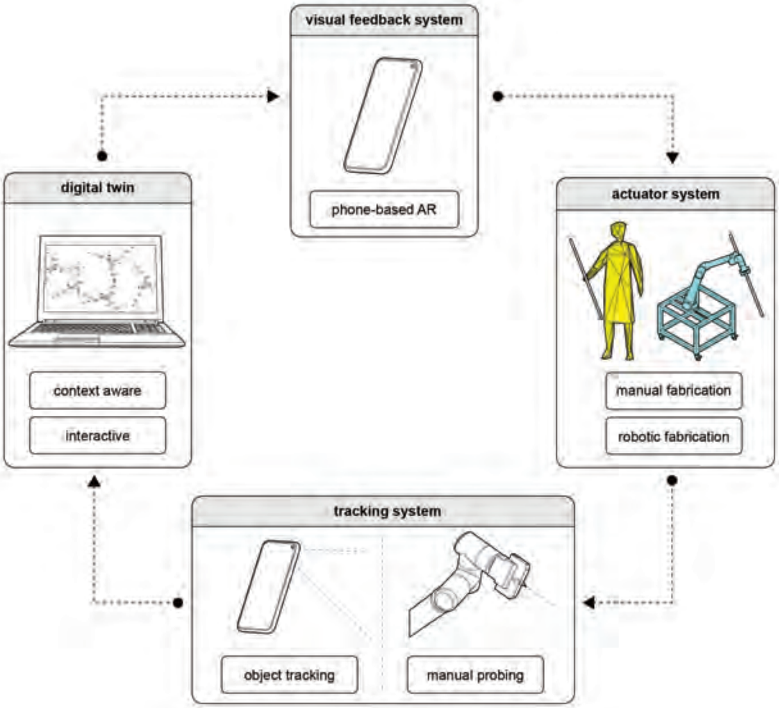


Figure 3.34: Diagram visualising the applied methodology for *Tie a Knot*: (a) context-aware and interactive computational model, (b) phone-based AR, (c) manual and robotic fabrication, (d) object tracking and manual probing

3.3 Hybrid human-robot cooperation

3.3.1 Summary and contribution to thesis

This paper[8] contributes to the concept of *human-robot cooperation* by enabling a cooperative human-robot team to assemble complex wooden structures using rope joints. This paper introduces methods that include manual human actions and decisions in the digital fabrication process, which facilitate on-the-fly design and allow follow-up robotic actions (Fig. 3.34). To achieve this cooperative workflow, the project uses a digital twin, which is informed by human actions through tracking and estimating manually placed objects. Two systems are tested for the tracking of these objects, a visual-inertial object tracking system and manual probing with the robot. To enable hybrid fabrication, humans are informed, and robots are instructed by the shared digital twin.

[8] This version of the article has been accepted for publication, after peer review and is subject to Springer Nature's AM terms of use, but is not the Version of Record. The Version of Record is available online at: https://doi.org/10.1007/s41693-022-00083-2


Robotnik

3.3.2 Tie a knot: Human-robot cooperative workflow for assembling wooden structures using rope joints

Daniela Mitterberger[1], Lidia Atanasova[2], Kathrin Dörfler[2], Fabio Gramazio[1], Matthias Kohler[1]

Abstract

In recent years, research in computational design and robotic fabrication in architecture, engineering, and construction (AEC) has made remarkable advances in automating construction processes, both in prefabrication and in-situ fabrication. However, little research has been done on how to leverage human-in-the-loop processes for large-scale robotic fabrication scenarios. In such processes, humans and robots support each other in fabrication operations that neither of them could handle alone, leading to new opportunities for the AEC domain. In this paper, we present Tie a Knot, an experimental study that introduces a set of digital tools and workflows that enables a novel human–robot cooperative workflow for assembling a complex wooden structure with rope joints. The system is designed for a dually augmented human–robot team involving two mobile robots and two humans, facilitated by a shared digital-physical workspace. In this shared workspace, digital spatial data informs humans about the design space and fabrication-related boundary conditions for decision-making during assembly. As such, humans can manually place elements at locations of their choice, following a set of design rules that affect the gradual evolution of the structure. In direct response to such manually placed elements, the cooperating robots can continue the assembly cycle by precisely placing elements and stabilising the overall structure. During robotic stabilisation, the humans make rope connections, which require high dexterity. The concept and workflow were physically implemented and validated through the cooperative assembly of a complex timber structure over five days. As part of this experimental investigation, we demonstrated and evaluated the performance of two tracking methods that allowed the digitisation of the manually placed elements. In closing, the paper discusses the technological challenges and how a hybrid human-robot team could open new avenues for digital fabrication in architecture, accelerating the adoption of robotic technology in AEC.

Keywords human-machine cooperation, human-robot cooperation, interactive fabrication, open-ended design, augmented reality, context-awareness

[1] Gramazio Kohler Research, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland
[2] TT Professur für Digitale Fabrikation, Fakultät für Architektur, Technische Universität München, Arcisstrasse 21, 80333 Munich, Germany

Introduction

In the last 17 years, research in computational design and robotic fabrication in architecture, engineering, and construction (AEC) has made remarkable advances. These advances have introduced a variety of approaches using diverse robotic and material systems, ranging from complex timber construction [164, 165], 3D printing with concrete [7, 8], to autonomous brick assembly [90, 166] both on and off-site construction scenarios. Robotic fabrication has enabled rapid and precise production with increased construction customisation, accuracy, and process reliability in various work environments and scales [3]. Since construction robots have been designed and programmed for relatively static work environments and predefined processes, most robotic processes require the robots to run in work cells, free from humans and unpredictable disturbances. Once the robot is programmed, the environment and objects that the robot interacts with are expected to remain within the same range of variance that the robot was programmed to. Therefore, especially in unstructured environments, such as construction sites, the level of robustness and autonomy of such robotic processes is still remarkably low [12]. Due to this low level of robustness and autonomy, these robots still rely on human operators to make critical decisions or assist the robotic fabrication process [19]. Moreover, the lack of autonomy limits the robots' ability to seamlessly and reliably interact and collaborate with humans, thereby missing out on the benefit of leveraging complementary skills. Research has not yet focused enough on complementary workflows and human-in-the-loop processes in AEC, leading to a lack of working and intuitive interfaces for robotic fabrication processes that enable seamless communication and data exchange between humans [115]. This deficiency, in turn, limits new design and manufacturing opportunities and delays the wider adoption and integration of robotic fabrication into AEC.

This research addresses this limitation by examining how to leverage the development of cooperative and semi-autonomous manufacturing systems between humans and robots. It focuses on hybridising robotic fabrication with traditional manual workflows, developing a balanced human–machine collaboration system that can enable novel, intelligent and economical workflows for AEC. Such workflows make equal use of human and machine capabilities—the autonomous and interactive capabilities of robots, such as robotic precision and computational iterations, and human cognitive and physical abilities, such as manual dexterity, material knowledge, and intuition. The research findings of this paper emerged through physical experimentation and a proof-of-concept prototype of a complex wooden structure with rope joints (Fig. 3.35).

The cooperative assembly workflow is designed for a dually augmented human–robot team involving two mobile robots and two humans. A shared digital-physical workspace is established to facilitate cooperative assembly tasks distributed between humans and robots. Humans can initiate assembly cycles and take turns with the robot to construct wooden Y-triplet units. These units are made of three struts—one from a previous triplet, one assembled by the robot, and one manually assembled by a human. The manually assembled element can be placed freely, following a set of local rules that influence the design of the structure on-the-fly. These additions made by humans to the built structure need to be continuously digitised and fed into the digital model, from which robot routines can be derived successively. Therefore, this research utilises recent advancements in mobile augmented reality (AR) technology and sensor-enabled context awareness [100] to track and detect such manually added changes to the built structure automatically and precisely. Alternatively, the collaborative robots themselves are utilised as precision instruments that are used by humans to track and register manual changes. In this paper, we evaluate the accuracy of both tracking methods to understand how humans and robots can collaborate in assembling a large-scale structure.

The remainder of this paper is structured as follows. The section *Background* provides an overview of the state-of-the-art of non-linear design-to-fabrication workflows and hybridised robotic and manual fabrication processes in AEC. The section *Case study - Tie a knot* introduces a set of digital tools enabling a novel cooperative assembly workflow of a wooden structure in a shared geometric workspace between humans and robots. It presents a system walkthrough and the hardware and software components. Section *Results and limitations* presents the results and current limitations. Section *Discussion* and *Conclusion* conclude the research, address the technical challenges of the case study and conclude with an outlook on future research directions. In summary, this paper discusses how—by getting humans and machines to communicate with one another—the notion of a hybrid human–robot work team could open new avenues for digital fabrication in architecture.

Figure 3.35: Cooperative assembly scenario by human-robot teams

Background

The following sections illustrate how our study expands on previous work by investigating non-linear design-to-fabrication workflows and cooperative fabrication processes in digital fabrication. Specifically, this research focuses on hybridising robotic and manual construction techniques by human–robot teams.

Nonlinear design-to-fabrication workflows:

Most digital design-to-fabrication workflows in architecture are linear due to the explicit nature of machine instructions, thus requiring most design decisions to be made prior to fabrication.

Traditional craft processes, on the contrary, are not necessarily linear but rather encourage practitioner creativity by not entirely specifying the path of execution [54]. To incorporate this non-linear approach, Knight and Stiny [55] introduced a computational theory of making grammars, which has expanded the theory of shape grammars [167] for the study and digital representation of the temporal performance of the craft. They articulated the fundamental creative processes of craft by segmenting spatial and temporal aspects and by applying rules to both the act of creation and sensory perception. They understood crafting as "doing and sensing with stuff to make things". Such procedures are open and do not entirely predetermine the result. Ultimately, through sensory perception, they enable practitioners to make changes to plans, for instance, to make design adjustments, pursue new design ideas, or accommodate mistakes. Further concepts for non-linear digital fabrication workflows utilising user input technologies have been demonstrated in the last few years. *Interactive Fabrication* [80] presents how users can control the digital fabrication of a physical form using real-time input devices. Another example of such a process is *IRoP* [168], an interactive augmented robotic plaster spraying process. In *Interlacing* [169], a robot makes a design decision within a constrained design space based on 2D camera tracking. *Prototype-as-Artifact* [144] presents core concepts of non-linear design-to-fabrication workflows. This research explores the possibilities of making bottom-up design decisions while building in a human–robot cooperative setting. However, the task distribution allocated to humans and robots was interchangeable and not explicitly tuned to their unique strengths.

Towards hybridising robotic and manual fabrication:

As has been explored in previous research, humans and robots have different strengths [24, 170], and cooperative processes should make the most of this by tailoring the role each agent plays. There are diverse strategies for such task distribution in cooperative processes [171]. In this research, we focus mainly on task distribution, where a machine assists a human while fabricating, a process we define as *machine-assisted human fabrication*[9]. In this case, human fabrication or human-made no longer applies only to handcrafted objects. Rather, machine-assisted human fabrication also incorporates partially automated processes whose physical output is still dependent on the human craftsperson who oversees and participates in the fabrication [41]. Only a few research projects combine difficult-to-automate manual fabrication tasks with robotic fabrication tasks. The research, *iHRC* [172], introduces a workflow that enables workers to decide actively on the human–machine cooperative task distribution. The human worker can take over specific process parts, such as picking and placing timber slats or slat fixation or give these tasks to the machine. Another human–robot cooperative building process is the *Hive pavilion* [79, 91]. The live building process coordinates multiple human workers via a phone-based app that provides humans with instructions to locate materials and respond to commands like tightening mechanical ratchets, placing finished elements, and supervising fabrication quality. Another example of combining robotic and manual processes is *CRoW* [78]. In turn-taking tasks, a user equipped with an AR headset can plan the placement of wooden elements by assessing the fabrication data beforehand. Subsequently, the robotic arm places the wooden plank, and the operator nails it manually. These projects show how such hybridisation of automated processes and manual construction techniques can increase the flexibility and robustness of automated workflows. However, in

[9] This case study focuses on *machine-assisted human fabrication* as humans are predominately fabricating, and require guidance and tools to assist them during fabrication. The difference to traditional manual manufacturing is that humans are enabled to fabricate geometrically complex and digitally informed objects.

these projects, the tasks selected for the human operator do not require extensive dexterity or elaborated context perception.

Hybridising robotic fabrication with manual tasks also includes the combination of manual aesthetics with automated processes. Projects such as *RobotSculptor* [120] or *Adaptive Robotic Carving* [36] allow the results of an automated process to achieve a handcrafted look. These projects show the potential of combining predefined robotic processes with human dexterity. However, the design in these projects is finished before fabrication starts, and therefore, these processes do not fully embrace the potential of combining human–machine collaborations with interactive fabrication.

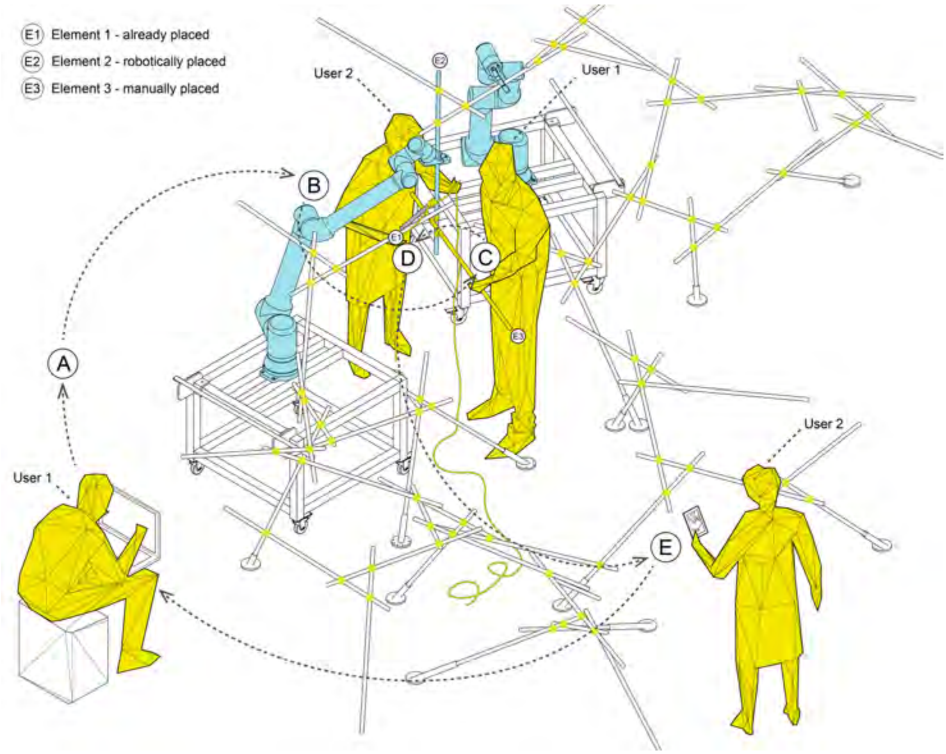


Figure 3.36: Overview cooperative assembly cycle, consisting of five main components (A) interactive design, (B) robotic assembly, (C) manual assembly, (D) rope jointing, (E) tracking of elements

Case study - Tie a knot

Overview

This research aims to combine non-linear design with an interactive fabrication process to facilitate a human–robot cooperative workflow for assembling a complex wooden structure using rope joints. The cooperative assembly workflow consists of turn-taking tasks between two humans and two robots according to predefined rules and action sequences. A shared digital-physical workspace enables the cooperation between humans and robots, in which tracking systems are used to update the digital-physical workspace continuously. An XR system informs the cooperating humans about the design space and fabrication-related boundary conditions. Humans can initiate design and assembly cycles that are continued, assisted, and completed by the cooperating robots. These assembly cycles are composed of five turn-taking steps: (A) interactive design, (B) robotic assembly, (C) manual assembly, (D) rope jointing, and (E) registration of manually assembled elements (Fig. 3.36).

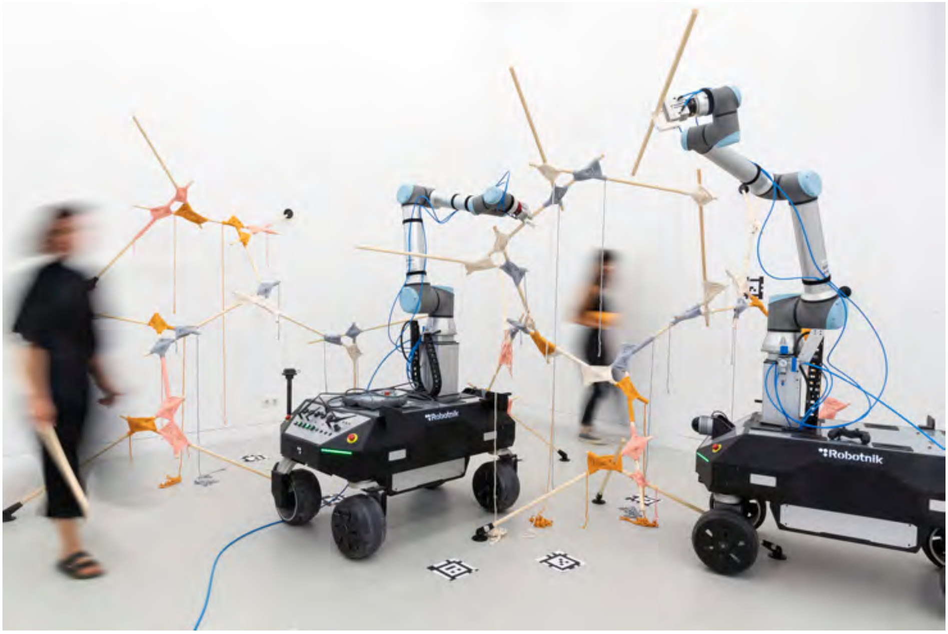


Figure 3.37: Proof-of-concept prototype to test the system's design principles and workflow.

Each assembly cycle consists of adding a wooden Y-triplet made of three struts, one from a previous triplet, one assembled by the robot (B), and one manually assembled by a human (C). At the beginning of each assembly cycle, users change global constraints such as growth direction and density (A). Then they move the robots within reach of the first element of the Y-triplet, which is already assembled and part of a previous Y-triplet. The second element is robotically assembled and held in place by robot one (B) until user one places the third element and closes the Y-triplet (C). The manually assembled element can be placed freely following a set of local rules that affect the design of the structure on-the-fly. After all the struts are placed, they are connected via rope joints by user two (D). After placing the joints, the manually placed element is tracked by user two and included in the digital model (E). While robot one stays in place to stabilise the structure, robot two is used to continue the building cycle in direct response to the manually assembled strut. To test the feasibility of the concept, a large-scale proof-of-concept timber structure was built with this open-ended design process (Fig. 3.37).

Collaboration and task distribution

A meaningful task distribution between humans, robots, and computational processes should fit the unique strengths of the cooperating agents. Based on the known set of higher-level actions (i.e., planning, picking, placing, stabilising, joining), the assembly process is formulated as a flexible task shop. The task distribution is sequence-dependent and incorporates spatial dependencies. The turn-taking task distribution presented in Fig. 3.38 shows the combination of human tasks assisted by follow-up robotic tasks.

Humans perform physical tasks that are difficult for the robot, such as positioning elements that dock onto existing structures and tying knots. Humans also perform cognitive and intuitive tasks such as spontaneous design decisions and adjustments, as well as the digitisation of manually placed elements. The robots perform precise spatial operations, i.e., spatially complex pick-and-place routines, as well as structural stabilisations to aid in assembling the Y-triplets as fully stable configurations, which is a difficult task for humans. A continuously updated digital model is necessary to enable a mutual distribution of tasks between humans and robots. Human actions, such as manually assembled elements, must be digitised and fed into the digital model to enable a direct reaction of the cooperating robots. We use and compare two different methods of digitising human actions; an inertial visual object tracking method using the mobile AR device and a point-to-point localisation method using the robots (refer to section *System Architecture* for more technical details).

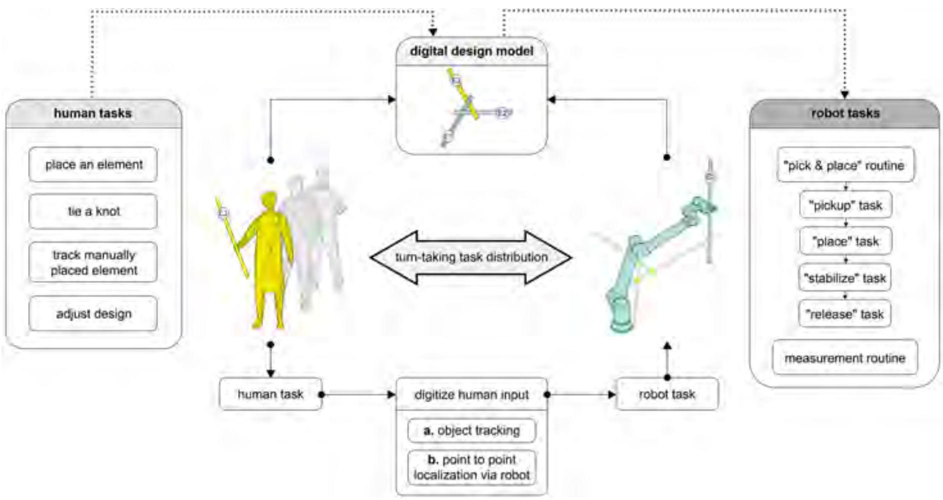


Figure 3.38: Turn-taking task distribution between humans and robots

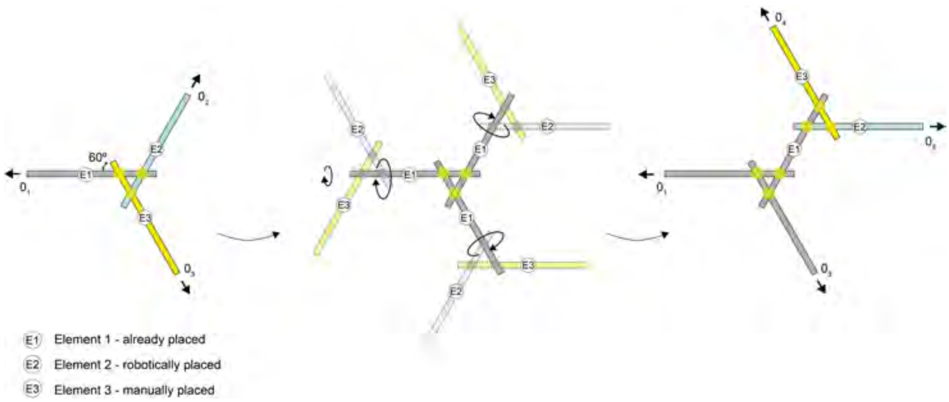


Figure 3.39: Reciprocal space frame structure from interlocking struts, referred to as Y-triplet.

Figure 3.40: *God's Eye* rope joint.

Material system

Timber struts: As building elements, we use timber struts with a length of 1000 mm and a radius of 20 mm. Three interconnected timber struts form a Y-triplet, and multiple interlocking Y-triplets define a reciprocal space frame (Fig. 3.39). The first timber strut in a Y-triplet is built-up from an already placed space frame (E1), a robot assembles the second strut (E2), and a human assembles the third strut (E3). Timber struts touching the existing context, i.e., ground or walls, are fixed with 3D-printed flexible joints.

Rope joints: To join the interconnected timber struts, rope joints are used. The advantages of rope joints are that they are reversible, lightweight, and flexible, allowing for a higher error margin during construction. Furthermore, the flexible connection by rope avoids the cutting and opening of holes in the material, which would weaken their cross-section. However, a rope joint connection requires a high level of dexterity in placement, making this method of joining very difficult to be carried out by a robot. Therefore, this task is assigned to be carried out by humans. In this research, we use the *God's Eye* rope joint (Fig. 3.40). This joint is typically used in basket weaving to join a pair of sticks together. We chose it because the knot can easily be converted to cover whole surface areas and can be used to define different spatial articulations. Different colours of thread were used to indicate the origins of the assembly, whether one strut was placed manually or robotically.

Cooperative assembly logic

As previously introduced in *Case study - Tie a knot*, the assembly logic incorporates five main turn-taking tasks distributed between humans and robots. These tasks are (A) interactive design, (B) robotic placement, (C) manual placement, (D) rope joints, and (E) registration of manually placed elements, comparing the use of (E1) a mobile AR device for automatic registration, and (E2) a robot's measurement tip for manual registration of manually placed elements (see Fig. 3.41).

A) Interactive design: The interactive design environment builds upon algorithmic modelling methods open for user input during assembly. The computational logic of the interactive design model is based on the Assembly Information Model, which expands on a serialisable network data structure available through the open-source Python-based *COMPAS* framework [109] within *Rhinoceros* and *Grasshopper*.

In the assembly model, each discrete element (strut) is stored as a node in a graph data structure. The edges of the graph represent the connections between the elements whose spatial arrangement is organised within global and local design rules. Three elements are combined into a Y-triplet featuring three connection options located on its open ends, referred to as connectors. Each connector is stored in the node's attributes as a frame, describing the position and orientation of the following triplet and a corresponding Boolean variable indicating whether the connector is closed or open. Therefore, each element in one already assembled triplet has one open and one closed connector. At each assembly cycle, humans can interactively generate design options abiding by specific local and global design rules, influencing the growth direction and geometry of the overall structure. To define growth direction, the user freely picks a starting element in the CAD environment that is an already-built element in the structure (Fig. 3.42- E1). After picking the first built element, the user visualises the corresponding two elements to complete the Y-triplet and specifies their rotation angle around the starting element. After that, the user chooses which element will be placed robotically (Fig. 3.42- E2) and which one manually (Fig. 3.42- E3). The visualised position of the third element, which will be placed manually, is used only as guidance. Its actual position will be chosen by the human when being manually placed and updated in hindsight through registration.

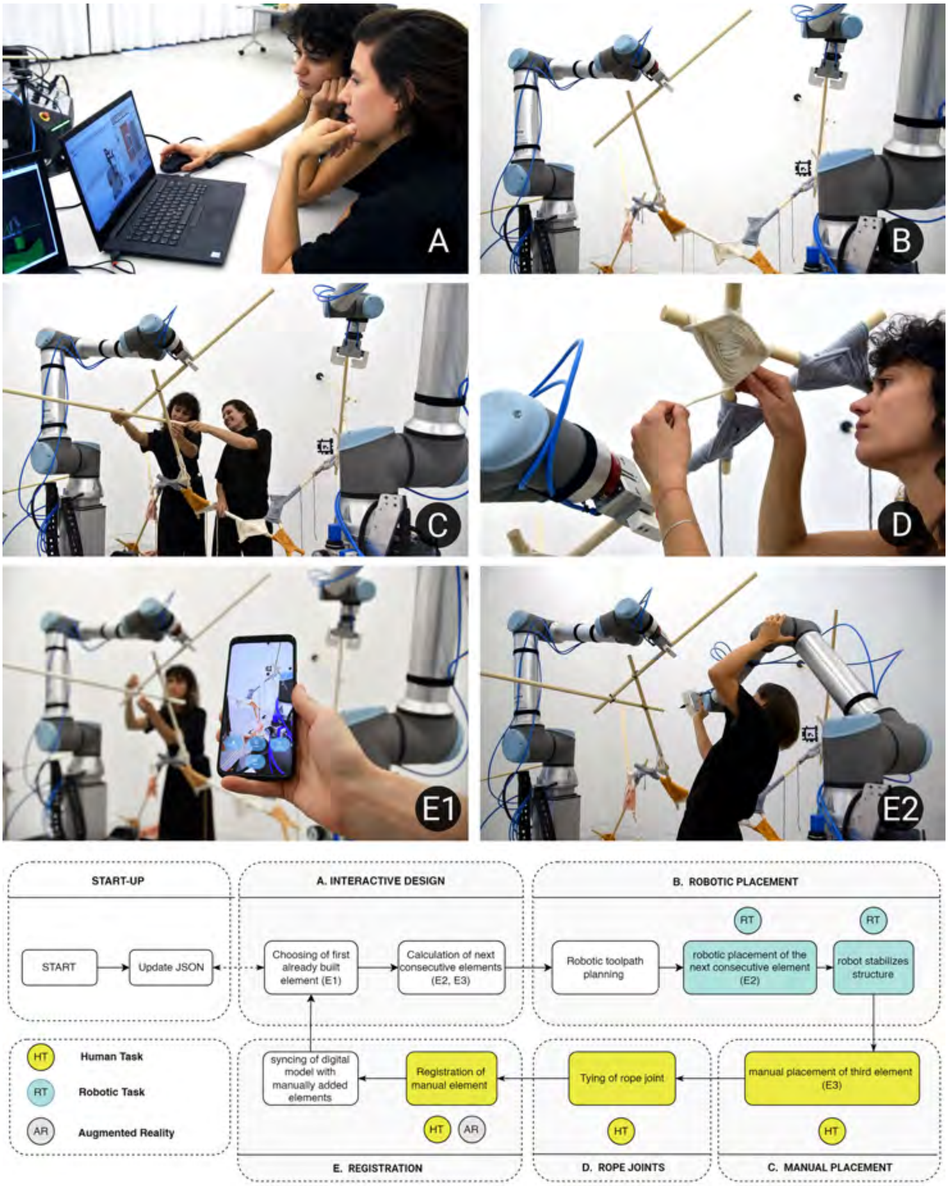


Figure 3.41: System walkthrough: (A) interactive design, (B) robotic, (C) manual, and (D) rope joint placement (E1) tracking with the phone, (E2) tracking with the robot

B) Robotic placement: After the user decides on the first element of a triplet (E1) upon the preview of the computed consecutive two elements (E2, E3) in the CAD design environment, the robot is used to place the next element (E2). The robotic assembly requires the calculation of a valid and collision-free trajectory for the associated pick-and-place routine according to the current robot's location in the workspace. We use Grasshopper and the *COMPAS FAB* library in combination with the *MoveIT* motion planner for the robot's trajectory planning. Each already placed strut, the mobile platform of the robot, and the robot manipulator are uploaded as collision objects to the planning scene, allowing for trajectory planning and taking the collision objects of the workspace into account. After computing a valid trajectory, the user sends the planned pick-and-place routine (target frames, IO control, and robot parameters) via a custom TCP/IP connection from the CAD design environment to the robot. Following, the robot picks up the wooden strut from the picking station, drives into a safe position, and then toward the target position. After the successful robotic placement of the consecutive element, the robot stabilises the element in place, waiting for the third element to be manually placed and joined into a stable reciprocal frame configuration.

Since the robots are mobile, they can be remotely controlled by humans within the workspace and always moved to where they are needed. Therefore, after each movement, the robots must be localised in relation to the assembled structure. Reference points with known coordinates in physical and digital environments are used for their localisation. These points are first probed manually with the robot's measurement tip and aligned with an iterative closest-point algorithm (ICP) to estimate the robot's position.

C) Manual placement: After the second strut has been placed and the structure is stabilised by the robot, the human places the third element (E3). The aim is to complete the triplet, with respect to the local design rule, and thus close the structural triangle in the overlapping area of the three elements. When placing the third strut manually, humans can test the ideal position

Figure 3.42: The user interface of the interactive design model provides input controls for selecting a starting element for a new triplet and defining the triplet's rotation angle via a number slider

for the element to stabilise the whole space frame. They can consider structural options, such as expanding the structure toward the floor or walls if needed. Furthermore, humans can interactively change spatial articulations of the structure, such as densities and openings of the space frames.

D) Rope joints: After finishing the manual placement, the second user connects the struts and places all three rope joints. During assembly and joining, a robot always stays in position to stabilise the structure until the next Y-triplet is built or equilibrium is reached. The other robot not used for stabilisation is free to be used for further assembly of the structure.

E) Digitisation of manual physical interventions: Before choosing the next Y-triplet, the manually placed strut needs to be registered in reference to the already built structure. The user has two options for registering the exact position of the strut.

The first (automated) option is via a custom AR app on a mobile device. The AR app uses the visual-inertial object tracking software by *incon.ai* in combination with message-passing capabilities allowing for information exchange with the CAD design environment. The tracking system uses edge detection to detect the position and orientation of the struts in relation to known geometry and pre-registered QR-Codes. For further technical details and implementations of the *incon.ai* software, refer to [100]. The message-passing capabilities are further explained in section *System Architecture*. After registration, the AR app updates the digital model with the as-built data and adds the strut to the assembly model.

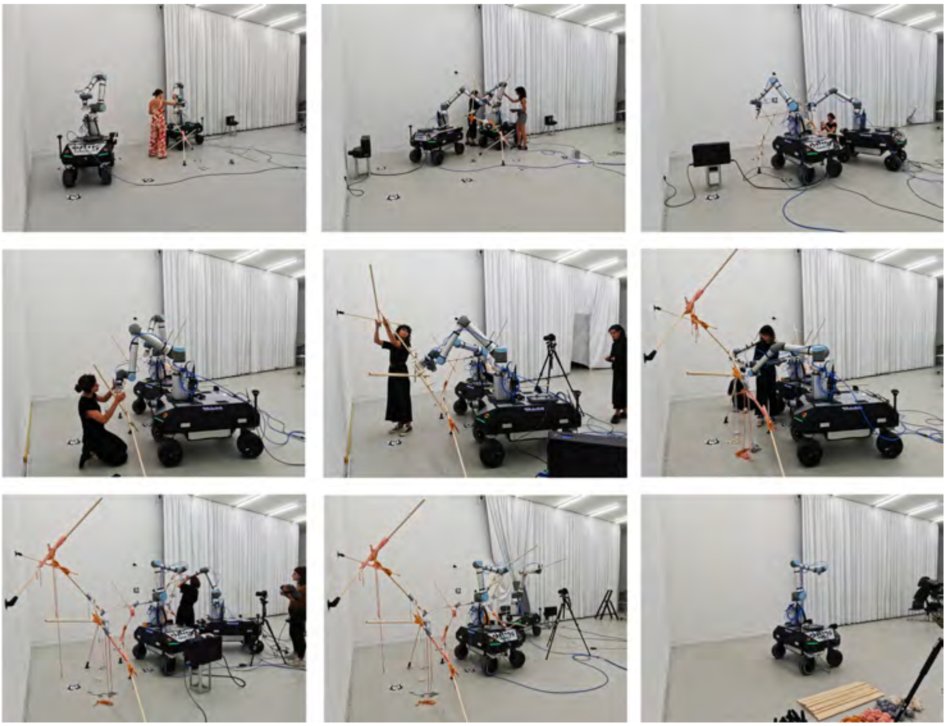


Figure 3.43: Time-lapse recordings of assembly and disassembly of the experimental prototype.

The second (manual) option is via the robot, where reference points are manually probed and used to fit the strut geometry. This registration is achieved by probing four points on the wooden struts required to define their exact position and rotation. Consecutively, the tracked location is sent to the digital model to update it with the as-built data.

After registration and syncing of the digital model with manually added elements, the user can pick the next Y-triplet to continue building and initiate a consecutive robotic action. The assembly cycles are repeated until the structure is finished (Fig. 3.43).

System Architecture

The system architecture consists of a hardware setup (Fig. 3.44) and a communication system (Fig. 3.45) that allows for interoperability between all devices used in the experiment.

Hardware setup: The hardware setup consists of two 6-DoF cooperative robotic arms (UR10e) with custom 3D-printed pneumatic grippers. To extend the working space of the UR10e, the robots are placed on mobile platforms, allowing humans to reposition the robots manually. Each robot has a timber strut pick-up station to collect wooden elements. For the mobile AR device, we use a Google Pixel 4. The hardware used for communication between all devices includes a Linux PC and a Windows PC used to run the interactive design model.

Communication workflow: A necessary component for an augmented human–robot cooperative process is a scalable communication system for connecting multiple devices and back-end computational processes, which in this case is achieved utilising a *ROS* publish-and-subscribe architecture and the *rosbridge* package [173]. Here, the *ROS* system architecture connects all devices (Fig. 3.45), the AR app, the interactive algorithmic model, and the MoveIT simulation. The AR app is a custom version of the *incon.ai* software, providing visual-inertial object tracking while also providing *ROS* functionalities such as the publish-and-subscribe architecture and data structure. The *Linux PC* runs the *ROSmaster*, the *rosbridge* server, and the *MoveIT* simulation. The second PC runs the interactive design model, which uses *Python*, *COMPAS*, and *Grasshopper* and visualises the data structures within *Rhinoceros*. As depicted in Fig. 3.45, the computational units and the AR devices are connected via WIFI to the same *ROSmaster* and *rosbridge* server. A direct *TCP/IP* communication is established between the CAD environment and the robots.

At the beginning of a work session, the user uploads the initial assembly model as *JSON* into the CAD environment and publishes it via *ROS* service. The mobile AR app subscribes to this service via the *rosbridge* server. Once the CAD design environment and the mobile AR app are in sync, the uploaded assembly model is visualised on the AR app. The user can initialise the object tracking when the assembly model aligns with the physical model. After a new element has been tracked and registered, its position and orientation are published via the *ROS* topic. The CAD design environment subscribes to this *ROS* topic and updates the digital model of the assembly with the received as-built data. In a consecutive step, the next assembly cycle can be initiated, that is, Y-triplets can be calculated and published again via a *ROS* service to sync the AR phone.

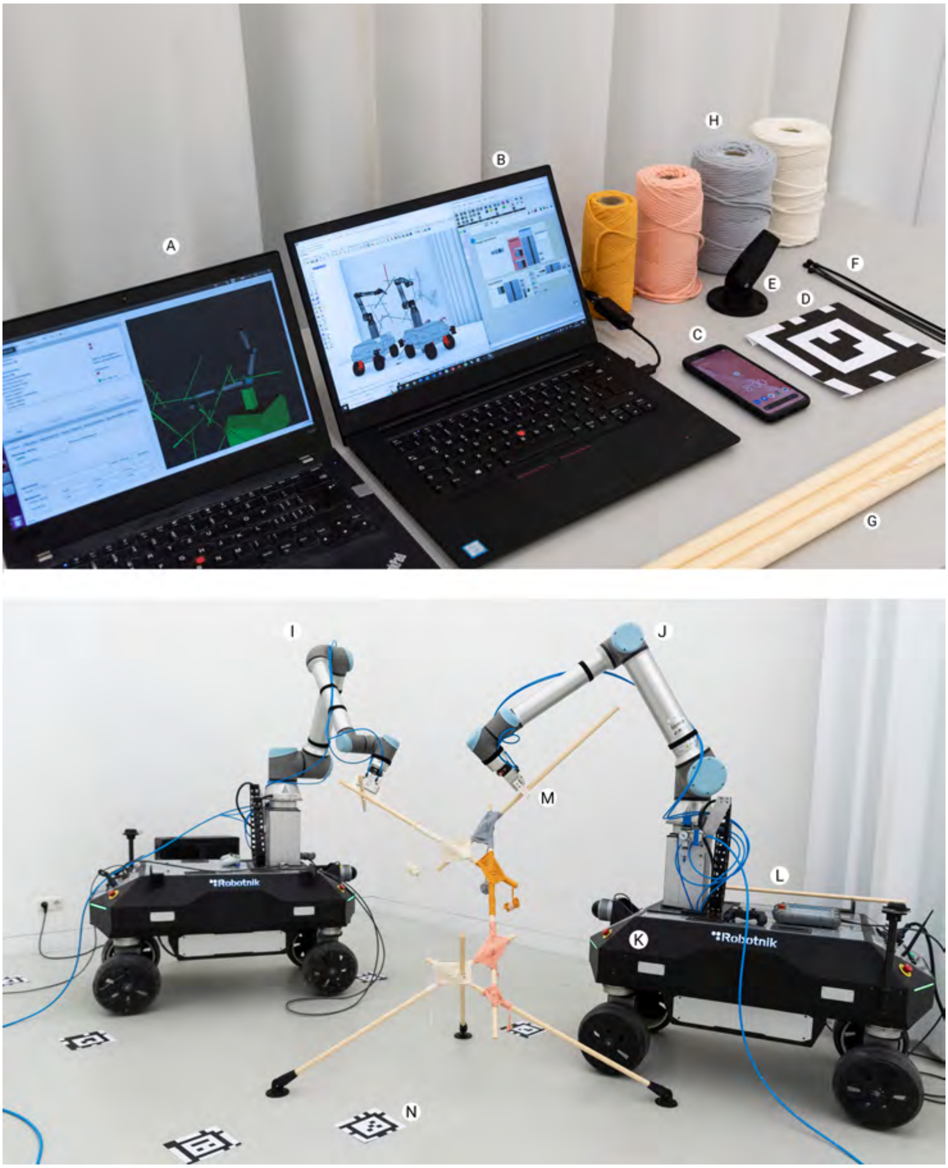


Figure 3.44: Hardware setup of the system. (A) Linux computer, (B) CAD computer, (C) mobile AR device, (D) QR-codes, (E) adjustable 3D printed feet, (F) zip-ties, (G) wooden struts, (H) wool, (I) robot 1, (J) robot 2, (K) mobile platform, (L) timber strut pick-up station, (M) pneumatic parallel gripper with custom 3D printed gripper fingers, and (N) measured-in fix points (QR codes).

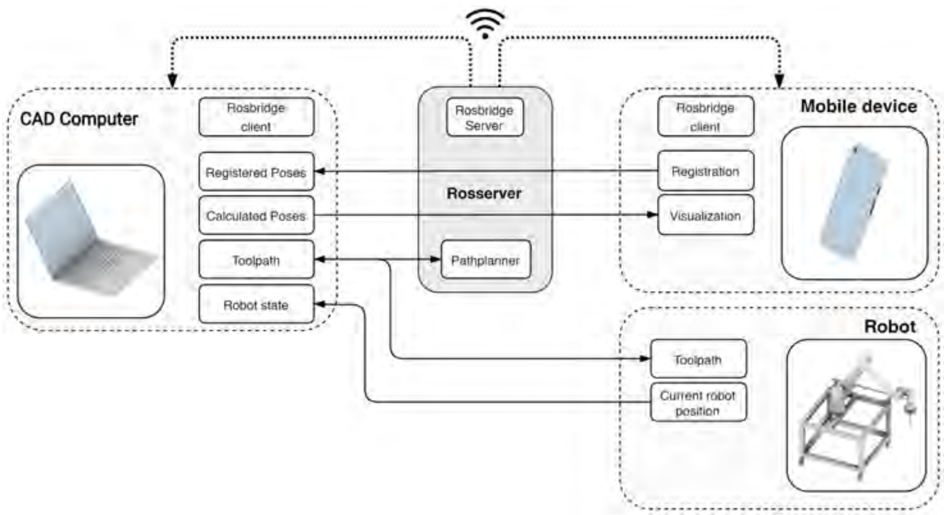


Figure 3.45: Communication workflow diagram showing the system setup consisting of 1) a computer with a CAD design environment, 2) a mobile AR app, and 3) a robotic unit

Results and limitations

We tested and validated our computational setup and assembly strategy by producing a proof-of-concept prototypical architectural structure over a period of 5 days. The floor area of the prototype was 6x4m. As described in section *Case study - Tie a knot*, two humans, in collaboration with two mobile robots, cooperatively and interactively assembled a wooden structure in turn-taking actions. The hybrid human–robot assembly process was initialised with three pre-assembled elements fixed to the ground. A total of 38 wooden struts were assembled, of which 29 were manually placed and tracked by a user. Nine were placed by the robot (Fig. 3.46). The design setup focused on the space frame logic due to the inherent rigidity of the triangle. Rope joints connected the different elements of the triplet. Over the period of 5 days, we placed 53 knotted joints, and the whole structure was disassembled within two hours (Fig. 3.43).

In this experimental study, more struts were placed manually than robotically because many connections to the walls and floors were required as *special scenario struts* to ensure structural stability. 10 of the 29 manually placed struts were registered with both the app and the robot. Not all manual struts were registered because only those used to continue the assembly robotically were tracked and included in the physical-digital model (Fig. 3.47). Another eight struts were registered during assembly as the structure deformed over time, and an updated version of the struts was required to continue a precise building process. The tracking discrepancy between struts registered by the AR app and the robot was measured by comparing the registered element frame located in the centre of the cylinder; the tracking discrepancy ranged between 19.74 and 78.9 mm positional difference and 2.81 degrees to 7.83 degrees rotational difference. The colour gradient in the error plot (Fig. 3.48a, 3.48b) indicates these deviations. The registration via visual-inertial object tracking reached its technological limits due to the distinct geometry of the struts. The long and thin wooden struts were not ideal for edge-detection-based algorithms as they were only marginally constrained in one

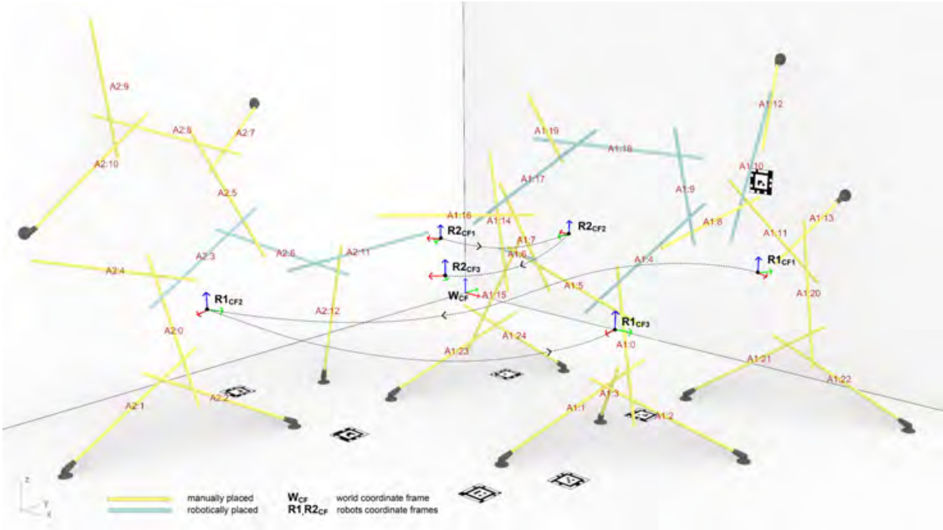


Figure 3.46: Screenshot of the digital model showing in blue the robotically placed elements and in yellow the manually placed elements

direction, which led to a shift along the strut's axis of the digital model. The alternative registration method of the manually placed struts using the robot's manipulator for probing reference points fulfilled the accuracy requirements. However, both methods proved to be time-consuming to use.

Discussion

Human-robot cooperation:

This experimental study has explored how the combination of manual and robotic actions might open new opportunities for future crafts and lead to new workflows for human agency in robotic construction. Examples of such human agency are tasks that are difficult to be carried out by robots. In this experiment, for example, such a task refers to the joining of the wooden elements using ropes. Most joining processes in robot manufacturing have focused on systems that can be automated and avoid such complex connections. On the contrary, *Tie a Knot* is characterised by the intentional incorporation of manual joining techniques into robotic processes, thus aiming to combine advanced robot-based methods with traditional craftsmanship knowledge. In addition, such human agency is also reinforced by the fact that the system presented is designed so flexibly that spontaneous design decisions and adjustments are made possible. The flexibility of a system to be open to spontaneous changes is particularly important for special situations, for example, when the elements have to be attached to the floor or the wall. However, a prerequisite for featuring such flexibility in a robotic construction process is the ability to continually feed human-induced changes into a digital model, here presented as the shared digital-physical workspace.

According to Shi's categorisation [86], our system falls into the category of human–machine cooperation because it supports an intermediate level of human–machine collaboration. Both

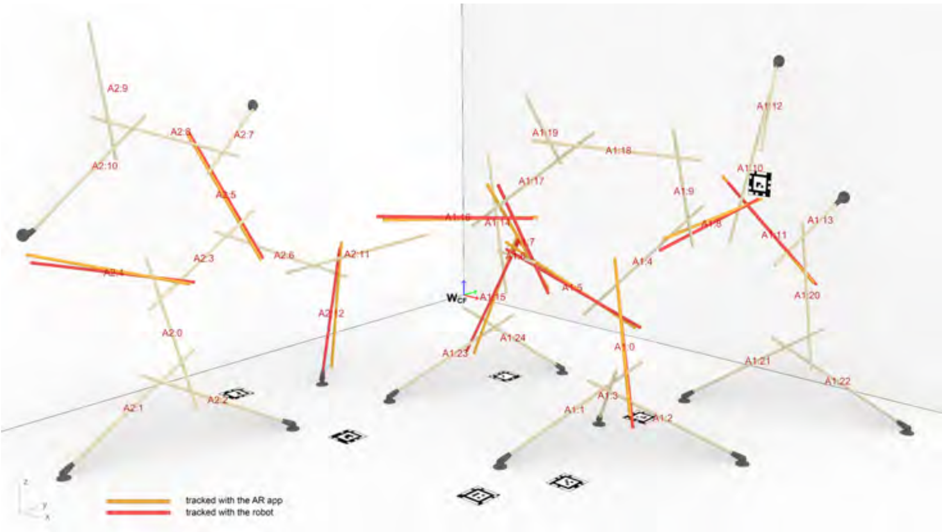


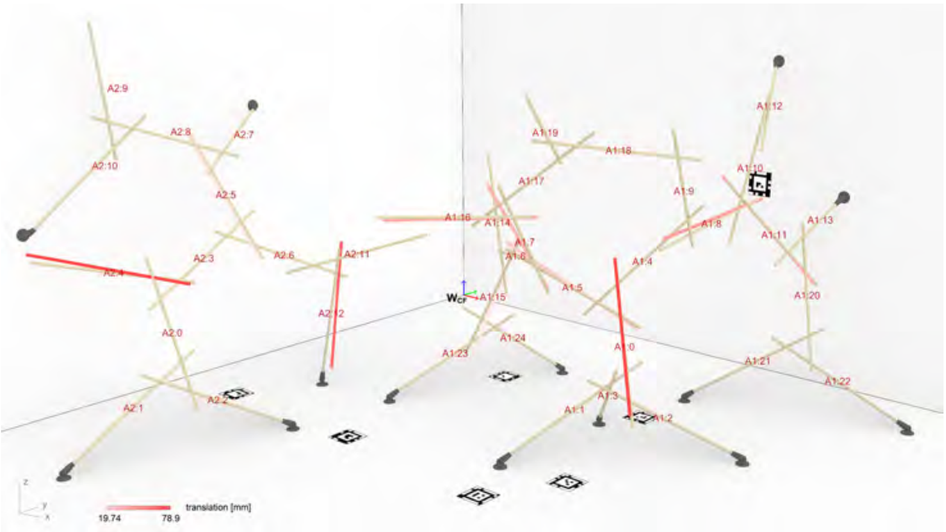
Figure 3.47: Different tracking results of manually placed elements: orange: tracked with the AR-capable phone, red: tracked with the robot.

cooperating entities, humans and robots, have the autonomy to achieve a common goal and to make use of the knowledge and skills of the other system. Both entities share the same workspace, and the human interacts directly with the robots in their workspace. The human assembles and joins the elements synchronously, while the robot holds single elements and thereby stabilises the overall structure. Currently, the robot's position relative to the human's position cannot be detected. Therefore, the robot did not continue the next pick-and-place task until the human initiated it and moved outside the robot's workspace. Tighter and more responsive sensor systems would be needed to enable parallel task execution with humans within the workspace.

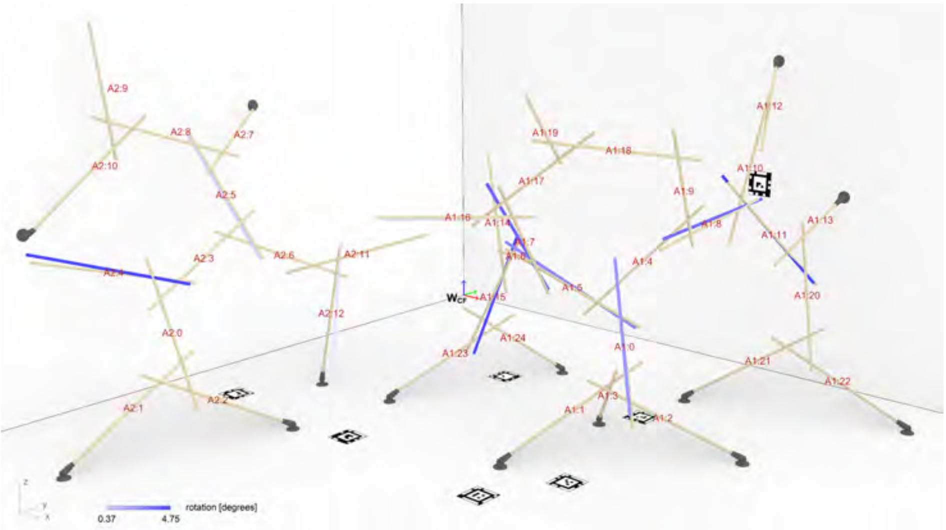
Potential for future work:

Tie a knot incorporated complexity on multiple levels involving mobile robotic systems, structures that deform over time, and non-predefined design. These systems require continuous localisation of the robots, tracking of built elements over more extended periods of time, and registration of manual physical interventions. Currently, only a relatively small architectural installation was fabricated with the workflow and tools developed here. Future research aims to assemble a larger-scale structure to test a broader range of spatial articulations. As scale increases, more robust computational support needs to be implemented for humans to guide decision-making processes, i.e., intelligent computational processes capable of observing, predicting, and controlling quantifiable performance targets such as structural stability and robot range. Such a real-time structural analysis would be required to ensure that spontaneously made decisions are statically valid, also considering future load cases.

Furthermore, the automatic object tracking workflow and implementation need substantial modifications and improvement. Future development needs to combine and automate the same object tracking for manually placed objects with the tracking system for locating the



(a)



(b)

Figure 3.48: The colour gradient (red for translation (a) and blue for rotation (b)) visualises the deviation between the tracking results of the AR app with those from the measurement executed with the robot.

mobile robots in relation to the built structure. Additionally, it is critical to speed up the tracking of manual changes made to the built structure.

Regarding the AR interface, in the future, we will focus on the visualisation of additional data such as design possibilities, robot reachability, and robot toolpath simulation, which will be shown overlaid on the physical world. AR could also be used in the future to inform people about the structural feasibility of currently selected options. These spatial visualisations could better support people collaborating to make more informed design decisions.

Conclusion

Instead of supporting a workflow that is object and end-product-oriented, *Tie a Knot* furthers the idea that traditional craft fulfils a deep-seated human need for direct engagement with material production [174]. The workflow developed here allows for intuitive interaction and direct tacit engagement with the material and process, thus deviating significantly from linear design-to-production workflows. At the same time, back-end computational processing combined with highly precise tracking algorithms provides new possibilities for human augmentation.

While it is common to include human collaborators in semi-autonomous processes, in which the human undertakes specific tasks such as manually loading the robot's material, placing and tightening joints, or manually drilling robotically placed elements, in these processes, human interaction is not linked with a digital model and happens outside supervision. In our workflow, human interventions are used strategically for decision-making, corrections, and tacit engagement with a physical process, while still being assisted by computational logic assuring quality.

Tie a Knot is a system that allows humans to negotiate the levels of task distribution and coordination and thereby reinvent the fundamental relationship between humans, skilled workers, and designers—machines and robots. Such a system reinforces human agency by increasing the social sustainability of automation, allowing humans to make decisions throughout fabrication procedures and interactively decide on task distribution. This workflow enables explicit machine intelligence (parameters, work range, structural boundary conditions) to be integrated with implicit human knowledge (creativity, intuition, fast reaction to complex situations), thus enabling a new cooperative workflow and building strategy. These cooperative strategies could be harnessed to extend robotically automated workflows to materials and construction scenarios that have resisted automation, including unpredictable and unstructured material processes or working within complex existing building structures. In such cases, humans could actively intervene, physically or cognitively, supporting or steering automated processes toward higher levels of robustness and efficiency in complex or unforeseen scenarios.

3.3.3 Credits and acknowledgments

Author's contribution:

From 2021 to 2022, the author of this thesis undertook the development of the hybrid human-machine fabrication workflow, defining its setup and implementing a design and fabrication workflow. The workflow included the integration of two tracking setups into the architectural design and planning environment, linking it with a digital twin. These two tracking setups, the visual-inertial object-tracking of Dr. Timothy Sandy and manual probing via the localised robot, enabled the registration of human actions via manually placed objects. An interactive computational model took these manual actions into account to generate design options and subsequent robotic fabrication data. The different design options were created using the Assembly Information Model by Lidia Atanasova and Dr. Kathrin Dörfler. To distribute assembly tasks either to a human or to a robot, the author developed an action-based workflow and linked it with the digital twin. To instruct and enable a human to place manual objects within the structure, the digital twin was linked to a phone-based AR system. This required the implementation of a high-level communication system for the sensor and actuator systems by the author.

Finally, the contributions of the author concluded with the conception and implementation of the architectural application scenario and physical prototypes presented in this thesis. The physical prototype served to qualitatively and quantitatively evaluate and validate the proposed method.

Collaboration:

The Assembly Information Model [144] was implemented by Lidia Atanasova and Dr Kathrin Dörfler (TT Professorship of Digital Fabrication, Technical University of Munich) using the data structures available through the open-source Python-based COMPAS framework [175]. The sensing solution of the visual-inertial object tracking was developed by Dr Timothy Sandy [100] at incon.ai. The final physical prototype was built in collaboration with Lidia Atanasova at the Technical University of Munich. The project was supported by ETH Zurich (Gramazio Kohler Research), TU Munich (TT Professorship of Digital Fabrication), and IAAC Barcelona (MRAC).

Authors contributions to the paper:

The contributions of each author in this paper are described using the Contributor Role Taxonomy[111].

Daniela Mitterberger Conceptualisation, Methodology, Software, Validation, Data Curation, Formal analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Project administration

Lidia Atanasova Conceptualisation, Methodology, Software, Validation, Data Curation, Formal analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Project administration

Kathrin Dörfler Conceptualisation, Methodology, Software, Validation, Investigation, Writing – Original Draft, Writing – Review and Editing, Supervision, Project administration

Fabio Gramazio Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Matthias Kohler Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Acknowledgements:

We want to thank *incon.ai*, especially Dr. Timothy Sandy, for the assistance in providing a custom version of the incon.ai software. We would also like to thank IAAC for hosting our *Robot See, Robot Do* workshop, which helped us develop and test our system. We especially want to thank Aldo Sollazzo and Alexandre Dubor for organising the workshop and Cecilia De Marinis, Daniil Koshelyuk, and Aslinur Taskin for their support throughout the workshop. Further, we want to thank all our students at IAAC for their excitement and engagement: Ipek Attaroglu, Robert Michael Blackburn, Christopher Booth, Alfred Bowles, Grace Boyle, Yeo Ami Jeong Kim, Huanyu Li, Andrea Lizette Nájera Rodríguez, Alberto Martínez, Abanoub Nagy Abdou Mikhail, Libish Murugesan, Mit Patel, Tomás Quijano, Beril Serbes, Sha-manth Siddaramu, Vincent Verster, and Jordi Vilanova. We thank the School of Engineering and Design at the Technical University of Munich for providing the space for our proof-of-concept prototype. Thanks to Begüm Saral and Ema Krakovska for helping with preparing the construction materials and assisting in the disassembly.

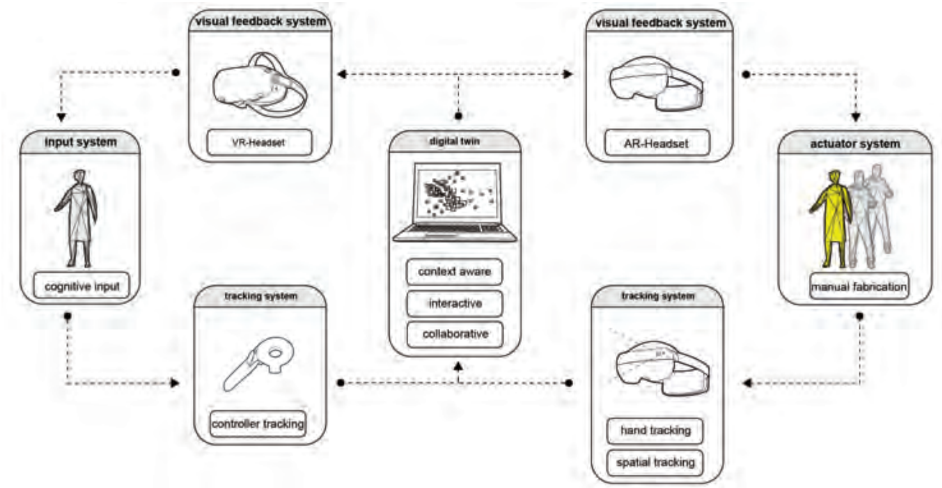


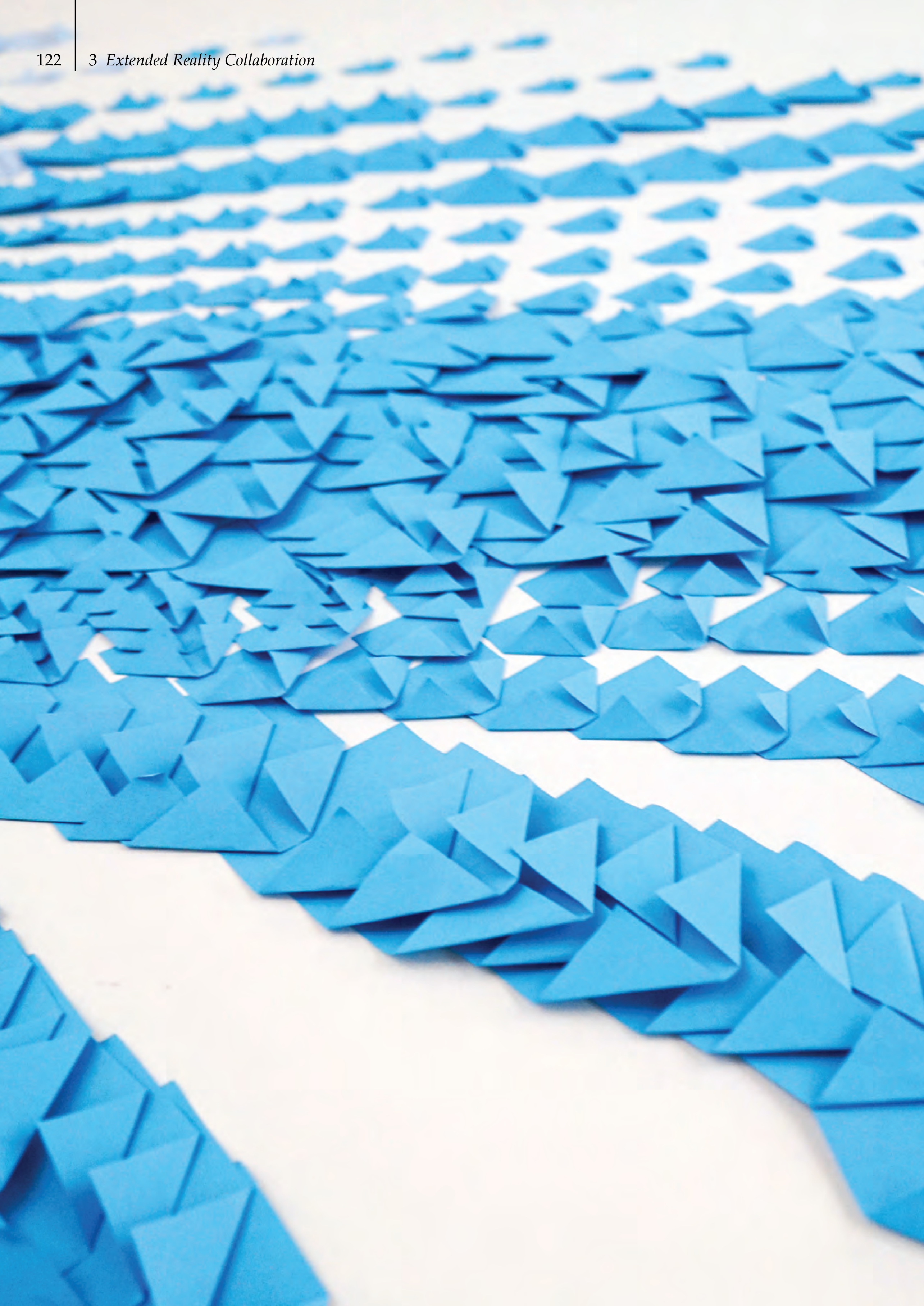
Figure 3.49: Diagram visualising the applied methodology for Extended Reality Collaboration: (a) context-aware, interactive and collaborative computational model, (b) AR Headset, VR Headset, (c) manual fabrication, (d) controller tracking, hand tracking and spatial tracking

3.4 Teleoperated human-human collaboration

3.4.1 Summary and contribution to thesis

This paper[10] contributes to the concept of *teleoperated human-human collaboration* by enabling humans to collaboratively design and fabricate in a mixed reality environment across remote locations. This paper introduces methods to enable collaboration between on-site and off-site users for design and fabrication tasks (Fig. 3.49). Here, a digital twin is accessible to both on-site and off-site users. Each user has a different interaction scenario; the on-site user interacts via hand tracking, and the off-site user via controller tracking with the digital twin. The current state of the construction site is included in the digital twin via spatial tracking by the on-site user. To access the digital twin, the on-site user uses an AR headset, and the off-site user utilises a VR headset. Both users have distinct visual user interfaces, so they can design, preview, and fabricate collaboratively.

[10] This version of the article has been accepted for publication, after peer review and is subject to Springer Nature's AM terms of use, but is not the Version of Record. The Version of Record is available online at: https://doi.org/10.1007/978-3-031-13249-0_24



3.4.2 Extended reality collaboration (ERC): Virtual and Mixed Reality System for Collaborative Design and Holographic-Assisted On-site Fabrication

Daniela Mitterberger[1], Evgenia-Makrina Angelaki[1], 1, Foteini Salveridou[1], Romana Rust[1], Fabio Gramazio[1], Matthias Kohler[1]

Abstract

Most augmented and virtual applications in architecture, engineering, and construction focus on structured and predictable manual activities and routine cases of information exchange, such as quality assurance or design review systems. However, collaborative design activities or tasks such as complex negotiation, task specification, and interaction are not yet sufficiently explored. This paper presents a mixed-reality immersive collaboration system that enables bi-directional communication and data exchange between on-site and off-site users, mutually accessing a digital twin. Extended reality collaboration (ERC) allows building site information to inform design decisions and new design iterations to be momentarily visualised and evaluated on-site. Additionally, the system allows the developed design model to be fabricated with holographic instructions. In this paper, we present the concept and workflow of the developed system, as well as its deployment and evaluation through an experimental case study. The outlook questions how such systems could be transferred to current design and building tasks and how such a system could reduce delays, avoid misunderstandings and eventually increase building quality by closing the gap between the digital model and the built architecture.

Keywords mixed reality, virtual reality, interactive design, collaborative virtual environments, remote collaboration, immersive virtual environment.

[1] Gramazio Kohler Research, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland

Introduction

In recent years, there have been remarkable advances in mixed-reality technologies for architecture, engineering, and construction (AEC). Most augmented and virtual applications in AEC focus on structured manual activities [77, 176, 177], more routine cases of information exchange such as quality assurance [94, 178], or design review [179, 180]. Collaborative design activities or interdependent collaborative tasks, such as complex negotiation, task specification, and interaction, are, however, not yet sufficiently explored [181–184].

Collaborative activities in the field of AEC can involve a plethora of different stakeholders with heterogeneous backgrounds and expertise. Furthermore, stakeholders can involve remote collaborators, ranging from on-site to off-site users. Especially for communication between remote users, knowledge transfer is critical for a successful collaboration, particularly for task decomposition, handover processes, and design revisions. Improved decision-making processes can enhance workflow efficiency and collaboration in the creative process as it supports the inclusion of expert knowledge.
Current computer-supported cooperative work (CSCW) systems focus on enhancing collaboration in AEC by providing users with diverse shared information. This information includes, for instance, access to shared digital context through common data structures and environments utilising building information modelling (BIM) software such as *Autodesk Revit* or *ArcGIS*. Other systems provide access to shared administrative tasks such as project management platforms, e.g., *Microsoft* planning software or *Autodesk Navisworks*.
Current CSCWs systems are suitable for very distinct and asynchronous tasks that do not require extensive communication and collaboration between users. Their structure allows users to complete individual tasks and inform other users about their progress. Nevertheless, due to their task-specific structure, these platforms are relatively rigid and do not provide an environment that fosters an immersive communication and discussion platform between users. This lack of a communication environment can cause user frustration and inhibit creativity. Especially interwoven negotiated task activities require a more comprehensive range of communication between different stakeholders.

The research presented in this paper, Extended Reality Collaboration ERC, aims to complement the functionalities of existing CSCWs systems and groupware tools in AEC by providing workflows for not yet well-supported collaboration and communication tasks. This paper proposes a mixed-reality immersive collaboration system that enables bidirectional communication and data flow between on-site and off-site users. It enables them to operate together on a digital twin in a collaborative virtual environment (CVE). The workflow and functionalities of *ERC* have been applied and validated in an architectural scale prototype - a sticky note installation.

Background

Our work builds upon two general fields of research: collaborative virtual environments and augmented fabrication.

Collaborative virtual environments (CVE): Churchill et al. [185] define CVEs as distributed virtual systems that enable users to collaborate with a digital environment and with each other. Asymmetric CVEs [186, 187] support users with different input and visualisation hardware, adapting to their various capabilities. *DollhouseVR* Ibayashi et al. [188] facilitates asymmetric collaboration between co-located users, one virtually inside the dollhouse using a head-mounted display (HMD) and the other using an interactive tabletop. Another asymmetric CVE of co-located users is *shareVR* [189], which uses floor projection and mobile displays with positional tracking to visualise a shared virtual world for non-HMD users. A system developed for geographically separated users is presented by Oda et al. [190], which supports a remote expert to assist a local user. The results showed that a local user understood task instructions faster when the remote user wore a VR HMD and demonstrated the task in virtual space compared to written annotations. Commercial software such as the *Wild* and *Iris VR* provide CVEs for multi-user object manipulation but do not link it with fabrication parameters and instructions and, therefore, miss out on streamlining the design and fabrication phase.

Augmented fabrication: Augmented fabrication in AEC focuses primarily on guiding a craftsperson in a manual fabrication process [69]. This guidance can be with audio instructions, projection mapping, or screen-based mixed reality (MR). *Fologram* uses MR headsets to see virtual holographic 3D models in space and assist unskilled construction workers in complex fabrication tasks [77]. An example of a screen-based augmented reality (AR) system is *Augmented Bricklaying* [145]. This system extends purely holographic AR with a context-aware AR system, providing humans with machine precision by tracking objects in space. *IRoP* [191] is a system that allows users to instruct robots via programming by demonstration and to preview generated designs on-site via projection-based AR. While the growing number of AR fabrication research shows the enormous potential of augmented fabrication, all the discussed systems are solely designed to be used in situ. None of the above examples links a local user with a remote user.

Methods

Our *ERC* system aims to combine design and fabrication functionalities in a collaborative virtual environment and enhance communication between two geographically separated stakeholders. Consequently, the system not only converges on- and off-site activities but also integrates the processes of design development and physical fabrication into one virtual shared environment.

User scenario:

ERC involves at least two different stakeholders with different expertise that are indifferent locations; one user is on-site, and the other is off-site (see Fig. 3.50). The on-site user, "MR-User", is equipped with a MR headset, whereas the off-site user, "VR-User," utilises a virtual reality (VR) headset. The MR-User represents an expert construction worker, craftsperson, or construction site manager. The role of the MR-User is to provide site-specific data, insight knowledge, and instruct manual fabrication. The VR-User represents a stakeholder such as an architect or planner who navigates in a digital twin of the construction site. The role of the VR-User is to request and receive on-site information and feedback on the design to adjust the design accordingly. Furthermore, the VR-User provides different design options and supervises fabrication. Both users meet in the virtual space collaborating synchronously.

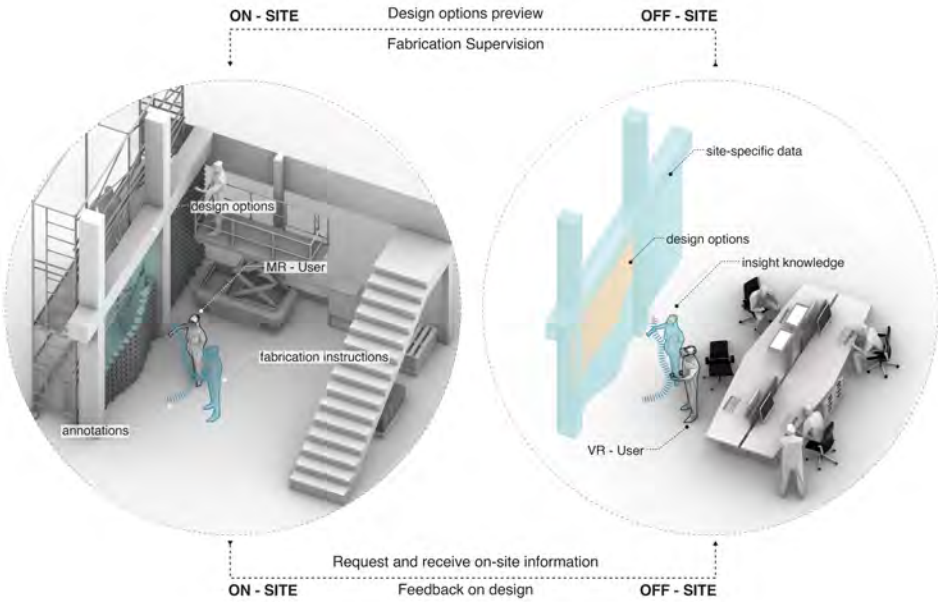


Figure 3.50: User scenario showing the on- and off-site scenario with two distinct stakeholders

System Walkthrough:

ERC is designed around two distinct phases, 1. Collaborative design phase, and 2. Augmented fabrication phase. In phase one, the VR-User (architect) and the MR-User (expert) evaluate the design options collaboratively. The MR-User localises and creates the digital twin (see Fig. 3.51a), and then both users can meet in virtual space (see Fig. 3.51b). The MR-User sees the design options as holographs on-site, while the VR-User sees them in the digital twin of the construction site. The collaborative design phase has two distinct features: 3D sketching and annotating (see Fig. 3.51c) and collaborative design on-the-fly (see Fig. 3.51d). Phase two allows the users to plan and fabricate the design and has two features: holographic fabrication (see Fig. 3.51e) and fabrication supervision (see Fig.3.51f). To illustrate a typical interaction, we consider the user scenario described in section *Methods - System Walkthrough*. The users follow a linear sequence of interactive design and fabrication sessions.

A - Creation of a digital twin: The creation of a shared digital twin model featuring both the construction site as well as the as-built model can be done in two ways, resulting in meshes with different resolutions. The first option is asynchronous, creating a high-resolution point cloud using a *Lidar* scanner. The second option is synchronous using the spatial awareness system of the MR headset. This option can be accessed in *ERC* via the 'scanning' feature allowing the users to receive a current as-built mesh of the construction site with customised levels of detail. This feature consists of several interactive modes to access further and edit the generated spatial data. The MR-User can select and send meshes to the VR-User. Based on these meshes, the VR-User can adjust and update the design options.

B - Localisation and meeting in virtual space: Both users need to be localised in physical and virtual space to correctly send correlated spatial, geometric, and temporal data. Therefore,

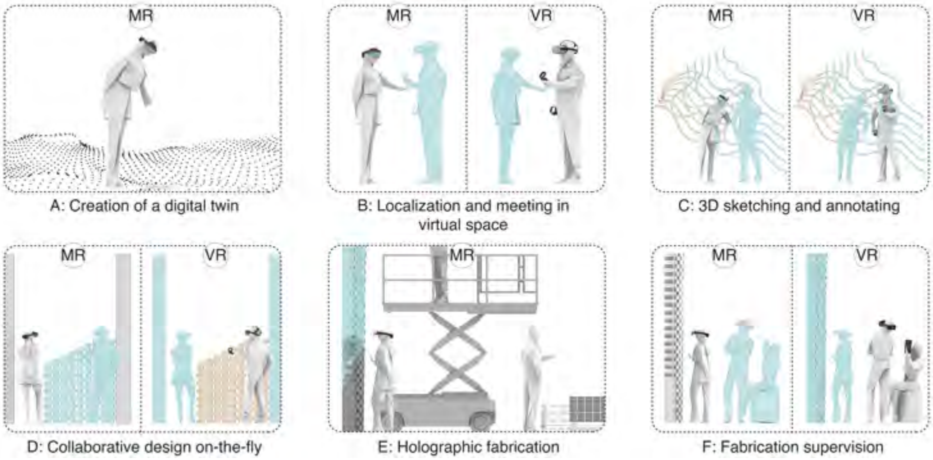


Figure 3.51: System walkthrough.

the local coordinate systems of the MR and VR spaces need to be aligned using relative transformation. The transformation requires the current position of each user relative to an origin frame. As an origin frame, the MR-User scans a referenced QR code in the physical space and then transmits the frame data to the VR-User. To share a mutual sense of presence, both users appear as avatars. The avatar position is updated in real-time and allows the users to communicate via hand movements and body motion trajectories.

C - 3D sketching and annotating: After localisation and setting up a digital twin of the construction site, both stakeholders use a sketching and annotating feature to draw in 3D, highlight specific target areas or annotate existing designs (see Fig. 3.52). In this phase, both users can discuss potential design problems with the construction site's current as-built state.

D - Collaborative design on-the-fly: This feature allows users to preview and adjust a parametric design model on-the-fly in MR and VR and directly preview it as a hologram in-situ (see Fig. 3.53). The VR-User loads the parametric model using Rhino.Inside1 and adjusts the parameters of the digital model according to the feedback of the MR-User. The VR-User has access to the properties of the parametric model and can adjust these parameters in near real-time. Both users can sketch directly on the design options using the "3d sketch and annotate" feature.

E - Holographic fabrication: After deciding on a final design, the users switch from the interactive design phase to the fabrication mode (see Fig. 3.54). The fabrication mode can also include multiple other users as the system can be deployed on various augmented reality devices. The MR-User receives fabrication-specific information such as the holographic 3D model, estimated fabrication time, and the number of elements deployed. Furthermore, the MR-User can switch between fabrication sessions. These sessions are visualised in different colours representing the estimated daily working hours (see Fig. 3.55-2).

F - Fabrication supervision: This mode allows the MR-User to enter information about completed tasks, current fabrication sessions, and problematic areas. Furthermore, the VR-User can virtually join the fabrication session to supervise the process (see Fig. 3.55).

Figure 3.52: 3D sketch and annotation feature. On the left is a first-person view of the MR-User watching the VR-User sketch. On the right side is a third-person view of the MR and VR-User drawing collaboratively within the VR space.

Figure 3.53: Collaborative design on-the-fly feature. On the left is a first-person view of a hologram of the design on the installation site. On the right side is a third-person camera view of the MR and VR-User discussing the design in VR.

Figure 3.54: A menu informing the MR-User about fabrication parameters and the holographic 3D model supporting fabrication.

Figure 3.55: Fabrication supervision feature. On the left is a first-person view of the MR-User looking at the VR-User. On the right side is a third-person camera view of the MR and VR-User discussing the fabrication in VR. The different coloured elements show the different fabrication sessions.

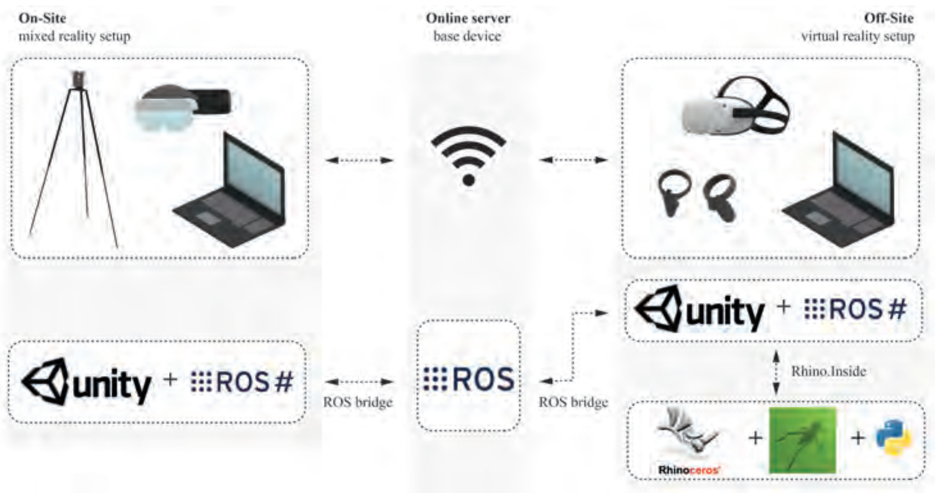


Figure 3.56: System architecture

System Architecture:

As displayed in Fig. 3.56, the system architecture consists of three main parts: (1) an on-site MR setup with a scanning system, (2) an online server, and (3) an off-site VR setup. The on-site MR setup consists of a laser scanning device (*Leica RTC 360*) providing high-resolution on-site scans, an MR headset (*Microsoft Hololens2*), a laptop, and a WIFI router. The off-site hardware consists of a VR headset (*Oculus Quest2*), a laptop, and a WIFI router.

The software setup is structured as follows. Two autonomous *Unity3D* applications were developed, one for MR and one for VR. The MR application *uses the Mixed reality toolkit* (*MRTK*) and *OpenXR* library to enable spatial awareness scanning and QR-code detection. The VR application is developed using the *OpenXR* library. Furthermore, *Rhinoceros3D*, *Grasshopper*, and *Python* are used to create algorithmic designs. *Rhino.Inside* [11], enabling compatibility and bidirectional communication between external Unity processes and Grasshopper. Online communication is based on the Robot Operating System (*ROS*) [108]. The *rosbridge* package is used to access the publish-and-subscribe architecture of *ROS* and *ROS#* for the *Unity3D* applications.

Case study

To validate the feasibility of the proposed method and demonstrate the potential for a concrete fabrication system such as façade panels, we focused on one full-scale experimental implementation. For a user-friendly experience, the user interface (UI) design was based on each user's different roles and work packages (see Fig. 3.57). We used sticky notes as placeholders to showcase the various and complex types of information that can be exchanged between two geographically separated users.

[11] *Rhino.Inside®* is an open-source project which allows Rhino and Grasshopper to run inside other 64-bit Windows applications

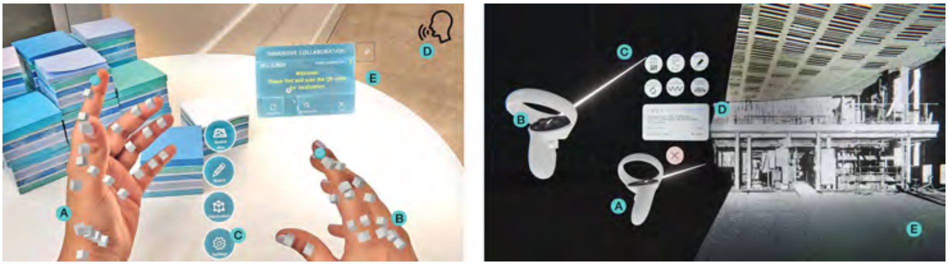


Figure 3.57: Left: The MR-User interacts via hand tracking (A), gesture tracking (B), menu buttons(C), and voice commands (D). The MR-User sees an info window superimposed over their view (E). Right: The VR-User navigates the space and interacts via controllers (A) using controller buttons (B) and virtual menu buttons (C). The VR-User sees an info screen (D)and moves within a digital twin of the construction site (E).

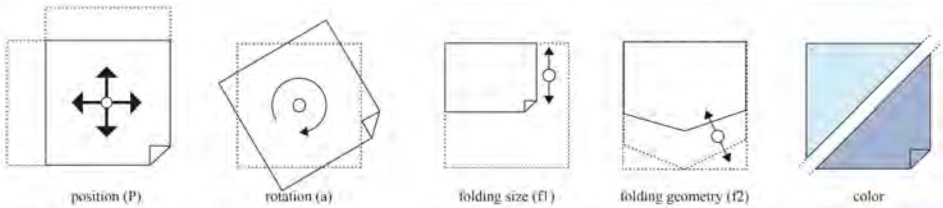
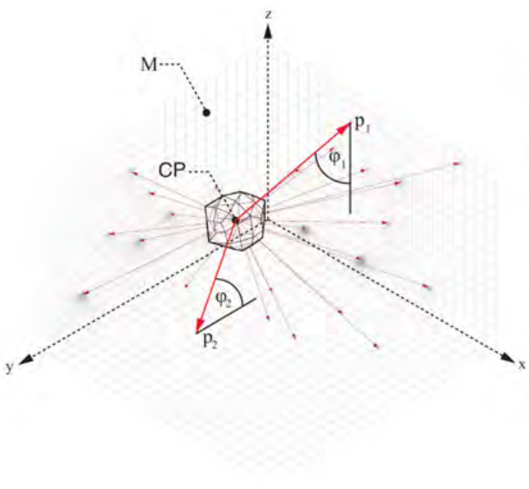


Figure 3.58: Various and complex parameters that can be exchanged with the system



Design Paramters	
CP	centerpoint of attractor
p1, p2	intersection point
[φ1,φ2....]	angle
M	scanned mesh
P	sticky note position
a	sticky note rotation
f	sticky note folding size
color 0,1	sticky note color

Remapping values		
P	=	p
a	=	φ
f	=	remapped value of φ
φ < tolerance	=	color 0
φ > tolerance	=	color 1

Figure 3.59: Computational attractor-based design logic and remapping values to determine sticky note position, rotation, folding size, and colour

This information includes the position (P), rotation (a), size (f1), geometry (folding type) (f2), and colour of each unit (see Fig. 3.58).

The total fabrication time was 26 hours, whereas the interactive design was around 1 hour. The final design was fabricated using two MR headsets, and a total of 4,000 sticky notes were placed. The final design was split into distinct fabrication sessions of 60-90 minutes. We used an attractor-based approach for the computational design, which influenced the design depending on its location in space and its distance from physical boundaries (see Fig. 3.59). Specifically, the attractor's location (CP) changed the position, rotation, colour, size, and folding type of the sticky notes. In our case study, the sticky note's location was projected onto the spatial mesh data (M) scanned by the MR User. This projection resulted in a precise position for each sticky note on the as-built data of the installation site. During the design phase, the VR-User moved the attractor as an interactive 3D prism in virtual space to control the number of projections. The VR-User could adjust the design parameters collaboratively with the MR-User while the MR-User saw the different results as holographs in-situ. Furthermore, the MR-User could interact with the design via sketching to adjust the outline of the design. After agreeing on a final design, the MR-User fabricated the full-scale experimental implementation (see Fig. 3.60) while the VR-User supervised and informed the process.

Results

Our *ERC* system allowed for an intuitive and real-time design interaction for users in different physical locations. The users had access to a full-scale impression of the architectural model augmented and contextualised by site-specific information.

Figure 3.60: Photograph of the fabrication of the final physical installation.

Both users collaboratively designed and fabricated a complex and full-scale architectural installation (see Fig. 3.61). Furthermore, personalised communication was achieved by creating avatars for all users. Implementing the *ERC* system and the case study provided us with insights into the hardware and software limitations.

System limitations:

We experienced hardware limitations regarding the environmental scanning and localisation as well as the jitter of the digital model (see table 3.2). The main software limitations were delays and transmission speed, especially between the Grasshopper environment and the Unity interface with increased mesh count and internet connection speed. To avoid delays between the MR and VR-User, we used a mesh resolution of 20 triangles per cubic meter. Furthermore, the system still has a limited amount of drawing tools in the "3D sketch and annotation" feature. Extending the drawing tool would allow users to interact with a broader range of communication options. In noisy environments, it was difficult to get the other user's attention. Therefore, it would be essential to implement an "attention feature". Additionally, the current system lacks a "documentation feature" that would allow users to upload videos, pictures, or voice memos to the digital model with the associated locations. Such a note collection could help on-site workers keep track of construction site notes and allow easier communication with off-site users. These notes could also be read asynchronously, allowing users to log into the system at different moments.

Table 3.2: Relation between QR Code placement and visibility and drift of the digital model. The QR code dimensions were 12.5cm x 12.5cm.

QR-code distance	drift of the digital model
< 0.45m and in view	0.1 - 0.3cm
~ 4m and in view	1.5 - 2.3cm
not in view	2 - 3cm

Conclusion and Outlook

This research investigates the potential of collaborative design activities and how they could lead to better knowledge and information flows between on-site and off-site stakeholders during design and fabrication processes. The functionalities of the system were evaluated via a full-scale case study, aiming to define collaboration protocols and improve interaction and communication. Even though there are still limitations, this research shows the potential of such a system to improve supervision and collaboration between on-site and off-site stakeholders, such as architects and construction supervisors, to support a paperless construction site. The key findings of this research are novel collaborative MR and VR interfaces, 3D workspace scenes with sufficient context awareness, and a fabrication protocol that includes remote monitoring and planning. As an outlook, such a system could be applied towards detecting deviations between the as-built and the digital model in order to decrease project costs and building time. Such a system could be applied to real building scenarios, i.e., on-site construction meetings, custom interior designs, renovations, and complex building elements. *ERC* allows dispersed personnel to have more direct contact, thereby reducing problems of isolation and miscommunication. Furthermore, such a system could accelerate workflows and support a teleoperated construction site.

Figure 3.61: Photograph of the final physical installation.

3.4.3 Credits and acknowledgments

Author's contribution:

From 2021 to 2022, the author of this thesis conceptualised, developed, and experimentally tested and validated a teleoperated collaborative workflow between humans. This workflow included implementing an AR/VR visual feedback system, controller, and hand-tracking setup and integrating them into a digital twin. This digital twin enabled tracking of human intentions via controllers and hand gestures and integrated a set of computational tools to use them for informing the interactive design and fabrication processes. Furthermore, the author of this thesis formulated the architectural application scenarios and conceptualised the workflows underlying the realisation of the physical prototypes presented in this study. Ultimately, the methods presented in this study were qualitatively and quantitatively assessed through experimentation and the realisation of physical prototypes using the AR interface of Foteini Salveridou and the VR interface of Evgenia-Makrina Angelaki.

Collaboration:

Part of the research was executed within the framework of the master thesis of Evgenia-Makrina Angelaki and Foteini Salveridou in their postgraduate Master of Advanced Studies (MAS) program in Architecture and Digital Fabrication at ETH Zurich. Evgenia-Makrina Angelaki developed the VR setup as part of her MAS master thesis and was responsible for the execution of the final prototype. Foteini Salveridou developed the AR setup as part of her MAS master thesis and was responsible for the execution of the final prototype. Dr. Romana Rust and Dr. Lauren Vasey were part of the supervision of the thesis.

Authors contributions to the paper:

The contributions of each author in this paper are described using the Contributor Role Taxonomy[111].

Daniela Mitterberger Conceptualisation, Methodology, Software, Validation, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Supervision, Project administration

Evgenia-Makrina Angelaki Methodology, Software, Validation, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation

Foteini Salveridou Methodology, Software, Validation, Investigation, Writing – Review and Editing, Visualisation

Romana Rust Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Project administration

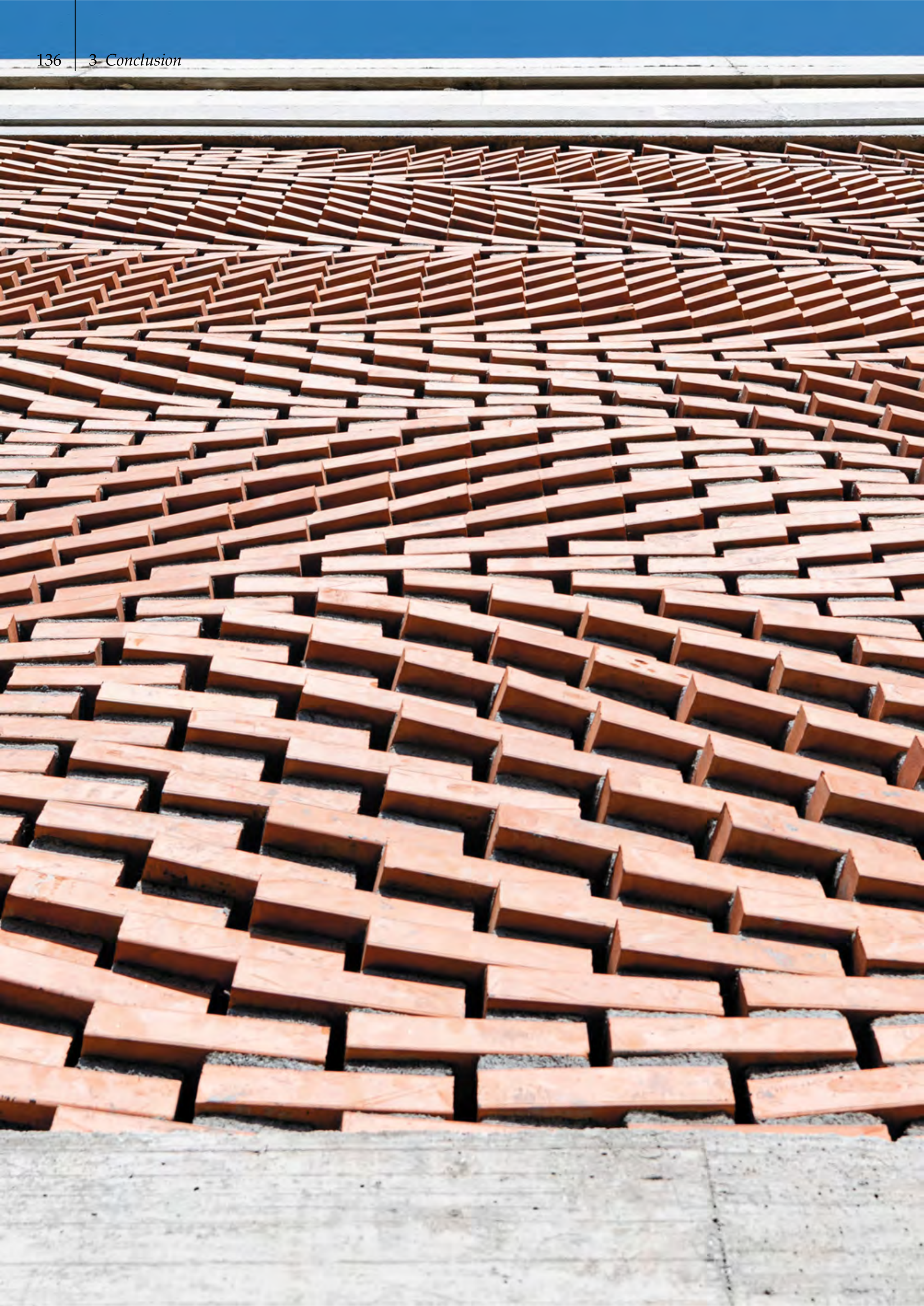
Lauren Vasey Conceptualisation, Supervision

Fabio Gramazio Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Matthias Kohler Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition

Acknowledgements:

We want to thank Gonzalo Casas (ETH Zurich) for supporting the research on online communication. Furthermore, we would like to express our thanks to the Design++ initiative for giving us access to the Immersive Design Lab (IDL), equipment, and support throughout the project.



4 Conclusion

4.1 Summary

This research aimed to investigate how to integrate human participation into digital fabrication workflows, which are typically conducted solely by numerical machines and robots. A dedicated workflow was developed that enhances intuitive interaction and human involvement in construction processes through the use of adaptive digital fabrication. To achieve this, the research incorporated process digital twins, visual feedback systems, and tracking setups resulting in novel forms of human enhancement and, vice versa, in the extension of machines.

Human involvement is common in digital fabrication in architecture, where tasks such as reloading material, connecting robotically assembled parts, monitoring and checking quality, and securing joints are performed. However, these human actions were not yet connected to a digital model or represented in a digital twin. This research bridges this gap by creating collaborative workflows and digital twins that incorporate human actions related to decision-making, fabrication correction, and quality assurance. At the same time, the computational logic informs and assists humans, i.e., craftspeople, throughout the digital fabrication process. The collaborative workflows and digital twins facilitate the distribution of tasks and coordination between humans, machines, and computational processes. As such, the thesis has investigated how humans can physically or cognitively intervene in complex or unforeseen fabrication scenarios to enhance the robustness and efficiency of semi-automated processes. The research hypothesis resulted in the conception and development of digital fabrication systems and experimental workflows that leveraged the strengths of both humans, i.e., creativity, intuition, and fast reaction to complex situations, and machines, i.e., precision, efficiency, and payload.

By combining such machine and human abilities, this thesis investigated novel cooperative workflows and developed collaborative building strategies, ultimately proving that this approach can increase the possibilities and applications for digital fabrication in architecture. This research has further highlighted the importance of human agency in digital fabrication and the potential for human involvement to increase the productivity and robustness of digital fabrication and, at the same time, promote its potential effect on social sustainability.

4.1.1 Summary of experiments

This thesis examined the topic of HMC in AEC from different perspectives in the following four scenarios:

- Case study 1 (Paper A): *Machine-assisted human fabrication* to handcraft architectural structures with machine-like precision.
- Case study 2 (Paper B): *Human-instructed machine fabrication* to robotically fabricate architectural structures with intuitive human guidance.
- Case study 3 (Paper C): *Human-robot cooperation* to assemble architectural structures merging manual and robotic fabrication procedures.
- Case study 4 (Paper D): *Teleoperated human-human collaboration* allowing humans to design and fabricate collaboratively while being physically separated.

Paper A successfully demonstrated the manual construction of intricate brickwork using human visual augmentation. This case study highlighted the benefits of *machine-assisted human fabrication* in producing handcrafted architectural structures with machine-like precision. Visual guidance strategies were used to assist craftspeople in accurately assembling bricks across a large building space. To enable humans to act intuitively, a gamified user interface (UI) was developed that was custom-designed for the craft process. The research showed quantifiable improvements in the accuracy, speed, and geometric precision of the manual in-situ brick assembly process through a context-aware AR system. The architectural design of the structure was pre-determined, and the system solely relied on manual fabrication without the use of robots.

The fabrication scenarios in Paper B and Paper C expanded on the approach used in the first case study by showcasing the interaction between humans and robots in the construction of architectural structures and the interaction between humans and computational processes for information exchange. In these scenarios, the architectural design was not entirely determined prior to fabrication, but rather it evolved as the fabrication progressed through design decisions made by the craftspeople and architects. These design decisions were guided by design principles and computer-based rules. These case studies successfully demonstrated how humans could be augmented both cognitively (by computation) and physically (by robots) to fabricate architectural-scale objects.

Paper B demonstrated *human-instructed machine fabrication*, where the humans provide input, and the machine responds with physical feedback and fabricates artefacts. The case study combines interactive design tools, an AR interface, and a robotic plaster spraying system.

Paper C presented a dually augmented human-robot team involving two mobile robots and two humans to explore how manual rope-joining techniques can be combined with a human-robot assembly process. Both case studies combined manual crafting principles and techniques with in-situ robotic fabrication.

Paper D investigated the implementation of a design-to-fabrication system that enabled collaboration between on-site craftspeople and remote architects, utilising XR technology. This system facilitated collaborative design and fabrication activities, such as complex design negotiation, task specification, and interaction between remote locations. Through a digital twin, the on-site craftsperson could view, evaluate, and adjust the design on a full scale via a visual AR interface. The off-site architect could simultaneously access the digital twin, viewing the as-built condition of the construction site and enabling them to adjust and inform the design. Hence, this system showed how XR could support paperless construction sites by closing the gap between the digital model and the physical built environment.

4.1.2 Summary of used visual augmentation systems

All four case studies utilised and developed a process digital twin shared between the humans and robots involved. This digital twin combined a continuous real-time flow of information between sensors, dedicated computational design models, robot actuators, and visual augmentations for humans. The sensing and the visual augmentation systems provided the craftspeople and architects with an interactive interface that linked fabrication parameters with visual instructions, enabling them to make deliberate choices and decisions while collaborating with a machine during fabrication. For each case study, different AR methods were developed, tested, and evaluated, including screen-based, projection-based, and phone-based AR, as well as AR with a HMD. The variety of systems employed allowed the advantages and disadvantages of different AR solutions to be evaluated.

Stationary screen-based augmentation: The experimental study carried out in Paper A required hands-free visual augmentation for bricklayers. We tested various hands-free AR systems for this study, such as screen-based AR and HMD-AR. Our user study (see Appendix C) has shown that screen-based AR is less distracting for the craftsperson if minor visual inaccuracies occur during the overlay of the digital model over the camera image. Such minor inaccuracies happened when the visualised outline of the brick did not perfectly match the physical brick on the camera image. Another advantage of a stationary screen-based AR compared to HMD devices is that all people involved in the building process have simultaneous access to building information. This was important when the craftspeople had to discuss upcoming tasks with their assistants and guide novices while pointing at a scene. Therefore, collaborative tasks were conducted more efficiently.

Projection-based augmentation: In Paper B, a projection-based AR system enabled craftspeople or architects to interactively design robotic plaster spraying surfaces. The projection-based AR system overlaid the robot's reach, design options, and the number of spray paths directly on the target spray surface. Using this fabrication-related information, craftspeople and architects could design plaster surfaces or patterns directly on-site, incorporating site conditions and machine requirements. Projection-based AR for flat surfaces is a low-maintenance technology that is easy to use and requires no prior experience. Further, projectors are robust, cost-effective, and easily accessible. One disadvantage of our AR projection-based interaction system was the limited projection surface and field of view of a single projector and camera view. This thesis partially overcame this by using multiple static projectors, but this method increased the complexity of our system. A potential solution to such limitations could be placing projectors on mobile platforms that can reorient a single camera at arbitrary locations in the room. Such a mobile projection would require a scan of the room, precise on-the-fly registration, and adjustable projection mapping. Other disadvantages of projection AR include focus shifting and registration issues, which must be considered if high precision is required.

Mobile screen-based augmentation: In Paper C, augmentation via a mobile phone was used to assemble a complex wooden structure with rope connections in a cooperative workflow between humans and robots. Phone-based AR is an excellent solution when craftspeople only need temporary AR instructions and do not use AR continuously throughout fabrication. Craftspeople can work hands-free when required and use the phone-based AR only selectively for actions such as design overview and object tracking to generate a shared physical-digital workspace. In the setup workflow, humans could manually place elements at locations of their choice and then use the phone-based AR to sense and register those objects to include them in the digital model. The design overview and visualisation of the fabrication-related boundary conditions with AR helped craftspeople to be informed about the design space and make computationally informed design decisions during assembly.

Head-mounted display augmentation: Paper D enabled two remote users, an on-site craftsperson and an off-site architect, to design and fabricate collaboratively. The on-site user was equipped with an HMD-AR, and the off-site user was equipped with a VR headset. Head-mounted augmented reality devices overlay digital information directly via a transparent screen onto the physical world, allowing craftspeople to see digital information while seeing the real environment. However, a qualitative survey showed that after using the system for multiple hours, the craftspeople and architects complained about headaches and a stiff neck. Other disadvantages of currently available head-mounted augmented reality devices are that they are costly and sensitive devices and might not be suitable for construction sites where dust, dirt and rough handling are prevalent. Therefore, HMD-AR might be more suitable for short preview sessions on construction sites rather than continuous fabrication sessions. Other difficulties of HMD-AR are registration and precision issues which make them unsuitable for precise manual fabrication.

4.2 Contribution

By conducting four individual case studies, this work established and experimentally validated various strategies and techniques for human-machine collaboration in digital fabrication in architecture. The following sections discuss the contributions of this research to the field of digital fabrication in architecture.

4.2.1 Hybridising traditional craft with digital fabrication

Humans and machines have different abilities and strengths that can be leveraged within digital fabrication processes in architecture and construction. This research thus proposed diverse strategies for combining manual fabrication with robotic fabrication techniques to improve and increase the range of possibilities for digital fabrication in the AEC domain. In the big picture of adopting these new technologies, this research addresses the importance of social sustainability by including humans in digital fabrication. Furthermore, this research introduces different methods to increase the productivity, adaptability, and robustness of digital fabrication processes. Finally, this research shows various workflows and systematic approaches to integrating traditional crafting techniques with digital fabrication.

The four papers contribute to different process-specific collaborative workflows and task allocations for humans and machines.

Paper A and Paper C have made a number of findings and achievements that can combine manual fabrication with machine assistance (physical and cognitive). These case studies present collaborative workflows in which tasks requiring dexterity and contextual knowledge are distributed to humans while supporting them with computer logic and machine precision. Paper A provides an adaptive digital workflow for masonry. Paper C introduces a hybrid human-machine fabrication workflow, including the human strategically tying complex joints (rope joints) or placing manual objects to influence the design on-the-fly. Paper B contributes with a system where the robot fabricates while the human assists the machine creatively through programming by demonstration. Paper D demonstrates a workflow that enables remote collaboration between an AR-VR system for manual fabrication.

Another contribution of this thesis is in establishing how tasks are allocated. Paper A, Paper B and Paper C demonstrate predefined task allocation in collaborative workflows. Paper C introduces a flexible task shop to distribute manual fabrication tasks either to humans or machines throughout the process.

4.2.2 Integration of human actions into process digital twins

The construction process involves inherent error margins and tolerances. These are caused by the sheer size of building sites, the complexity of construction processes, and the involvement of multiple stakeholders. In addition, error margins are caused by the imperfection of building materials that expand or contract with temperature change. All these factors can lead to local deviations from globally defined plans and models. Humans can adapt their actions and can factor in these deviations because of their sufficient context awareness. This adaptability ensures local accuracy without being constrained by global measurements. For example, a building part can be fitted to its neighbouring parts without affecting the overall performance of the material or component.

Current digital fabrication processes are not well structured and flexible enough to consider such tolerances and require precise global measurements. Due to this lack of adaptability, digital manufacturing processes are often not robust enough, as any deviation from the digital model may lead to failure. Therefore, one contribution of this thesis is the creation of adaptive digital fabrication models that include human actions into a computational model, improving overall tolerance handling while providing local accuracy.

To achieve this, this thesis demonstrates how we can use digital twins to integrate human actions in digital fabrication. This research resulted in digital twins that were able to

- **synchronise** a design and fabrication space through a digital-physical environment
- **track** human actions
- **provide visual feedback** for the human

Synchronising a design and fabrication space: To handle tolerances, the fabrication space needed to be synchronised with the digital model. To achieve this objective, data from sensors were connected with adaptive computational models.

Manually placed building elements were registered to update the digital model, enabling the craftsperson to correct potential errors in the model and on the workpiece. This synchronisation between the digital model and physical space also enabled humans to physically interact with a machine.

Tracking human input: This thesis demonstrates how tracking human actions or the built structure facilitates a new dialogue between the digital and the physical world. This thesis focuses on two tracking methods – via the workpiece or via the human body. Paper A and Paper C exemplify how the built structure can be used as a tangible UI. In both case studies, humans could physically intervene in the built structure, which, once registered by sensors, triggered a change or adjustment to the digital model of the structure.

Paper B and Paper D exemplify two methods of interaction using the human body. Craftspeople were able to use tacit knowledge to manipulate and adapt designs on-the-fly.

Providing visual feedback to the human: This thesis shows how different XR-UIs could instruct humans throughout fabrication. Through these visual feedback systems, craftspeople could consciously interact with a machine via crafts-specific UIs.

4.2.3 Interactive computational models

This thesis presents the potential of interactive and adaptive digital fabrication by redefining the notion of site and craftsperson-specific design. This ranges from more creative interaction in earlier stages of architectural design production to more restrictive design adjustments during on-site fabrication. All four case studies show a wide range of interactive modalities for AEC and demonstrate the potential of adaptive digital fabrication workflows.

Most design and fabrication processes in AEC are based on linear and well-defined workflows. In the case of human-machine collaboration processes, the domains of design and fabrication are brought closer together. Such a blending of design and fabrication realm requires novel computational models that enable user interaction and bi-directional feedback loops. Thus, three different interactive computational models were developed throughout this research as part of digital twins. Paper A demonstrated the potential of a **scene-aware computational model**, where the position of each physical object was updated in the digital model in real-time. Paper B and Paper C extended the **scene-aware computational model** with **interactive modalities**, enabling changes to the digital model in real-time via human gestures or objects. In both case studies, the design was manipulated parallel to the robotic fabrication process. Paper D extended the **interactive computational model** with **collaborative modalities**, enabling multiple on and off-site users to design and fabricate together. The users could use gestures or controllers to inform the design interactively.

4.2.4 Contribution of human-machine collaboration to architecture

This research shows the potential of human-machine collaboration, especially in three distinct architectural domains.

On-site fabrication of new buildings: All case studies presented here were tested for on-site fabrication, illustrating that such workflows are essential to further integrating digital fabrication into current building processes. This research showed how we could use digital twins to create a link between the physical world and the design realm. The proposed interactive computational models enabled humans to change the digital model on-the-fly and update it to on-site conditions. Such systems allowed users to adapt designs to already built elements, such as uneven surfaces, corner situations, or holes. The human augmentation systems presented in Paper A and Paper C also increased the precision of manual work, combining tacit human interaction with machine precision. All systems demonstrate that increased flexibility in the computational model is necessary to enable digital fabrication for difficult-to-automate processes.

Prefabrication: The research results are valid for the on-site construction of new buildings and renovations and are beneficial for current prefabrication setups. These prefabrication setups include the prefabrication of new buildings as well as prefabrication for architectural renovation and refurbishment. Timber prefabrication, in particular, is a domain that could benefit from the workflows presented. Paper C introduces how craftspeople can use the digital twin to define task distribution between a semi-automated machine and a human. The dynamic task shop presented in Paper C helps with flexible task distribution, distributing some tasks to humans and others to the machine. Humans can freely choose which task to take on and which task to allocate to a machine. Furthermore, a flexible task shop in combination with a machine learning system can inform humans about building parts which are out of reach for the robot or too difficult to place for humans. Such a process design could facilitate human decision-making in task selection.

Architectural renovation: Renovation is one of the most challenging domains for digital fabrication as it requires precise 3D models of the as-built context. Plans of existing buildings often lack the precision and level of detail needed to build an insightful 3D model, making construction automation unattainable in existing contexts. Therefore, adequately synced digital twins, as presented in this thesis, are necessary to develop digital fabrication in a renovation scenario. These digital twins can enable the distribution of fabrication tasks between diverse stakeholders, humans, and machines. They can be used for manual manufacturing and hybrid human-robot fabrication, enabling teleoperated collaboration between on-site and off-site users. As presented in Paper C, humans could fabricate or assemble elements that are difficult to reach for a robot. At the same time, the robot could be used for heavy lifting or as a precision instrument. Teleoperated collaboration, as presented in Paper D, could improve the communication between an on-site user, such as a construction lead, and an off-site user, e.g., an architect. Such a process would inform design decisions with the current as-built state of a building, enabling a highly flexible design-to-fabrication workflow.

Furthermore, such a digital twin could assist in disassembling and reusing existing building structures. For this, building parts have to be registered and included in the digital twin. The digital twin is then used to design the disassembly, re-manufacturing, and recycling of these building components. For this process, the digital twin has to be connected to supply chain management to evaluate building parts through key performance indicators and define further use or distribution. Such systems have the potential to support more sustainable construction.

Research methodology: Also contributing to architecture are the methods and concepts developed throughout this thesis. This thesis has shown that empirical research and *research through design*, analysed quantitatively and qualitatively, are successful means for developing human-in-the-loop processes in AEC. The reasons for this are twofold. First, if the researchers conducting the *research through design* are architects, they are already part of a target user group. Therefore, their experience during the development of the prototypes can already improve the applicability of the workflows. Second, research findings with this method are produced by building full-scale prototypes. Fabricating these prototypes allows workflows and systems to be continuously tested on different scales, in various environmental conditions (indoor and outdoor) and by diverse stakeholders. Therefore, all concepts and methods presented in this thesis have been quantitatively and qualitatively analysed and validated in terms of their applicability, accuracy, and usability under indoor and outdoor conditions and on a large scale.

Another significant advantage of *research through design* and full-scale prototyping is the potential to involve target user groups, such as craftspeople and architects, in the development phase of the systems. This target user group in Paper A were masons, who were actively involved in developing the intuitive interface. The user group of Paper B were designers and plasterers, and both were actively involved in developing and evaluating the system. This methodology shows that producing full-scale prototypes as research drivers enables a more rapid system evaluation, as user studies can be a continuously active part of the development.

4.3 Outlook

Based on the successful demonstration of the case studies presented in this thesis, possible directions for future research are identified as follows:

4.3.1 Tracking of humans, machines and objects

The case studies introduced different tracking methods for humans, machines and objects. For each agent, human or machine, different tracking systems were used. This was time-consuming and made the systems more error-prone. Therefore, future development would require tighter integration of the individual tracking systems into one system that can track all agents simultaneously. Such merging of tracking setups would increase critical tracking speed and improve localisation.

4.3.2 Augmented reality for process and machine parameters

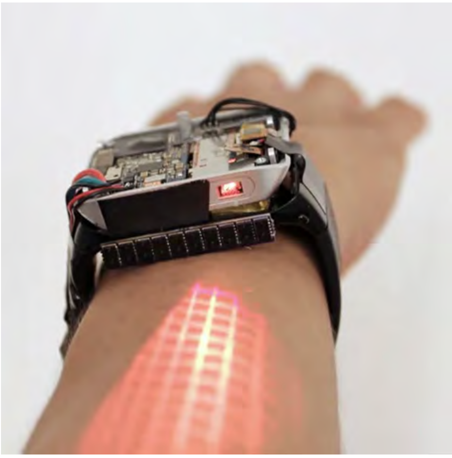
The case studies introduced AR interfaces that instructed users about process parameters (robot reachability, design options, fabrication duration) and assisted them in manually placing objects. Future research could extend the process parameters with more information about motion intent, such as live animations of robot movements and preplanned toolpaths. Rosen et al. [192] show an attempt at efficient motion intent communication for safe and collaborative work environments with colocated humans and robots. For this, users wear an HMD-AR to visualise the proposed robot motion over the user's real-world view.

Furthermore, future AR interfaces could also visualise additional process parameters such as structural analysis. An example of such a structurally informed AR is the work of Huang et al. [193], who present a system which superimposes real-time finite element analysis directly onto real-world objects to provide intuitive interfaces for enhanced data exploration. Their research used a wireless sensor network to acquire spatially distributed loads. Such a system could support humans in making more informed design decisions during interactive fabrication.

AR for construction sites

This research shows how augmentation and collaboration protocols improve interaction and communication between humans, machines, and robots. This thesis investigates four different visual augmentation methods for on-site design and fabrication, providing object tracking (Paper A), interactive design (Paper B), design adaptation (Paper C) and team collaboration (Paper D). Construction sites, in particular, are challenging environments for XR systems because they are dusty, loud and exposed to direct sunshine. The case studies present various AR systems for construction sites, such as screen-based AR (Paper A), projection-based AR (Paper B), phone-based AR (Paper C), and HMD-AR system (Paper D) to tackle these challenges.

Projection-based and phone-based AR technologies have proven very suitable for on-site fabrication because they are cheap, easy to use, and ubiquitous. Despite the advantages of phone-based AR, this system does require craftspeople to suspend their manual work while using the AR system, which limits the use of phone-based AR for manual construction. Therefore future research could investigate different methods to switch from hands-on to hands-free phone-based AR. This could include combining phone-based AR with wearable devices. While this would free the hands of the users while providing a window into the digital model, it also requires embodied UIs. These interfaces would allow workers to remain present in the physical and digital world. An example of such a compact UI is the *LumiWatch* [146], a self-contained projection smartwatch implementation. Although it does not allow users to overlay design options over the existing building, it enables people to interact with a digital model via an embodied touchscreen (Fig. 4.1a). Another example of an embodied and mobile UI is *Litho* [194] (Fig. 4.1b). This small wearable device clips between the index and middle fingers and connects to a phone via Bluetooth. Users can provide intuitive and precise input through a touch surface and motion-tracking sensors. Another example of an embodied interface is Facebook's wrist-based wearable [195]. Users can wear the device throughout the day and interact with an AR device.



(a) *LumiWatch* is a compact UI worn around the wrist [146]

(b) *Litho* is a wearable device that can be clipped between the index and middle finger [194]

Figure 4.1: Examples of different wearable devices

Paper B focused on 2D projection-based AR. This is useful for surface and planar treatment such as plastering, drilling, screwing, and tiling but does not allow for more spatial construction or supervision. Furthermore, the field of view of the non-mobile projector used in Paper B was limited. Therefore, future research on projection-based AR for construction sites should focus on mobile platforms that can reposition a single projector and camera to view arbitrary locations in space or move from planar projection to spatial projection. An example of such an adaptable projection is the research by Ehnes et al. [152]. This research presents a system with a rotatable projector that follows objects equipped with a marker. Doing so ensures the augmentation is maintained in the correct place even while the object or projector moves. The placement of a projector on a four-legged robot was tested as part of this thesis in collaboration with Yunfan Gao for her master's thesis on mobile spatial projection (supervised by Marco Hutter, Franklin Perry, and Ryan Luke Johns).

4.3.3 Human-machine collaboration for larger-scale architectural implementation

The presented experiments hybridised manual with robotic fabrication, leading to novel digital fabrication scenarios. The size of the prototypes in the case studies ranged from small to building scale. To enhance the workflows and increase the scale, it is necessary to improve the robustness of the systems presented. Increased robustness would allow multiple construction teams to use the systems across numerous construction phases. Additionally, more performance targets must be included in the workflows, including structural stability, human reach, and robot reach. This performance evaluation would need to be conducted in real-time to ensure that adjustments to the design and workflow are structurally and logistically valid. Paper C is an example of an application scenario for such a performance evaluation. Such a system must be able to inform humans about structurally valid solutions to limit possible design options to those that are valid.

A possible technical solution for more robust and intelligent computational processes is integrating machine learning into human-in-the-loop processes. Wearable devices could be used to build a database of human-robot interactions and create predictive models of dynamic human behaviour. The *AnDy Suit* [196, 197] is an example of a wearable suit that could gather such data and track human motion and force torque. With the help of machine learning, structures could be analysed in real-time, and human behaviour and movements could be predicted faster to increase the adaptability of robotic processes and provide faster collision planning.

Appendix

A Human-machine setups

This appendix explains distinct human-machine setups in more detail. These categories are based on Shi et al.'s levels of human and robot collaboration for automotive manufacturing [86]. These levels include human-machine coexistence, interaction, cooperation and collaboration.

In **human-machine coexistence**, humans and machines do not physically interact. Their workspaces are clearly separated by physical fences or light curtains[1], and the machine stops moving once the human enters its workspace.

In robotic fabrication setups in AEC, research focuses mostly on processes with human-machine coexistence. These processes include concrete 3D printing [7], metal welding [198], and concrete spraying [199]. An example of human-machine cooperation is the *Sequential Roof* by Gramazio Kohler Research [200] (Fig. A.1). This research used a digital process that combined design, structural analysis and fabrication details. Humans locally controlled the robotic process but did not work on the same workpiece as the robot. In such low-level human-machine collaborations, humans do not interact with the machine or the object that the machine currently handles. When providing parts to the machine, the human agent loads them onto an intermediary transferring device, such as extra fixtures or turntables. Such intermediate hardware prevents direct engagement between the two agents, which

Figure A.1: Sequential Roof (photo by Gramazio Kohler Research).

[1] Light curtains create a barrier-free safety zone for robotic production. Entry into the safety zone is monitored, and the robot is safely shut down when a person enters. Human entry into the safety zone is monitored, and the robot is safely shut down as soon as a person enters.

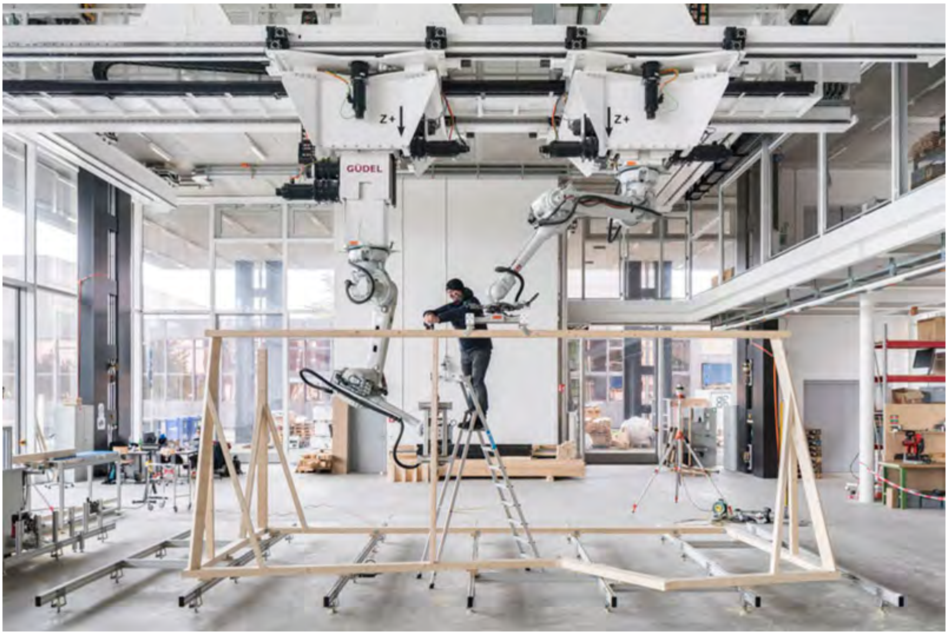


Figure A.2: Spatial Timber Assemblies (photo by Gramazio Kohler Research).

allows humans to work outside the robotic working area and supports humans in performing independent tasks asynchronously with the robotic unit. Transferring devices increase safety for human workers but also increase the production cost, make work cells less flexible, and cannot be easily adjusted for a new fabrication process. Furthermore, the fabrication workflow in human-machine coexistence must be well-defined, unambiguous, and predictable, which might not be possible in all scenarios. Research in human-machine coexistence focuses primarily on fence design and architecture and includes research on unexpected intrusion detection with reliable sensor systems instead of physical barriers. These novel sensor-based safety zones must perform equally or better than current light screen guards or physical barriers. Additionally, novel safety procedures must be implemented to protect humans from accidental contact with the robot's movement in these sensor-based barriers. Of course, in these scenarios, human workers need to comply with security measures.

In **human-machine interaction**, humans and machines interact in the same physical workspace but perform distinct tasks sequentially. This asynchronous task allocation ensures that the robot remains inactive when humans are present to complete their tasks. Despite the task separation, both agents interact and communicate by various means. This communication can happen through many channels; one agent might guide or control the other, and this control can happen either locally or remotely. In this scenario, the level of human-machine collaboration switches between low and medium. Human-machine interaction still requires light fences or physical barriers to ensure a separation between humans and machines. Therefore, research in this field focuses on sensor systems that detect intrusion into the machine's safety zone to automatically stop, slow down or modify the robot's movement. These systems could prevent injury or damage. An example of human-machine interaction can be found in the spatial timber assemblies used in the DFAB house project (Fig. A.2). In this project, a robot was used

Figure A.3: CROW: Collaborative Robotic Workbench (photo by ICD University of Stuttgart).

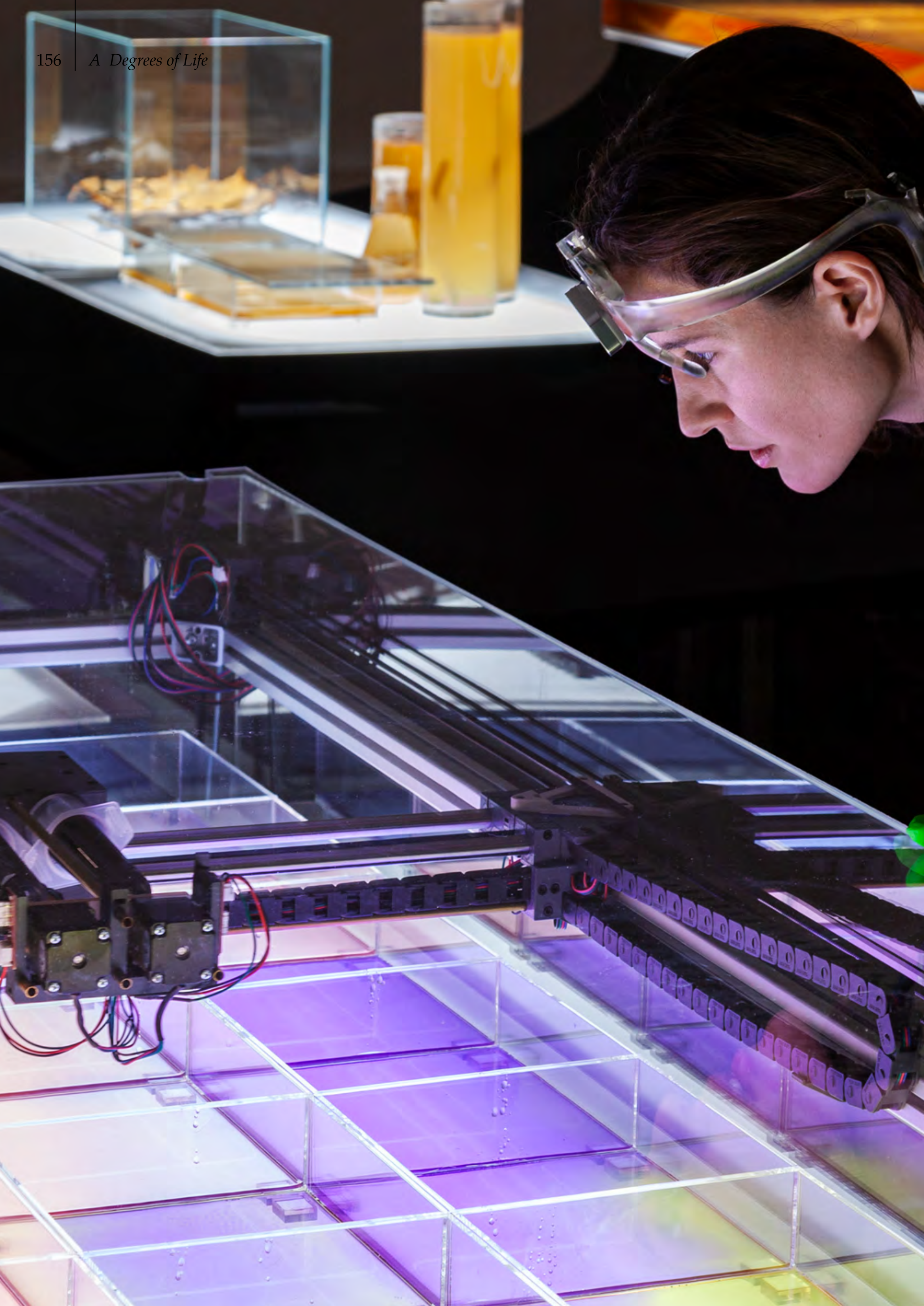
to position timber frame elements, while a human was responsible for screwing them together to produce timber frame modules. The human executed their task while the robotic engine was turned off. The prefabricated modules were then assembled on-site.

Human-machine cooperation is developed if both agents have autonomy in achieving common goals. Cooperation is defined as individual agents working together to accomplish a task [201]. Each agent can harness the knowledge and capacities of the other system to reach a common goal. Cooperation is, therefore, a form of collective action and falls into the categorisation of egalitarian cooperation [202], as it is a relationship between two agents of different capacities that work well in combination. A shared workspace is required in this scenario, but not necessarily direct physical contact between the agents. Human-machine cooperation has a medium amount of collaboration. The respective working tasks are sequential and executed in a task-turning fashion. Even though the machine's engines keep running, the machine does not move until the human exits its working space and actively initiates a command to activate the machine. An example of human-machine cooperation is *CROW: Collaborative Robotic Workbench* [78], where humans and robots assemble a wooden structure together (Fig. A.3). *Interlacing* is another example of a cooperative workflow [169], where humans can place individual sticks to influence the growth of a structure sequentially built by a robotic arm. *iHRC* [172] is another cooperative project where users are equipped with an AR headset to work alongside robots in a turn-taking manner. In all these case studies, both agents are active in the same workspace but have sequential tasks and do not interact physically. In the presented projects, physical fences and enclosures were eliminated and replaced with safety sensor systems.

The key characteristic of this medium-level human-machine collaboration is the machine state once the human operator enters its working space. The human enters the machine's workspace during the loading period, but the machine is not in motion. After the loading or interaction period, the human agent leaves the machine's working zone and executes the initialisation of the machine motion. The human may or may not use intermediate hardware to fill the machine and can directly interact with the machine.

Figure A.4: Lift assist device for rolls of metallic banding (photo by Dalmec).

Human-machine collaboration is a joint activity of two or more agents in a shared working environment. This relationship typically requires a coordinated and synchronous task execution from all agents with physical contact. Collaboration requires shared, goal-oriented action from all parties in a collaborative environment without temporal or spatial separation. Humans and machines perform simultaneous actions in the same digital or physical workspace. The machine moves in fully automatic mode, and its motions occur while humans are within a part of its working space. This type of collaboration is more common in human-computer environments rather than in robotics, where the human and the computer work simultaneously on a shared goal. With industrial robots, there are currently almost no applications installed that allow such a high level of human and machine collaboration. Intelligent lift-assisting devices are one of few examples (Fig. A.4), allowing the human agent to directly control a robotic unit to lift heavy items and place them where necessary. The robot senses the human agent's motions and adjusts its speed accordingly. This device adds strength and precision to the human operator's movements, allowing free path movement and human decision-making. The only movement not directly under human control is the movement back to the home position once the human operator releases the control. In human-machine collaborative examples, humans and machines act as a single unit during fabrication. This requires situation-aware machines [203], machines adaptive to dynamic situations [204], and machines with a shared understanding of task contexts and the ability to anticipate tasks. Current research focuses on automated machine programming to adjust the motion and speed in synchronisation with the human position and speed to achieve a synchronised task. This would allow the machine to become part of the human's physical entity and act as a partner or co-worker. It would operate in automatic mode, syncing its motion in relation to the human agent while constantly communicating [205].



Degrees of Life B

B.1 Human-bacteria interaction in architectural space

Daniela Mitterberger, Tiziano Derme, Barbara Imhof

Production notes

Architect: Co-corporeality, MAEID
Status: Exhibition / built
Site Area: 91 sqm
Location: Zentrum Fokus Forschung, Rustenschacherallee 2–4
Date: 2022

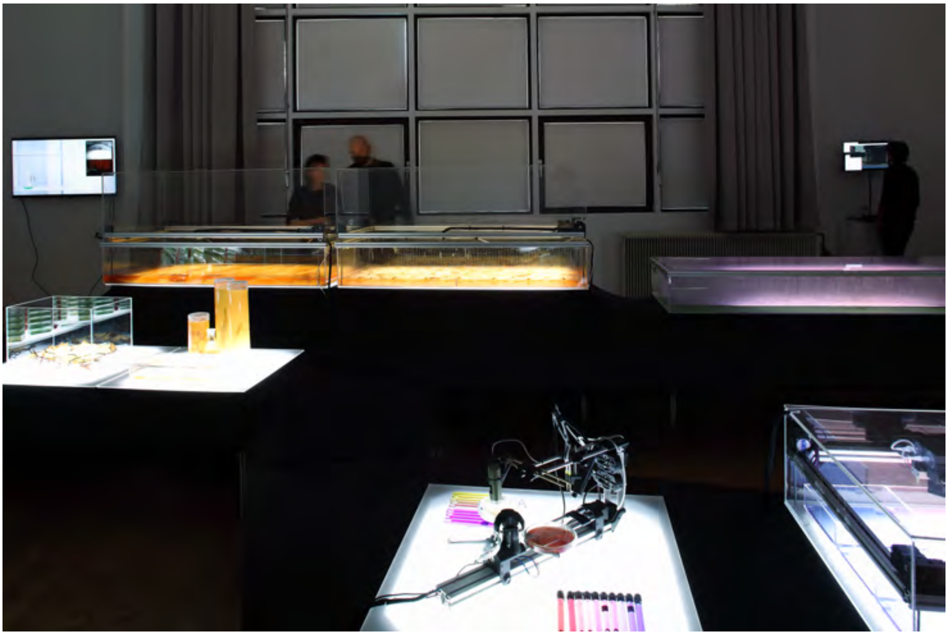


Figure B.1: Responsive environments were reacting to human presence and behaviour.

Degrees of Life is a responsive environment exhibited in February 2022 at *Zentrum Fokus Forschung* in Vienna. The project explored the interaction between humans and living systems at an architectural scale. The research aims to develop interactive environments within an architectural space that learn, grow and decay in relation to human presence and behaviour (Fig. B.1). The space reflects on the concept of biomediality and biofacts [206], and the possible applications of living technologies and human sensory interfaces in architecture [207, 208].

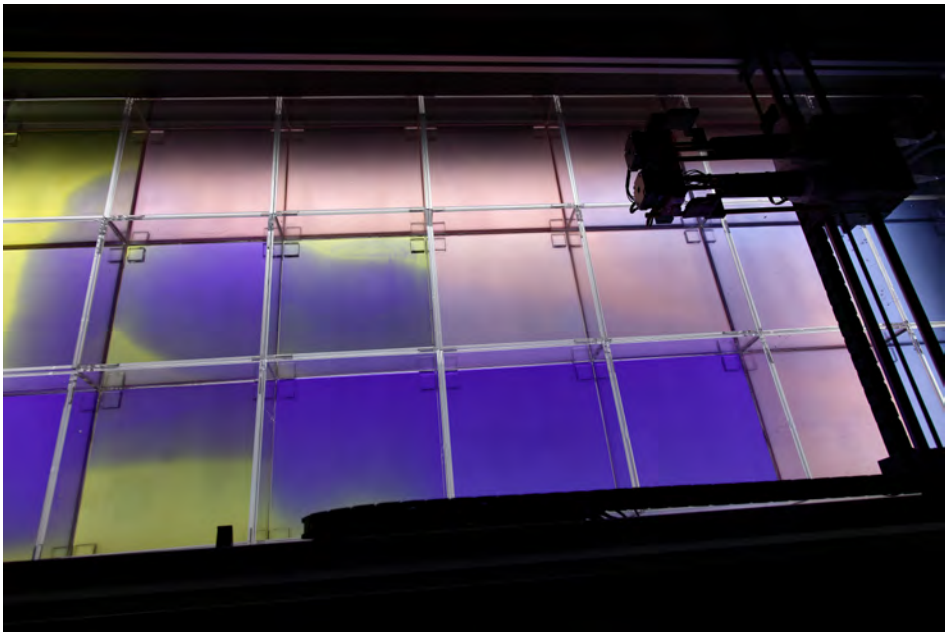


Figure B.2: ECo is an enclosed environment hosting Escherichia Coli bacteria.

Degrees of Life is the result of a larger artistic research context called *Co-corporeality* that weaves together architectural design, sensor systems, machine learning, and microbiology.

Environmental setup: The exhibition was articulated around three distinct self-sustaining closed environments, hosting three types of bacteria: Escherichia coli, Sucrofermenta and Cyanobacteria strains (Fig. B.2, B.3, B.5). The three enclosed environments are named after the bacteria: SuCr, CyA, and ECo. Although the enclosed environments provided the necessary environmental conditions for the bacteria to survive, they relied on human interaction and mechanical actuation to thrive.

Human interaction system: Human interaction was registered in real-time by a wearable eye-tracking device that recorded the human visitor's local position and pupil gaze direction (Fig. B.4, B.1). The local position and gaze direction were defined using three cameras: a world camera, an eye camera, and a tracking camera (Fig. B.6). This setup allowed us to record conscious actions, such as gaze direction, as well as unconscious human actions, such as gaze duration and pupil diameter (Fig. B.7). The visitor wore an eye-tracking device, and a Raspberry Pi sent the gaze data via ethernet to a server in the exhibition room. The server ran the pupil core software and 3D localisation and activated the visualisation and interaction routine. The interaction routine included the activation of machines according to different rulesets.

These rules included selecting the environment to look at, the exact gaze location within this environment, and the intensity of the gaze (pupil diameter, time of gaze, frequency). This eye-tracking data was then used to activate a machine within the selected bacterial environment. This machine distributed chemicals or activated a light setup to stimulate, visualise, or direct bacterial growth and behaviours (Fig. B.4). Each environment had its own

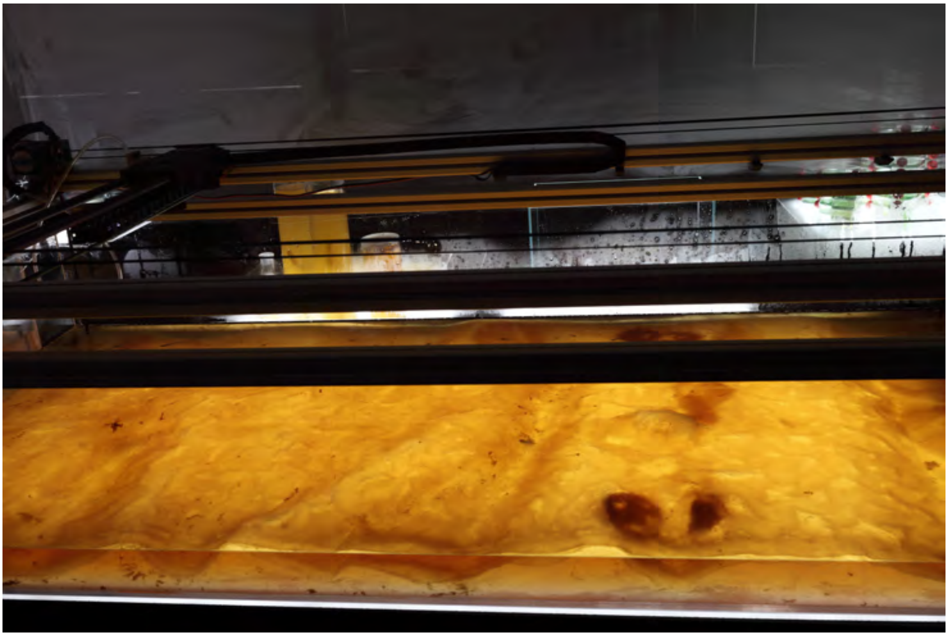


Figure B.3: SuCr is an enclosed environment hosting Sucrofermentas bacteria and microbial biomass production.

set of environmental parameters which could be stimulated, including the chemical setup of the environment, lighting conditions, and the dispersion of nutritional supplements. All three environments were triggered according to the needs of the bacteria hosted.

The ECo-environment: ECo was inhabited by the Escherichia coli bacteria (E.coli). The metabolic process of E.coli led to a change in pH level in the culture medium, which was easily detected using pH-sensitive compounds commonly known as pH indicators. The direction of gaze and the pupil diameter of the visitor activated the machinery distributing a specific amount of sodium hydroxide (NaOH) at a precise point into the liquid glucose medium where E.coli were cultured. The release of NaOH results in real-time reversibility of the colour change of the medium. After that, the metabolic process of the bacteria slowly changes the pH level again, thus also altering the colour of the medium.

SuCr-environment: The SuCr environment supported the Sucrofementas bacteria strain. Due to metabolic activity, these cellulosic bacteria secrete a thick mat of biomass. The growth of the microbial mat was controlled via a spray nozzle, which moved in two axes and sprayed a nutritional solution (glucose, water and acetic acid) at a specific location (Fig. B.8). Human interaction defined the spray location and, thus, the growth rate of the microbial mat by looking at specific points in the environment.

CyA-environment: The CyA environment hosted the Synechocystis, a genus of cyanobacteria. These bacteria obtain energy via photosynthesis. Human interaction changed the light conditions of the environment by switching the bacteria's growth strategy from photo-autotrophy (light period) to heterotrophy (dark period). The interaction was visualised in real-time by continuously measuring/monitoring dissolved oxygen and pH kinetics. This change in light condition either activated the photosynthetic activity of the bacteria or reversed it (Fig. B.1). The environments were placed alongside a visual interface depicting the ego-perspective of the human visitor, the data collected from the visitor's gaze, and the head position in real-time (Fig. B.7). A soundscape made the interaction audible and assisted the human visitor in using the system.

Degrees of Life was exhibited for three weeks and evolved depending on the interaction of human visitors with the environment. The ECo and CyA environments flourished, and no contamination was detected. Conversely, the microbial activity of the SuCr environment accelerated the rusting of the machine's mechanical components due to the acidic level. The growth of this environment was only partially attributed to human interaction and primarily automated. This exhibition pursues the idea of interactive architecture as a living system [209, 210], in which physical presence and new modes of observation [211] are intertwined with tangible forms of computation [212].

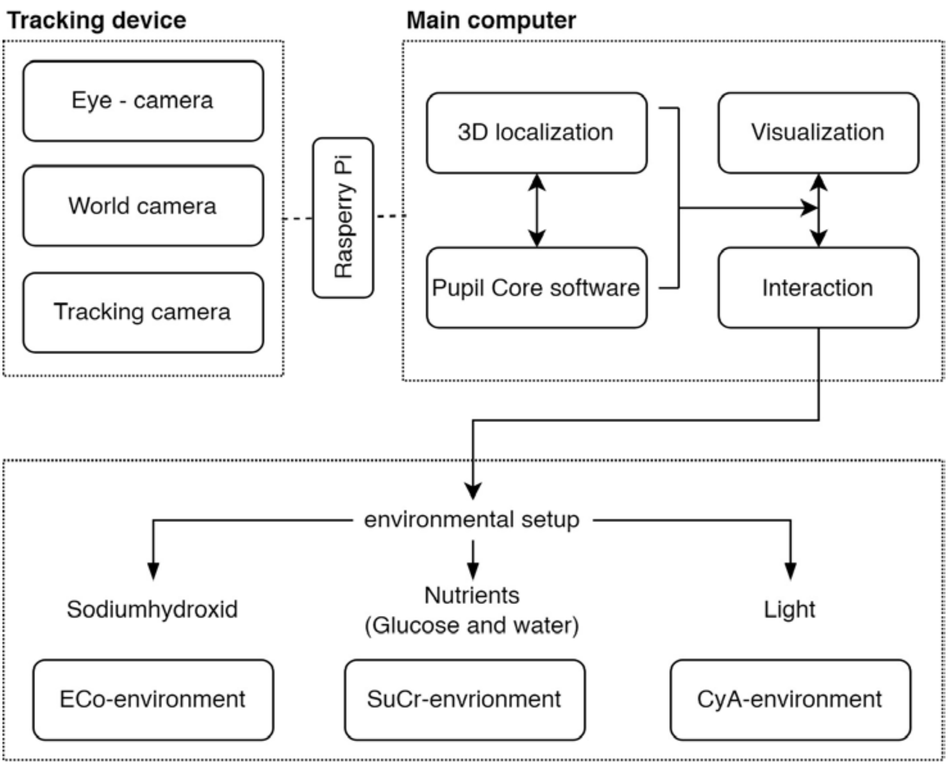


Figure B.4: Interaction diagram.

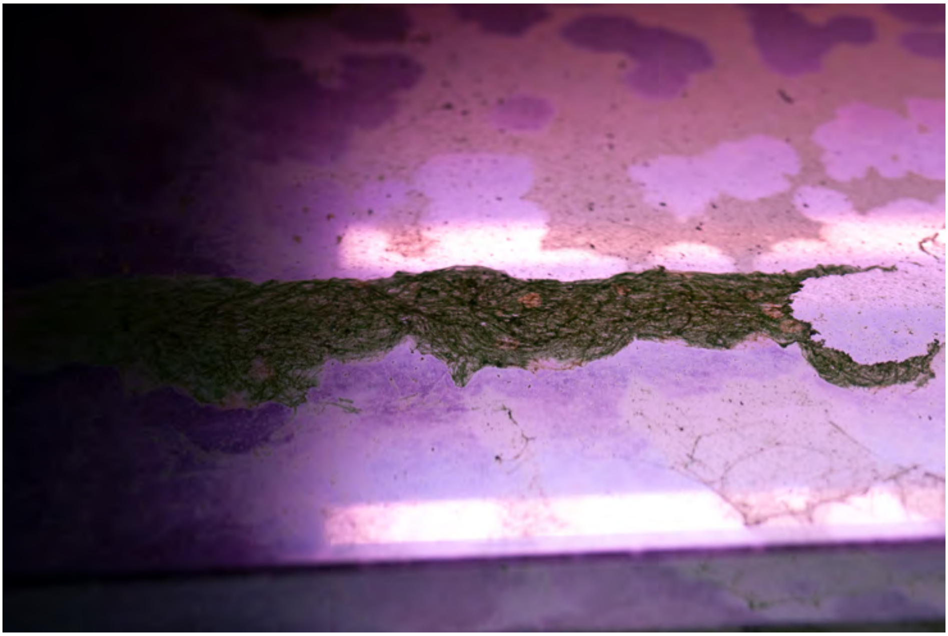


Figure B.5: CyA environment with Cyanobacteria reacting to different light stimuli.

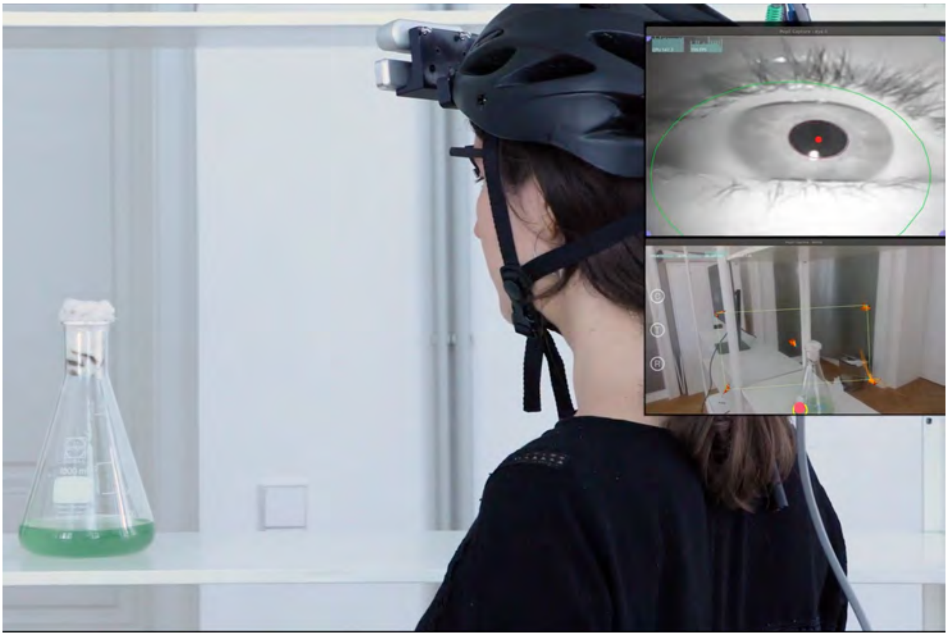


Figure B.6: Eye-tracking device (prototype 1) detects the gaze direction and position of the visitor.

Figure B.7: Image showing a typical interaction of a visitor with the ECo environment. Visualisation projected onto the back wall shows the ego perspective of the visitor.

Figure B.8: SuCr enclosed environment and supplementary microbial prototypes.

C AR Bricklaying User Study

Post-session usability study for bricklaying in augmented reality focusing on visualisation platforms and learning curve

Daniela Mitterberger, Luigi Sansonetti

This project investigates the user's perception and feeling of an in-progress novel augmented reality (AR) system allowing a construction worker to be assisted in positioning bricks in space. For proper brick placement, the bricklayer first needs to know the brick's current position and orientation (pose) and then follow instructions to adjust its position and orientation to achieve a desired pose. To analyse the user's perception, a self-reported metrics questionnaire was used. In addition, respondents were observed during task completion to gather additional information. Two studies with different focus points were conducted. The first study compared two visualisation interfaces, screen-based AR and HMD-AR. The second case study focused on the learning curve and the ability of novice users to use the system.
The survey was taken anonymously and in solitude to avoid social desirability bias. The outcome of the questionnaire showed that the lack of assistance made novice users' experience of the system significantly worse. Moreover, compared to unassisted users, assisted users reported that the system required less training. Another key finding is that the interface was perceived similarly by every group. The AR headset allowed the users to focus more on the actual bricks than the screen-based interface did. Lastly, observation of untrained users showed that, without assistance, the users found the system to be too demanding in terms of multitasking.

C.1 Introduction

Building complex 3-dimensional brick walls (brick rotation along the lateral axis through differentiation of mortar height) is almost impossible to achieve using solely analogue templates and guiding systems. Purely manual masonry of complex 3D brick facades following physical templates is further neither cost nor time-effective. In comparison, robotic bricklaying [9, 166] offers precise digitally informed brick walls but has spatial limitations and presents more difficulties with regard to working on-site and with complex and irregular building materials. Mortar and hand-made bricks were the desired material of the client in this project and, therefore, drivers for this research. Therefore, an AR system was developed using a custom-made sensor system to assist the mason in positioning bricks. With the implementation of AR, the use of paper-based plans was no longer necessary as the system was able to detect the current position of a brick in space in relation to the desired position. A craft-specific user interface showed the mason where to place the next brick, clearly displayed the current placement instructions and indicated the workers' performance in terms of errors made and speed of completion.

The following was expected of a computer-aided bricklaying system:

- The instructions should be clear and readable and cannot be easily mistaken for one another.

- The users should be able to complete a task with as few errors as possible.
- The users should be able to complete tasks quickly.
- The system, despite not needing to be perfectly accessible to inexperienced users, needs to be learnable quickly.

The system under evaluation was still in its earlier development stage, so this study was, therefore, formative [159]. As such, we sought to find the most appropriate visualisation platform for this AR system by comparing a screen-based interface with an head-mounted displayHMD-AR. Additionally, we were interested in finding out the importance of human assistance for novice users during the first time using the system and the evolution of their performance over time.

C.2 Method

To evaluate the system, two user studies were conducted. Study 1 evaluated the advantages of different visualisation interfaces for augmented bricklaying, such as screen-based AR and HMD-AR. Study 2 investigated the long-term use and learning curve of the augmented bricklaying software.

The two studies aimed to answer the following questions:

1. Can the system be used without prior training?
2. Is the system safe to be used by novices without supervision?
3. Are the users satisfied with the system?
4. How much did the user's performance improve?
5. Which visualisation platform is more appropriate, screen-based AR or HMD-AR?

To address these questions, both user studies had different setups and participants.

Study 1 was an experimental setup where six architecture PhD students without prior knowledge of the system had to build a brick object. Three PhD students tested the screen interface, and 3 PhD students tested the HMD-AR interface (*Magic Leap*).

Study 2 followed the construction of a wooden acoustic wall and investigated the learning curve of five construction workers involved in building the wall element. The five construction workers were interviewed as they were building an indoor acoustic wall supported by the AR system.

We used a between-subject approach for the user studies, as explained in [213]. Typically, between-subject approaches generally require more participants. Some studies state that five users are enough to detect 80% of the usability problems [161], whereas others recommend more [160].

In both case studies, users were informed of the following points:

1. The data collected from them is anonymous.
2. The system is under evaluation and not their performance.
3. In case of Study 2: The questioners were independent of the project
4. Should the need arise, they were free to terminate the experiment at any time.

C.2.1 Evaluation

The user performance was evaluated through observations of their behaviour and voiced opinions during the task (only for the PhD students), as well as the use of self-reported metrics in paper form after task completion (all participants).

Observations

Before the task, users were encouraged to think out loud and freely express their opinions and feelings about the system under evaluation. This method provides very useful feedback [159], as users might point out flaws that are otherwise completely unknown to the testers and were thus not covered by the questionnaire.

In addition, experimenters also took notes on the user's behaviour during the testing to observe patterns of actions that may hinder performance.

Questionnaire

After task completion, users were asked to fill out a paper questionnaire following the Questionnaire for User Interface Satisfaction (QUIS) model [110], which measures the overall perceived usability after the completion of a session. Through positive and negative wording, it encourages the user to express a wider range of opinions. Furthermore, it allows us to individually study different categories of the system, such as the interface, system, and learning curve.

The questionnaire consisted of 14 questions (13 for the construction workers) in which users rated their level of agreement with statements using a 10-point Likert-type scale (as depicted in Table C.1).

The questionnaires were divided into the following categories:

1. Overall Reaction
2. Screen and Display
3. Learning
4. System Performance

Table C.1: An example of the questionnaire's item.

	0	1	2	3	4	5	6	7	8	9
The information on the display was well organised										

C.3 Study 1 - Visualisation platform - procedure

In case study 1, six participants were asked to assemble a small pyramid out of bricks using the system, as depicted in Figure C.1 on the next page. First, the users built the pyramid using only a screen-based interface and, afterwards, the HMD-AR. None of the six users had experience with the system.

Screen-based AR: The screen-based AR experiment was conducted with and without assistance. A within-subject approach [213] was used, and, in every case, to avoid a learning bias, half the participants would start with assistance, and the other half would start without.

HMD-AR: The experiment was conducted with assistance - users with no previous experience with HMD-AR or any other AR headsets were unable to use the interface correctly.

Figure C.1: On the left, participants were presented with the setup before starting. On the right is the desired outcome.

C.3.1 Results

Questionnaire

After completing their assembly task, the users had to complete a questionnaire, as described previously. Their answers can be found in Figure C.2, C.3.

Observations

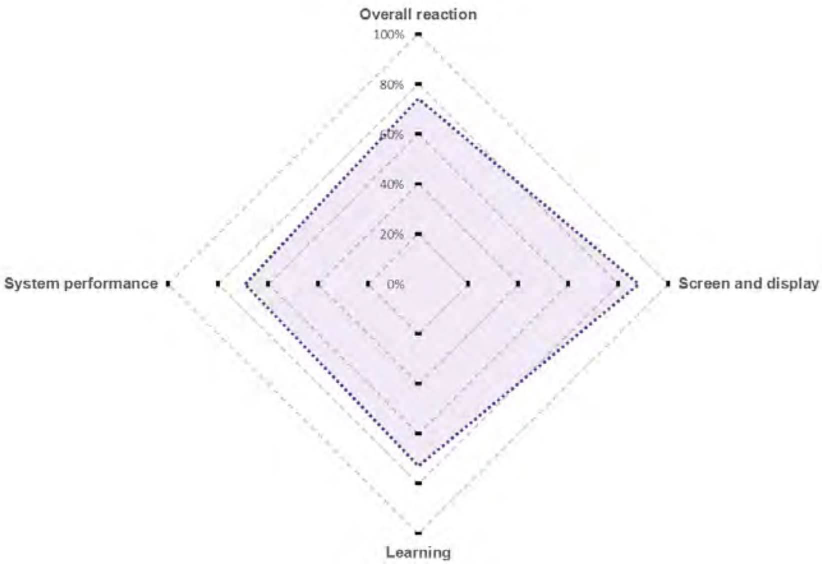
In addition to the questionnaire filled out by users at the end of the testing procedure, the experimenters took notes while performing the tasks. The following observations were made.

Assistance: While using the system for the first time, it was clear that a short introduction of around 15 minutes was not enough to introduce an inexperienced user to the system, which was confirmed by the test results depicted in Figures C.3a and Figure C.3b on page 172. Users trying the system without assistance had a worse experience than those who were guided by someone holding the sensor system. The study clearly shows that specific tasks (such as holding the sensor system and guiding the tracking) require more time to learn. Moreover, every unassisted user mentioned that holding the camera while placing the brick made the task too hard - as such, many camera calibration problems occurred for this group. Study 2, with experienced users (construction workers), was conducted to evaluate this statement. Nevertheless, it was also noted that the perception of the interface did not depend on the assistance offered or the level of expertise. Assisted or not, the novices felt that their performance increased over time.

Screen observation: Using the screen interface, users had to divide their attention between their construction and the display. This proved troublesome, and they often tried to place bricks while looking at the screen, which resulted in more errors. Using the HMD-AR, users had the information displayed right on their workspace, which resulted in significantly fewer errors.

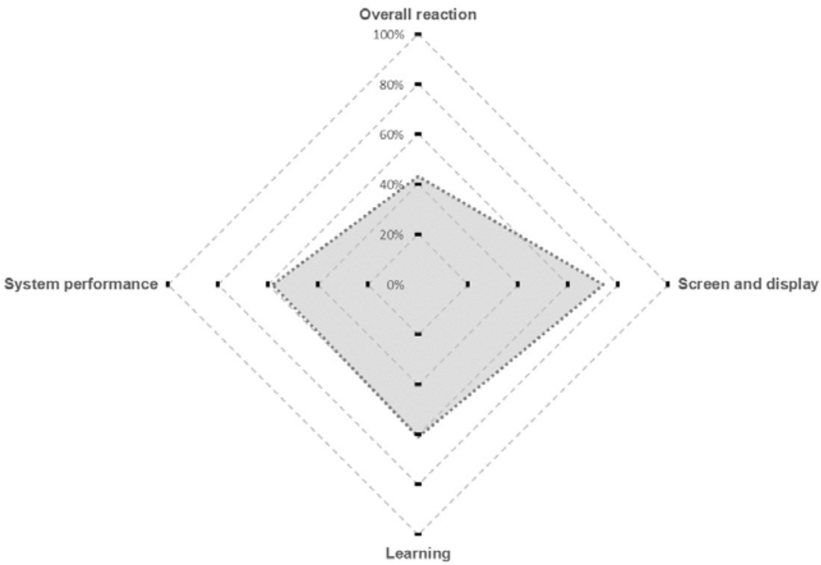
Given that the *Magic Leap* interface can be considered to be a transparent display, this observation is consistent with those of Lindlbauer et al., which compares an opaque screen at different offsets against a transparent display [214].

High expectations of the HMD-AR: Users were very excited at first to try out the HMD-AR system; however, their expectations were also quite high. In particular, they found small inaccuracies (such as the virtual brick outline not perfectly aligned with the real brick) more irritating than the screen interface. These imprecisions were perhaps much more visible in the HMD-AR devices, so although the same errors happened on both interfaces, the users were more forgiving of the inaccuracies when evaluating the screen.

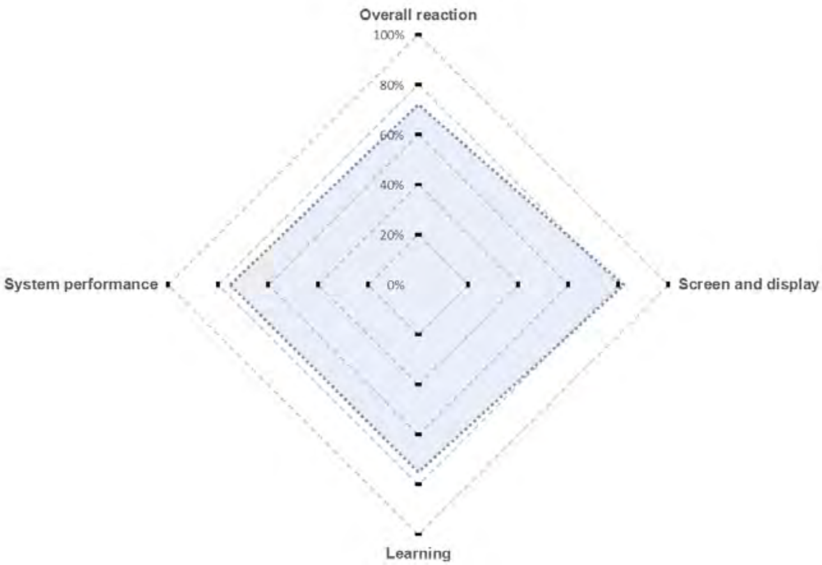


(a) Reaction to the HMD-AR interface

Figure C.2: Reaction of the novices to the HMD-AR interface.



(a) Unassisted novices' reaction



(b) Assisted novice's reaction

Figure C.3: Reaction of unassisted and assisted novices to the system.

C.4 Study 2 - Learning curve

Users were interviewed after using the system for several weeks in a row. At the beginning of the project, the system required two people (one holding the sensor devices and one laying the bricks). After a learning period, some of the construction workers no longer required a second person and were able to lay bricks and navigate the system simultaneously.

The construction workers were tasked with building three indoor acoustic walls, as depicted in Figure C.4, using only the system and some additional analogue control systems, such as a level.

Figure C.4: Final indoor acoustic walls

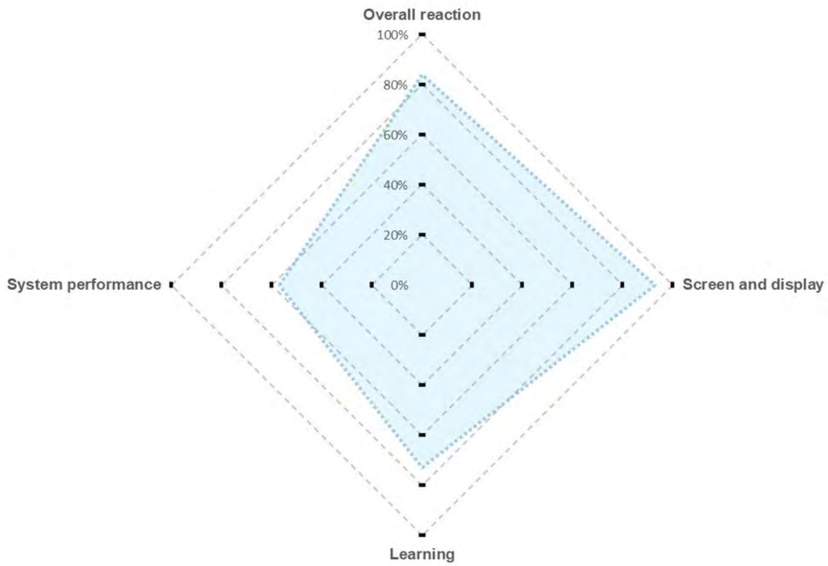
C.4.1 Results

Questionnaire

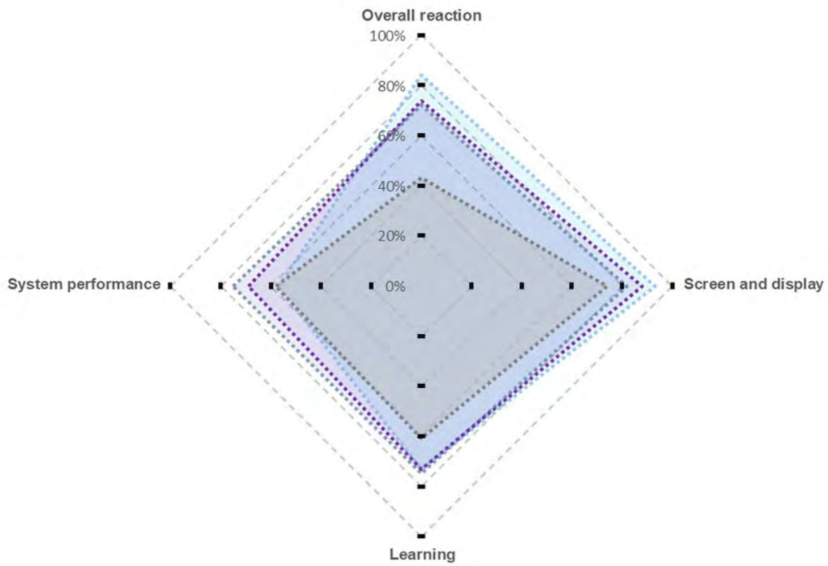
After a day of work, users had to complete a questionnaire, as described previously. This questionnaire was filled out privately without the experimenter's assistance. The results are depicted in Figure C.5a on the following page and compared against the results of all other group's results in Figure C.5b.

Observations

Similar to Study 1, the experimenters observed the users' behaviour during the task completion and concluded the following:



(a) Trained users' perception of the system



(b) Overlap of trained users (light blue), untrained and unassisted (dark blue), untrained and assisted users (grey), and users using the AR set (purple)

Figure C.5: visualised questionnaires' results.

Assistance: Users described a necessary learning period to navigate the system securely and precisely, which is consistent with the findings of Study 1. After a specific period, some construction workers were even able to hold the sensors and lay bricks at the same time without needing another worker to help them in the process.

Screen observation: The results found were the same as those of Study 1 - namely, that the workers tended to observe the screen too much and the physical brick too little.

C.4.2 Answers to the original questions

Considering the results of both studies conducted, the following answers correspond to the initial questions about the interface.

1. Can the system be used without prior training?

   The system in its current state needs a period of training. The presence of an assistant and the redistribution of "high maintenance work", such as scanning and localisation, helps novices use the system. After this training period, they can become independent and navigate the system without the help of an additional worker.

2. Are the users satisfied with the system?

   Users are satisfied with the system if they start with a prior training session and with the help of an assistant introducing them to the system, as depicted in Figure C.5b. The satisfaction increased with the learning effect and stagnated after a specific point. This might be due to missing software developments and an occasional lack of software stability. Users intuitively understand the user interface and perceive the usefulness of the AR system.

3. Is the system safe to be used by novices without supervision?

   In the beginning, novices require the presence of an assistant - however, after a learning period, it is safe for them to work independently. The interface is then immediately and intuitively understood.

4. How much did the user's performance increase?

   Users' performance, according to the questionnaire, increased noticeably. As such, when asked whether or not an unassisted novice can use the system without training, the trained users answered with a stronger no than assisted and untrained users, as depicted in Figure C.6.

5. Which visualisation platform is more appropriate, screen or head-mounted augmented reality devices?

   Evaluation of the screen interface showed a higher distraction, as users focus more on the screen than the physical brick. Additionally, users had difficulty fitting the first brick into the initial guess.

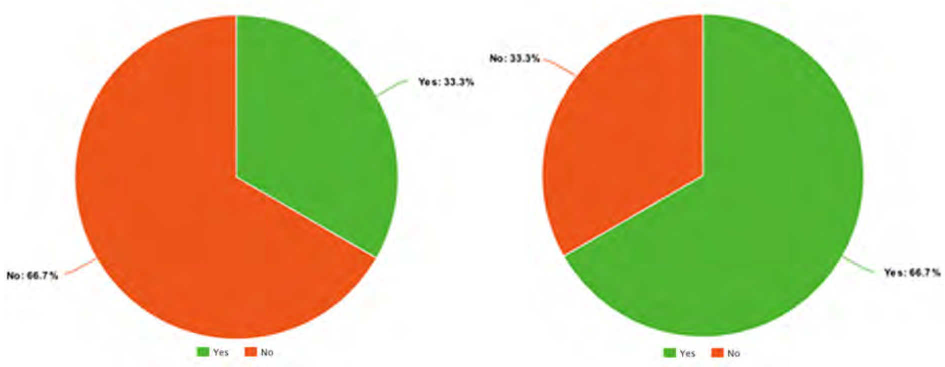


Figure C.6: When asked if the system could be used by novices, this is how the users answered: left side: experienced; right side: untrained and assisted

C.5 Conclusion

The conclusion of this study can be summed up in the following points:

- Novices require assistance to use the system properly. Unassisted, the time to complete a task and the number of errors were significantly higher, leading to a much worse experience for this group.
- Because users had to divide their attention between the screen and their workspace, the errors made with the screen interface were higher than with the HMD-AR.
- Users had high expectations of the HMD-AR interface but were disappointed in its imperfections.
- The user performance increased noticeably over time, regardless of the visualisation platform or the assistance given.

The system, therefore, cannot be used by unassisted novices, as the number of errors made is too high. However, given that the users' performance increased greatly over time, they became competent in using the system alone after training with an assistant.

The HMD-AR interface clearly outperformed the screen interface in terms of errors and is thus the best-adapted visualisation platform for this task.

Bibliography

References in citation order.

[1] Thomas. Bock and Thomas. Linner. *Construction Robots.* 2016 (cited on pages 3, 64).

[2] Shiyao Cai et al. 'Construction automation and robotics for high-rise buildings over the past decades: A comprehensive review'. In: *Advanced Engineering Informatics* 42 (Oct. 2019). DOI: 10.1016/j.aei.2019.100989 (cited on pages 3, 64).

[3] Fabio Gramazio, Matthias Kohler, and Jan Willmann. *The robotic touch : how robots change architecture*. Zürich: Park Books, 2014 (cited on pages 3, 42, 64, 98).

[4] Wes McGee and Monica Ponce de Leon, eds. *Robotic Fabrication in Architecture, Art and Design 2014*. en. Cham: Springer International Publishing, 2014. (Visited on 05/17/2022) (cited on page 3).

[5] Jan Willmann et al. *Robotic Fabrication in Architecture, Art and Design 2018: Foreword by Sigrid Brell-Çokcan and Johannes Braumann, Association for Robots in Architecture*. Springer, 2018 (cited on pages 3, 64).

[6] Jan Willmann et al. 'Robotic timber construction - Expanding additive fabrication to new dimensions'. In: *Automation in Construction* 61 (2016). Publisher: Elsevier B.V., pp. 16–23. DOI: 10.1016/j.autcon.2015.09.011 (cited on page 3).

[7] C. Gosselin et al. 'Large-scale 3D printing of ultra-high performance concrete - a new processing route for architects and builders'. In: *Materials and Design* 100 (2016). Publisher: Elsevier Ltd, pp. 102–109. DOI: 10.1016/j.matdes.2016.03.097 (cited on pages 3, 98, 151).

[8] Ana Anton et al. 'A 3D concrete printing prefabrication platform for bespoke columns'. en. In: *Automation in Construction* 122 (Feb. 2021), p. 103467. DOI: 10.1016/j.autcon.2020.103467. (Visited on 09/06/2022) (cited on pages 3, 98).

[9] Kathrin Dörfler et al. 'Mobile Robotic Brickwork'. In: *Robotic Fabrication in Architecture, Art and Design 2016*. Springer International Publishing, 2016, pp. 204–217. DOI: 10.1007/978-3-319-26378-6_15 (cited on pages 3, 85, 167).

[10] Ticho Ooms et al. 'A parametric modelling strategy for the numerical simulation of 3D concrete printing with complex geometries'. In: *Additive Manufacturing* 38 (Feb. 2021). Publisher: Elsevier B.V. DOI: 10.1016/j.addma.2020.101743 (cited on pages 3, 64).

[11] Yiwei Weng et al. 'Empirical models to predict rheological properties of fiber reinforced cementitious composites for 3D printing'. In: *Construction and Building Materials* 189 (Nov. 2018). Publisher: Elsevier Ltd, pp. 676–685. DOI: 10.1016/j.conbuildmat.2018.09.039 (cited on pages 3, 64).

[12] Aaron Edsinger and Charles C. Kemp. 'Human-robot interaction for cooperative manipulation: Handing objects to one another'. In: *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*. 2007, pp. 1167–1172. DOI: 10.1109/ROMAN.2007.4415256 (cited on pages 3, 98).

[13] Karl D.D. Willis et al. 'Interactive Fabrication: New Interfaces for Digital Fabrication'. In: *ACM TEI*. Association for Computing Machinery, 2011, pp. 69–72 (cited on pages 4, 64, 66).

[14] Stefanie Mueller et al. 'Formfab: Continuous interactive fabrication'. In: *TEI 2019 - Proceedings of the 13th International Conference on Tangible, Embedded, and Embodied Interaction*. Issue: October. New York, NY, USA: Association for Computing Machinery, Mar. 2019, pp. 315–323. DOI: `10.1145/3294109.3295620` (cited on pages 4, 19, 20, 64, 66).

[15] Scott R. Klemmer, Björn Hartmann, and Leila Takayama. 'How bodies matter'. In: Association for Computing Machinery (ACM), 2006, p. 140. DOI: `10.1145/1142405.1142429` (cited on page 4).

[16] Jean Piaget. *The Origins of Intelligence in Children*. Vol. 3. Publication Title: Psychology in the Schools Issue: 2 ISSN: 00333085. Apr. 1963 (cited on pages 4, 64).

[17] Donald A. Schön. *Reflective Practitioner*. Basic Books, 1983 (cited on pages 4, 29, 64).

[18] Ben Shneiderman. 'Direct Manipulation: A Step Beyond Programming Languages'. In: *Computer* 16.8 (1983), pp. 57–69. DOI: `10.1109/MC.1983.1654471` (cited on pages 4, 64).

[19] António Moniz and Bettina-Johanna Krings. 'Robots Working with Humans or Humans Working with Robots? Searching for Social Dimensions in New Human-Robot Interaction in Industry'. en. In: *Societies* 6.3 (Aug. 2016), p. 23. DOI: `10.3390/soc6030023`. (Visited on 05/25/2022) (cited on pages 4, 98).

[20] Tim Stock et al. 'Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential'. In: *Process Safety and Environmental Protection* 118 (2018). Publisher: Institution of Chemical Engineers, pp. 254–267. DOI: `10.1016/j.psep.2018.06.026` (cited on pages 4, 42).

[21] David Romero, Johan Stahre, and Marco Taisch. 'The Operator 4.0: Towards socially sustainable factories of the future'. en. In: *Computers & Industrial Engineering* 139 (Jan. 2020), p. 106128. DOI: `10.1016/j.cie.2019.106128`. (Visited on 01/28/2023) (cited on page 4).

[22] Elizabeth Z Goh and Tariq Ali. 'Robotic surgery: an evolution in practice'. en. In: *Journal of Surgical Protocols and Research Methodologies* 2022.1 (Jan. 2022), snac003. DOI: `10.1093/jsprm/snac003`. (Visited on 06/22/2023) (cited on page 4).

[23] Masakazu Ejiri. 'Towards meaningful robotics for the future: Are we headed in the right direction?' In: *Robotics and Autonomous Systems* 18.1-2 (1996), pp. 1–5. DOI: `10.1016/0921-8890(95)00083-6` (cited on pages 4, 42).

[24] Sami Haddadin et al. 'Towards the Robotic Co-Worker'. In: *Robotics Research*. Ed. by Cédric Pradalier, Roland Siegwart, and Gerhard Hirzinger. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 261–282. DOI: `https://doi.org/10.1007/978-3-642-19457-3_16` (cited on pages 4, 100).

[25] Ronald J. Planer. 'What is Symbolic Cognition?' en. In: *Topoi* 40.1 (Feb. 2021), pp. 233–244. DOI: `10.1007/s11245-019-09670-5`. (Visited on 06/29/2022) (cited on page 8).

[26] Daniel Kahneman. *Thinking fast and thinking slow*. Publication Title: Farrar, Strauss and Giroux, New York, NY. 2011. (Visited on 08/22/2019) (cited on page 8).

[27] Michael Polanyi. *Personal knowledge : towards a post-critical philosophy*. Routledge, 1958. (Visited on 08/21/2019) (cited on pages 8, 196).

[28] Rolf Pfeifer, Josh Bongard, and Simon Grand. *How the body shapes the way we think: a new view of intelligence*. eng. OCLC: 65644796. Cambridge, Mass.: MIT Press, 2007 (cited on page 8).

[29] Louis Sanzogni, Gustavo Guzman, and Peter Busch. 'Artificial intelligence and knowledge management: questioning the tacit dimension'. en. In: *Prometheus* 35.1 (Mar. 2017). DOI: 10.1080/08109028.2017.1364547. (Visited on 02/02/2023) (cited on page 8).

[30] Davide Picca. 'From Intelligent to Wise Machines: Why a Poem Is Worth More Than 1 Million Tweets'. en. In: *Informatik Spektrum* 43.1 (Feb. 2020), pp. 28–39. DOI: 10.1007/s00287-020-01245-8. (Visited on 02/02/2023) (cited on page 8).

[31] Johanna Hautala. 'Can robots possess knowledge? Rethinking the DIK(W) pyramid through the lens of employees of an automotive factory'. en. In: *Humanities and Social Sciences Communications* 8.1 (Sept. 2021), p. 212. DOI: 10.1057/s41599-021-00893-9. (Visited on 02/02/2023) (cited on page 8).

[32] J.J. Gibson. *The senses considered as perceptual systems.* The senses considered as perceptual systems. Oxford, England: Houghton Mifflin, 1966 (cited on page 8).

[33] royalzig. *Antique Teak Wood Hand Carving Furniture Manufacturers*. Dec. 2019. URL: https://royalzig.com/antique-teak-hand-carved-furniture-wood-carving-furniture-manufacturers/ (visited on 02/18/2023) (cited on page 9).

[34] Jugetsudo. *Terracotta Teapot / Tokoname Shimizu Genji Kokuyohen*. URL: https://www.jugetsudo.fr/en/produit/terracotta-teapot-tokoname-shimizu-genji-kokuyohen/ (visited on 02/27/2023) (cited on page 9).

[35] Namita Kulkarni. *the better india*. Mar. 2017. URL: https://www.thebetterindia.com/89092/discover-ziveli-bring-kauna-craft-manipur-to-world/ (visited on 02/27/2023) (cited on page 9).

[36] Giulio Brugnaro and Sean Hanna. 'Adaptive Robotic Carving: Training Methods for the Integration of Material Performances in Timber Manufacturing'. In: *Robotic Fabrication in Architecture, Art and Design 2018 (ROBARCH 2018)*. Zürich, 2018, pp. 9–14 (cited on pages 9, 67, 101).

[37] Adrian Rosebrock. *Measuring size of objects in an image with OpenCV*. Mar. 2016. URL: https://pyimagesearch.com/2016/03/28/measuring-size-of-objects-in-an-image-with-opencv/ (visited on 01/29/2023) (cited on page 9).

[38] Oliver Herwig. *Semiramis von Gramazio Kohler Research*. Jan. 2023. URL: https://www.detail.de/de/de_de/semiramis-von-gramazio-kohler-research (visited on 01/29/2023) (cited on page 9).

[39] Douglas C. Engelbart. *Augmenting Human Intellect: A Conceptual Framework*. SRI Summary Report AFOSR-3223. Writing science. Washington DC: Director of Information Sciences, Air Force Office of Scientific Research, 1962 (cited on page 9).

[40] Manfred Clynes and Nathan Kline. 'Cyborgs and Space'. In: *Astronautics* 13.26-27 (1960), pp. 74–75 (cited on page 10).

[41] Daniela Mitterberger. 'CHRONOTOPE: Digital Craft and Embodiment in Architecture'. In: *Inflection: Journal of the Melbourne School of Design Presence*. Melbourne School of Design. Vol. 08. Melbourne: Melbourne Books, 2021 (cited on pages 10, 100).

[42] stelarc. *STELARC | EARLIER TEXTS*. URL: http://stelarc.org/?catID=20317 (visited on 08/06/2022) (cited on page 10).

[43] marco donnarumma marco. *marco donnarumma*. URL: https://marcodonnarumma.com/ (visited on 01/29/2023) (cited on page 10).

[44] *Glass Enterprise*. URL: https://www.google.com/glass/start/ (visited on 01/29/2023) (cited on page 11).

[45] Campbell Madeleine. *Suzanne Ciani*. Feb. 2019. URL: https://www.womeninsound.com/issue-6/suzanne-ciani (visited on 01/29/2023) (cited on page 11).

[46] Ivan Berger. *The "Switched-On Bach" Story*. Feb. 2021. URL: https://www.thereminvox.com/stories/music/the-switched-on-bach-story/ (visited on 02/27/2023) (cited on page 12).

[47] *Eyeharp*. URL: https://eyeharp.org/ (visited on 01/29/2023) (cited on page 12).

[48] Anzu Kawazoe et al. 'Tactile Echoes: Multisensory Augmented Reality for the Hand'. In: *IEEE Transactions on Haptics* 14.4 (Oct. 2021), pp. 835–848. DOI: 10.1109/TOH.2021.3084117. (Visited on 01/27/2023) (cited on page 12).

[49] S. Perrin, A. Cassinelli, and M. Ishikawa. 'Gesture recognition using laser-based tracking system'. In: *Sixth IEEE International Conference on Automatic Face and Gesture Recognition, 2004. Proceedings.* Seoul, Korea: IEEE, 2004, pp. 541–546. DOI: 10.1109/AFGR.2004.1301589. (Visited on 01/27/2023) (cited on page 12).

[50] Martha Pollak, ed. *The Education of the Architect: Historiography, Urbanism, and the Growth of Architectural Knowledge*. en. The MIT Press, 1997. (Visited on 01/27/2023) (cited on page 12).

[51] Daniela Mitterberger et al. 'Extended Reality Collaboration: Virtual and mixed reality system for collaborative design and holographic-assisted on-site fabrication'. In: *Towards Radical Regeneration*. Berlin: Springer, 2022 (cited on page 13).

[52] David Pye. 'The Nature and Art of Workmanship'. In: *Technology and Culture* 10.2 (1969), p. 307. DOI: 10.2307/3101490 (cited on pages 13, 195).

[53] Jeffrey Karoff. *Cave Digger*. Documentary. Jan. 2014 (cited on page 13).

[54] Terry Knight. 'Craft, performance, and grammars'. In: *Computational Studies on Cultural Variation and Heredity*. Springer, 2018, pp. 205–224 (cited on pages 15, 100).

[55] Terry Knight and George Stiny. 'Making grammars: From computing with shapes to computing with things'. en. In: *Design Studies*. Special Issue: Computational Making 41 (Nov. 2015), pp. 8–28. DOI: 10.1016/j.destud.2015.08.006. (Visited on 09/06/2022) (cited on pages 15, 100).

[56] Evan Thompson and Mog Stapleton. 'Making Sense of Sense-Making: Reflections on Enactive and Extended Mind Theories'. en. In: *Topoi* 28.1 (Mar. 2009), pp. 23–30. DOI: 10.1007/s11245-008-9043-2. (Visited on 01/27/2023) (cited on page 15).

[57] Camilla Groth. 'Doctoral_dissertation_Groth.pdf'. en. In: (). (Visited on 12/04/2022) (cited on page 15).

[58] Patrick Baudisch and Stefanie Mueller. 'Personal Fabrication'. In: *Foundations and Trends® in Human–Computer Interaction* 10.3–4 (2017). DOI: 10.1561/1100000055 (cited on pages 15, 18, 66).

[59] Stefanie Mueller, Pedro Lopes, and Patrick Baudisch. 'Interactive Construction: Interactive Fabrication of Functional Mechanical Devices'. In: *Proceedings of the 25th annual ACM symposium on User interface software and technology* (2012). Publisher: ACM Place: New York, NY, USA ISBN: 9781450315807. DOI: 10.1145/2380116. (Visited on 12/06/2021) (cited on pages 16, 18).

[60] Chris Harrison, Hrvoje Benko, and Andrew D. Wilson. 'OmniTouch: wearable multitouch interaction everywhere'. In: *Proceedings of the 24th annual ACM symposium on User interface software and technology*. UIST '11. New York, NY, USA: Association for Computing Machinery, Oct. 2011, pp. 441–450. DOI: 10.1145/2047196.2047255. (Visited on 06/20/2022) (cited on page 16).

[61] Ryo Suzuki et al. 'Augmented Reality and Robotics: A Survey and Taxonomy for AR-enhanced Human-Robot Interaction and Robotic Interfaces'. In: *CHI Conference on Human Factors in Computing Systems*. CHI '22. New York, NY, USA: Association for Computing Machinery, Apr. 2022, pp. 1–33. DOI: 10.1145/3491102.3517719. (Visited on 05/03/2022) (cited on pages 16, 18).

[62] Maria Larsson, Hironori Yoshida, and Takeo Igarashi. 'Human-in-the-loop fabrication of 3D surfaces with natural tree branches'. en. In: *Proceedings of the ACM Symposium on Computational Fabrication*. Pittsburgh Pennsylvania: ACM, June 2019, pp. 1–12. DOI: 10.1145/3328939.3329000. (Visited on 05/25/2022) (cited on pages 16, 17).

[63] Amit Zoran and Joseph A. Paradiso. 'The FreeD - A handheld digital milling device for craft and fabrication'. In: *Adjunct Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology, UIST'12*. New York, NY, USA: Association for Computing Machinery, 2012, pp. 3–4. DOI: 10.1145/2380296.2380299 (cited on pages 16, 17, 66).

[64] Alec Rivers, Ilan E. Moyer, and Frédo Durand. 'Position-correcting tools for 2D digital fabrication'. In: *ACM Transactions on Graphics* 31.4 (2012), pp. 1–7. DOI: 10.1145/2185520.2185584 (cited on pages 16, 66).

[65] Rundong Tian and Eric Paulos. 'Adroid: Augmenting Hands-on Making with a Collaborative Robot'. In: Association for Computing Machinery (ACM), Oct. 2021, pp. 270–281. DOI: 10.1145/3472749.3474749 (cited on pages 16, 66).

[66] *Eine Oberfräse revoluziониert das Tischlerhandwerk*. URL: https://rehform-tischlerei.de/eine-oberfraese-revoluzioniert-das-tischler-handwerk/ (visited on 01/29/2023) (cited on page 17).

[67] *Augmented Robotics: Mixed reality environments for on-demand fabrication, assembly and analysis of complex steel structures*. URL: http://www.robarch2018.org/mixed-reality-environments-on-demand-fabrication-assembly-analysis-complex-steel-structures/ (visited on 01/29/2023) (cited on page 17).

[68] Mark Billinghurst, Adrian Clark, and Gun Lee. 'A survey of augmented reality'. In: *Foundations and Trends in Human-Computer Interaction* 8.2-3 (2014), pp. 73–272. DOI: 10.1561/1100000049 (cited on page 17).

[69] A.Y.C. Nee et al. 'Augmented reality applications in design and manufacturing'. en. In: *CIRP Annals* 61.2 (2012), pp. 657–679. DOI: 10.1016/j.cirp.2012.05.010. (Visited on 05/25/2022) (cited on pages 18, 45, 125).

[70] Gwyllim Jahn et al. 'Holographic Construction'. en. In: *Impact: Design With All Senses*. Ed. by Christoph Gengnagel et al. Cham: Springer International Publishing, 2020, pp. 314–324. DOI: 10.1007/978-3-030-29829-6_25. (Visited on 02/06/2023) (cited on page 18).

[71] Hironori Yoshida et al. 'Architecture-scale human-assisted additive manufacturing'. en. In: *ACM Transactions on Graphics* 34.4 (July 2015), pp. 1–8. DOI: 10.1145/2766951. (Visited on 05/25/2022) (cited on pages 18, 45, 69).

[72] Jose Molineros and Rajeev Sharma. 'Vision-based Augmented Reality for Guiding Assembly'. In: *Virtual and Augmented Reality Applications in Manufacturing* (2004), pp. 277–309. DOI: 10.1007/978-1-4471-3873-0_15 (cited on pages 18, 42).

[73] Mark Billinghurst, Mika Hakkarainen, and Charles Woodward. 'Augmented assembly using a mobile phone'. In: *MUM'08 - Proceedings of the 7th International Conference on Mobile and Ubiquitous Multimedia* (2008). ISBN: 9781605581927, pp. 84–87. DOI: 10.1145/1543137.1543153 (cited on pages 18, 42, 69).

[74] Andrea Settimi, Julien Gamerro, and Yves Weinand. 'Augmented-reality-assisted timber drilling with smart retrofitted tools'. en. In: *Automation in Construction* 139 (July 2022), p. 104272. DOI: 10.1016/j.autcon.2022.104272. (Visited on 05/14/2022) (cited on page 18).

[75] Marianna Kopsida and Ioannis Brilakis. 'Markerless BIM Registration for Mobile Augmented Reality Based Inspection'. In: *International Conference on Smart Infrastructure and Construction* July (2016), pp. 1–7 (cited on page 18).

[76] Franco Tecchia, Leila Alem, and Weidong Huang. '3D helping hands: a gesture based MR system for remote collaboration'. In: *Proceedings of the 11th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry*. VRCAI '12. New York, NY, USA: Association for Computing Machinery, Dec. 2012, pp. 323–328. DOI: 10.1145/2407516.2407590. (Visited on 08/06/2022) (cited on page 18).

[77] Gwyllim Jahn and Andrew Wit. '[BENT] Holographic handcraft in large-scale steam-bent timber structures'. In: *Ubiquity and Autonomy / ACADIA 2019*. Ed. by Briscoe Danielle Odom Clay Bieg Kory. Acadia Publishing Company, 2019, pp. 438–447 (cited on pages 18, 42, 124, 125).

[78] Ondrej Kyjanek et al. 'Implementation of an Augmented Reality AR Workflow for Human Robot Collaboration in Timber Prefabrication'. In: May 2019. DOI: 10.22260/ISARC2019/0164 (cited on pages 18, 45, 64, 100, 153).

[79] Benjamin Lafreniere et al. 'Crowdsourced Fabrication'. In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. New York, NY, USA: ACM, Oct. 2016, pp. 15–28. DOI: 10.1145/2984511.2984553 (cited on pages 18, 45, 64, 100).

[80] Karl D.D. Willis et al. 'Interactive fabrication: new interfaces for digital fabrication'. en. In: *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*. Funchal Portugal: ACM, Jan. 2010, pp. 69–72. DOI: 10.1145/1935701.1935716. (Visited on 05/25/2022) (cited on pages 18, 100).

[81] Christian Weichel et al. 'ReForm: Integrating physical and digital design through bidirectional fabrication'. In: *UIST 2015 - Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology*. New York, NY, USA: Association for Computing Machinery, 2015, pp. 93–102. DOI: 10.1145/2807442.2807451 (cited on pages 19, 20, 66).

[82] Volker Helm et al. 'Mobile robotic fabrication on construction sites: DimRob'. In: *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. ISSN: 2153-0866. Oct. 2012, pp. 4335–4341. DOI: 10.1109/IROS.2012.6385617 (cited on pages 19, 20, 66).

[83] Huaishu Peng et al. 'RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer'. en. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Montreal QC Canada: ACM, Apr. 2018, pp. 1–12. DOI: 10.1145/3173574.3174153. (Visited on 05/25/2022) (cited on pages 19, 20, 66).

[84] Microsoft. *The T win Digital Process A step towards : operational excellence Published: December 2017 For the latest information, please see http://aka.ms/digitaltwin*. Dec. 2017. URL: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://info.microsoft.com/rs/157-GQE-382/images/Digital%20Twin%20Vision.pdf (visited on 01/29/2023) (cited on page 21).

[85] Johanna Pirker et al. 'Immersive Virtual Reality for Virtual and Digital Twins: A Literature Review to Identify State Of The Art and Perspectives'. In: *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. Christchurch, New Zealand: IEEE, Mar. 2022, pp. 114–115. DOI: 10.1109/VRW55335.2022.00035. (Visited on 01/30/2023) (cited on page 21).

[86] Jane Shi et al. 'Levels of human and robot collaboration for automotive manufacturing'. In: *Proceedings of the Workshop on Performance Metrics for Intelligent Systems*. PerMIS '12. New York, NY, USA: Association for Computing Machinery, Mar. 2012, pp. 95–100. DOI: 10.1145/2393091.2393111. (Visited on 10/24/2022) (cited on pages 22, 112, 151).

[87] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 'Research through design as a method for interaction design research in HCI'. In: *Conference on Human Factors in Computing Systems - Proceedings*. 2007, pp. 493–502. DOI: 10.1145/1240624.1240704 (cited on pages 29, 69).

[88] Horst WJ Rittel and Melvin M Webber. 'Dilemmas in a general theory of planning'. In: *Policy sciences* 4.2 (1973). Publisher: Springer, pp. 155–169 (cited on page 29).

[89] Nigel Cross. 'Design Research: A Disciplined Conversation'. In: *Design Issues* 15.2 (1999), p. 5. DOI: 10.2307/1511837. (Visited on 01/31/2023) (cited on page 29).

[90] Kathrin Dörfler, Timothy Sandy, and Markus Giftthaler. 'Robotic Fabrication in Architecture, Art and Design 2016'. In: *Robotic Fabrication in Architecture, Art and Design 2016* June (2016). ISBN: 9783319263786. DOI: 10.1007/978-3-319-26378-6 (cited on pages 42, 98).

[91] Lauren Vasey et al. 'Collaborative construction'. In: *ACADIA 2016: Posthuman Frontiers: Data, Designers, and Cognitive Machines - Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*. ACADIA, 2016, pp. 184–195. DOI: 10.1002/9780470696125.ch9 (cited on pages 42, 100).

[92] Michael Polanyi. *Implizites Wissen*. Suhrkamp, 1985. (Visited on 08/21/2019) (cited on page 42).

[93] Vanessa Kohn and David Harborth. 'Augmented reality-A game changing technology for manufacturing processes?' In: *Twenty-Sixth European Conference on Information Systems (ECIS 2018)*. Portsmouth, UK, 2018, p. 111 (cited on page 42).

[94] Sebastian Büttner et al. 'The Design Space of Augmented and Virtual Reality Applications for Assistive Environments in Manufacturing: A Visual Approach'. en. In: *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments*. Island of Rhodes Greece: ACM, June 2017, pp. 433–440. DOI: 10.1145/3056540.3076193. (Visited on 05/25/2022) (cited on pages 42, 124).

[95] Michael Chu, Jane Matthews, and Peter E.D. Love. 'Integrating mobile Building Information Modelling and Augmented Reality systems: An experimental study'. en. In: *Automation in Construction* 85 (Jan. 2018), pp. 305–316. DOI: 10.1016/j.autcon.2017.10.032. (Visited on 05/25/2022) (cited on page 42).

[96] Erkan Bostanci et al. 'User Tracking Methods for Augmented Reality'. In: *International Journal of Computer Theory and Engineering* January (2013), pp. 93–98. DOI: 10.7763/ijcte.2013.v5.654 (cited on page 42).

[97] P. Hübner, M. Weinmann, and S. Wursthorn. 'MARKER-BASED LOCALIZATION OF THE MICROSOFT HOLOLENS IN BUILDING MODELS'. en. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-1 (Sept. 2018), pp. 195–202. DOI: 10.5194/isprs-archives-XLII-1-195-2018. (Visited on 05/25/2022) (cited on page 42).

[98] Greg Welch et al. 'High-Performance Wide-Area Optical Tracking: The HiBall Tracking System'. en. In: *Presence: Teleoperators and Virtual Environments* 10.1 (Feb. 2001), pp. 1–21. DOI: 10.1162/105474601750182289. (Visited on 05/25/2022) (cited on page 42).

[99] Chee Oh Chung, Yilun He, and Hoe Kyung Jung. 'Augmented reality navigation system on android'. In: *International Journal of Electrical and Computer Engineering* 6.1 (2016), pp. 406–412. DOI: 10.11591/ijece.v6i1.9345 (cited on pages 42, 68).

[100] Timothy Sandy and Jonas Buchli. 'Object-Based Visual-Inertial Tracking for Additive Fabrication'. In: *IEEE Robotics and Automation Letters* 3.3 (July 2018). Publisher: Institute of Electrical and Electronics Engineers Inc., pp. 1370–1377. DOI: 10.1109/LRA.2018.2798700 (cited on pages 42, 45, 54, 98, 108, 116).

[101] Fabio Gramazio and Matthias Kohler. *Digital Materiality in Architecture: Bridging the Realms of the Virtual and Physical*. Pages: 179-199 Publication Title: Explorations in Architecture. 2008 (cited on page 44).

[102] Kathrin Dörfler et al. 'Mobile Robotic Brickwork - Automation of a Discrete Robotic Fabrication Process Using an Autonomous Mobile Robot'. In: *Robotic Fabrication in Architecture, Art and Design 2016*. Ed. by Dagmar Reinhardt, Rob Saunders, and Jane Burry. Springer, 2016, pp. 204–217. DOI: 10.1007/978-3-319-26378-6 (cited on page 44).

[103] Chen Feng et al. 'Vision guided autonomous robotic assembly and as-built scanning on unstructured construction sites'. In: *Automation in Construction* 59 (2015), pp. 128–138. DOI: 10.1016/j.autcon.2015.06.002 (cited on page 44).

[104] Ryan L. Johns. 'Augmented Materiality: Modelling With Material Indeterminancy'. In: *Fabricate 2014*. Ed. by Gramazio Fabio, Matthias Kohler, and Silke Langenberg. UCL Press, 2017, pp. 216–223 (cited on page 45).

[105] Gwyllim Jahn et al. 'Making in Mixed Reality'. In: *ACADIA 2018 RECALIBRATION: on imprecision and infidelity: Project Catalog of the 38th Annual Conference of the Association for Computer Aided Design in Architecture*. Ed. by Andrew John Wit Philip Anzalone Marcella Del Signore. Acadia Publishing Company, 2018, 2018, pp. 1–11 (cited on pages 45, 69).

[106] Gwyllim Jahn et al. 'Holographic construction'. In: *Design Modelling Symposium Berlin*. Springer, 2019, pp. 314–324 (cited on page 45).

[107] D. Schmalstieg and Tobias Höllerer. *Augmented reality: principles and practice*. en. Addison-Wesley usability and HCI series. OCLC: ocn802326915. Boston: Addison-Wesley, 2016 (cited on page 46).

[108] Morgan Quigley et al. 'ROS: an open-source Robot Operating System'. en. In: (2009), p. 6 (cited on pages 46, 129).

[109] Tom Van Mele et al. *COMPAS: A framework for computational research in architecture and structures*. 2017. URL: http://compas-dev.github.io/compas/ (cited on pages 48, 105).

[110] John P. Chin, Virginia A. Diehl, and Kent L. Norman. 'Development of an instrument measuring user satisfaction of the human-computer interface'. In: *Conference on Human Factors in Computing Systems - Proceedings*. Vol. Part F1302. Association for Computing Machinery, May 1988, pp. 213–218. DOI: 10.1145/57167.57203. (Visited on 01/15/2020) (cited on pages 51, 169).

[111] Liz Allen, Alison O'Connell, and Veronique Kiermer. 'How can we ensure visibility and diversity in research contributions? How the Contributor Role Taxonomy (CRediT) is helping the shift from authorship to contributorship'. en. In: *Learned Publishing* 32.1 (Jan. 2019), pp. 71–74. DOI: 10.1002/leap.1210. (Visited on 02/10/2023) (cited on pages 54, 89, 116, 134).

[112] Aaron Willette, Sigrid Brell-Cokcan, and Johannes Braumann. *Robotic fabrication in architecture, art and design 2014*. Springer, 2014 (cited on page 64).

[113] Bing Lu et al. 'Effect of printing parameters on material distribution in spray-based 3D concrete printing (S-3DCP)'. In: *Automation in Construction* 124 (Apr. 2021). Publisher: Elsevier B.V. DOI: 10.1016/j.autcon.2021.103570 (cited on page 64).

[114] Carmen Hull and Wesley Willett. 'Building with Data'. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, May 2017. DOI: 10.1145/3025453.3025850 (cited on page 64).

[115] Azin Aryania et al. 'New trends in industrial robot controller user interfaces'. In: *2012 IEEE 3rd International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE, 2012, pp. 365–369 (cited on pages 64, 98).

[116] Scott R Klemmer, Björn Hartmann, and Leila Takayama. 'How Bodies Matter: Five Themes for Interaction Design'. In: *Proceedings of the 6th ACM conference on Designing Interactive systems - DIS '06* (2006). Publisher: ACM Press Place: New York, New York, USA ISBN: 1595933670. DOI: 10.1145/1142405. (Visited on 12/09/2021) (cited on page 64).

[117] Harshit Agrawal et al. 'Protopiper: Physically sketching room-sized objects at actual scale'. In: *UIST 2015 - Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology* November (2015). Publisher: Association for Computing Machinery Place: New York, NY, USA ISBN: 9781450337793, pp. 427–436. DOI: 10.1145/2807442.2807505 (cited on page 66).

[118] Maria Larsson, Hironori Yoshida, and Takeo Igarashi. 'Human-in-the-loop fabrication of 3D surfaces with natural tree branches'. In: *Proceedings: SCF 2019 - ACM Symposium on Computational Fabrication*. Association for Computing Machinery, Inc, June 2019. DOI: 10.1145/3328939.3329000. (Visited on 08/30/2019) (cited on page 66).

[119] Karl D.D. Willis et al. 'Spatial sketch: Bridging between movement & fabrication'. In: *TEI'10 - Proceedings of the 4th International Conference on Tangible, Embedded, and Embodied Interaction* (2010). ISBN: 9781605588414, pp. 5–12. DOI: 10.1145/1709886.1709890 (cited on page 66).

[120] Zhao Ma et al. 'RobotSculptor: Artist-Directed Robotic Sculpting of Clay'. In: (2020). ISBN: 9781450381703. DOI: 10.1145/3424630.3425415. (Visited on 12/14/2021) (cited on pages 66, 101).

[121] Norman Hack et al. 'Mesh Mould: An On Site, Robotically Fabricated, Functional Formwork'. In: (2017). (Visited on 12/14/2021) (cited on page 67).

[122] Daniela Mitterberger. 'Is Body Architecture?' In: *ADATO Magazine* 1 -20.Architecture and Medicine (2019) (cited on page 67).

[123] Ena Lloret Fritschi et al. 'Smart Dynamic Casting'. In: *HPC/CIC Tromsø 2017* (2017). Publisher: Norwegian Concrete Association ISBN: 9783033046412, Paper no. 27. DOI: 10.3929/ETHZ-B-000219663. (Visited on 12/22/2021) (cited on page 67).

[124] H. Lindemann et al. 'Development of a Shotcrete 3D-Printing (SC3DP) Technology for Additive Manufacturing of Reinforced Freeform Concrete Structures'. In: *RILEM Bookseries* 19 (Sept. 2018). Publisher: Springer, Cham, pp. 287–298. DOI: 10.1007/978-3-319-99519-9_27. (Visited on 12/21/2021) (cited on page 67).

[125] Xuhai Xu et al. 'Enabling Hand Gesture Customization on Wrist-Worn Devices'. In: *CHI Conference on Human Factors in Computing Systems*. CHI '22. New York, NY, USA: Association for Computing Machinery, Apr. 2022, pp. 1–19. DOI: 10.1145/3491102.3501904. (Visited on 05/04/2022) (cited on page 67).

[126] Aude Billard et al. 'Robot Programming by Demonstration'. In: *Springer Handbook of Robotics*. Ed. by Bruno Siciliano and Oussama Khatib. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 1371–1394. DOI: 10.1007/978-3-540-30301-5_60 (cited on page 67).

[127] Paul Bakker and Yasuo Kuniyoshi. 'Robot See, Robot Do : An Overview of Robot Imitation'. In: *AISB Workshop on Learning in Robots and Animals* (1996) (cited on page 67).

[128] Sing Bing Kang and Katsushi Ikeuchi. 'A robot system that observes and replicates grasping tasks'. In: *Proc. International Conference on Computer Vision (ICCV)* (1995) (cited on page 67).

[129] Yasuo Kuniyoshi, M. Inaba, and H. Inoue. 'Teaching by showing: Generating robot programs by visual observation of human performance'. In: *Inter national Symposium of Industrial Robots* (1989), pp. 119–126 (cited on page 67).

[130] Chao-Ping Tung and A Kak. 'Automatic learning of assembly tasks using a DataGlove system'. In: *Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots* 1 (1995), 1–8 vol.1 (cited on page 67).

[131] Joshua David Bard et al. 'Reality is interface: Two motion capture case studies of human–machine collaboration in high-skill domains'. In: *International Journal of Architectural Computing* 14.4 (Dec. 2016). Publisher: SAGE Publications Inc., pp. 398–408. DOI: 10.1177/1478077116670747 (cited on page 67).

[132] Masato Ito et al. 'Dynamic and interactive generation of object handling behaviors by a small humanoid robot using a dynamic neural network model'. In: *Neural Networks* 19.3 (Apr. 2006). DOI: 10.1016/j.neunet.2006.02.007 (cited on page 67).

[133] Joshua Bard et al. 'Seeing is Doing: Synthetic Tools for Robotically Augmented Fabrication in High-Skill Domains'. In: 2014 (cited on page 67).

[134] William Millar, George Percy Bankart, and Jeff Orton. *Plastering plain and decorative*. eng. Ed. by William Millar, George Percy Bankart, and Jeff Orton. Genre: book. Shaftesbury: Donhead, 2009 (cited on page 67).

[135] Johan Forsberg, Daniel Graff, and Åke Wernersson. 'An Autonomous Plastering Robot for Walls and Ceilings'. en. In: *IFAC Proceedings Volumes* 28.11 (June 1995), pp. 301–306. DOI: 10.1016/S1474-6670(17)46989-8. (Visited on 05/27/2022) (cited on page 67).

[136] G Pritschow et al. *On-Site Mobile Plastering Robot: A Practical Design Concept*. Tech. rep. 1997, pp. 277–285 (cited on page 67).

[137] Yehiel Rosenfeld, Abraham Warszawski, and Uri Zajicek. *Full-scale building with interior finishing robot* *. Tech. rep. Publication Title: Automation in Construction Volume: 2. 1993, pp. 229–240 (cited on page 67).

[138] Thomas Bock, Natalia Buzalo, and Alexey Bulgakov. 'Mathematical Description and Optimization of Robot Control for Plastering Works'. In: *2018 International Multi-Conference on Industrial Engineering and Modern Technologies, FarEastCon 2018* (2019). Publisher: IEEE ISBN: 9781538695357, pp. 1–5. DOI: 10.1109/FarEastCon.2018.8602717 (cited on page 67).

[139] Guy German et al. *Smart Robots For Construction Sites*. 2021 (cited on page 67).

[140] Joshua Bard, Steven Mankouche, and Matthew Schulte. 'Morphfaux: Probing the Proto-Synthetic Nature of Plaster Through Robotic Tooling'. In: *ACADIA 14: Design Agency [Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]* 5.1 (2012), pp. 177–186 (cited on page 67).

[141] Selen Ercan Jenny et al. 'Robotic Plaster Spraying: Crafting Surfaces with Adaptive Thin-Layer Printing'. In: *3D Printing and Additive Manufacturing* (Aug. 2021). DOI: 10.1089/3dp.2020.0355 (cited on page 67).

[142] Selen Ercan Jenny et al. 'Crafting plaster through continuous mobile robotic fabrication on-site'. In: *Construction Robotics* 4.3-4 (Dec. 2020). Publisher: Springer Science and Business Media LLC, pp. 261–271. DOI: 10.1007/s41693-020-00043-8 (cited on pages 68, 85, 89).

[143] Ronald T. Azuma. 'A Survey of Augmented Reality'. In: *Presence: Teleoperators and Virtual Environments* 6 (1997), pp. 355–385 (cited on page 68).

[144] Lidia Atanasova et al. 'Prototype As Artefact'. In: CUMINCAD, 2020 (cited on pages 68, 100, 116).

[145] Daniela Mitterberger et al. 'Augmented bricklaying: Human–machine interaction for in situ assembly of complex brickwork using object-aware augmented reality'. en. In: *Construction Robotics* 4.3-4 (Dec. 2020), pp. 151–161. DOI: 10.1007/s41693-020-00035-8. (Visited on 01/13/2022) (cited on pages 68, 125).

[146] Robert Xiao et al. 'LumiWatch: On-arm projected graphics and touch input'. In: *Conference on Human Factors in Computing Systems - Proceedings*. Vol. 2018-April. Association for Computing Machinery, Apr. 2018. DOI: 10.1145/3173574.3173669 (cited on pages 69, 145).

[147] Hrvoje Benko, Andrew D. Wilson, and Federico Zannier. 'Dyadic projected spatial augmented reality'. In: *UIST 2014 - Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, Inc, Oct. 2014, pp. 645–656. DOI: 10.1145/2642918.2647402 (cited on page 69).

[148] Brett Jones et al. 'RoomAlive: Magical experiences enabled by scalable, adaptive projector-camera units'. In: *UIST 2014 - Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, Inc, Oct. 2014, pp. 637–644. DOI: 10.1145/2642918.2647383 (cited on page 69).

[149] Andrew D. Wilson et al. 'Steerable Augmented Reality with the Beamatron'. In: *UIST*. ACM, 2012, pp. 413–422 (cited on page 69).

[150] Stanislaw Borkowski, Julien Letessier, and James L Crowley. 'Spatial Control of Interactive Surfaces in an Augmented Environment'. In: *EHCI 2004 Spatial Control of Interactive Surfaces in an Augmented Environment. Lecture Notes in Computer Science.* 2004, pp. 228–244 (cited on page 69).

[151] A. Butz and A. Kruger. 'Applying the peephole metaphor in a mixed-reality room'. In: *IEEE Computer Graphics and Applications* 26.1 (Jan. 2006). DOI: 10.1109/MCG.2006.10 (cited on page 69).

[152] Jochen Ehnes, Koichi Hirota, and Michitaka Hirose. 'Projected Augmentation - Augmented Reality using Rotatable Video Projectors'. In: *Proceedings of the 3rd IEEE/ACM International Symposium on Mixed and Augmented Reality*. ISMAR '04. USA: IEEE Computer Society, Nov. 2004, pp. 26–35. DOI: 10.1109/ISMAR.2004.47. (Visited on 12/17/2022) (cited on pages 69, 145).

[153] Claudio Pinhanez. *The Everywhere Displays Projector: A Device to Create Ubiquitous Graphical Interfaces*. Tech. rep. Publication Title: LNCS Volume: 2201. Springer-Verlag, 2001, pp. 315–331 (cited on page 69).

[154] Alexei Pevzner et al. 'Construction Operation Assessment and Correction Using Laser Scanning and Projection Feedback'. In: Oct. 2020. DOI: 10.22260/ISARC2020/0171 (cited on page 69).

[155] Peyman Milanfar. 'A tour of modern image filtering'. In: *IEEE Signal Processing Magazine* 30.1 (2013). Publisher: Institute of Electrical and Electronics Engineers Inc., pp. 106–123. DOI: 10.1109/MSP.2011.2179329. (Visited on 12/21/2021) (cited on page 70).

[156] Morgan Quigley et al. 'ROS: an open-source Robot Operating System'. In: *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*. arXiv: 1106.4561 ISSN: 01628828. 2015, pp. 4754–4759. DOI: 10.1109/IECON.2015.7392843 (cited on page 74).

[157] S. Ercan et al. 'Automated Localization of a Mobile Construction Robot with an External Measurement Device'. In: *Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC 2019)* (2019). Publisher: International Association on Automation and Robotics in Construction, pp. 929–936. DOI: 10.22260/ISARC2019/0124. (Visited on 12/23/2021) (cited on page 80).

[158] James R. Lewis. 'Psychometric Evaluation of the Post-Study System Usability Questionnaire: The PSSUQ'. In: *Proceedings of the Human Factors Society Annual Meeting* 36.16 (Oct. 1992), pp. 1259–1260. DOI: 10.1177/154193129203601617 (cited on page 81).

[159] J Lazar, JH Feng, and H Hochheiser. 'Research methods in human-computer interaction'. In: (2017), pp. 2016–2017. (Visited on 09/07/2021) (cited on pages 82, 168, 169).

[160] Jared Spool and Will Schroeder. 'Testing web sites: Five users is nowhere near enough'. In: *Conference on Human Factors in Computing Systems - Proceedings*. 2001, pp. 285–286. DOI: 10.1145/634067.634236 (cited on pages 83, 168).

[161] Robert A. Virzi. 'Refining the Test Phase of Usability Evaluation: How Many Subjects Is Enough?' In: *Human Factors: The Journal of the Human Factors and Ergonomics Society* 34.4 (Aug. 1992). DOI: 10.1177/001872089203400407 (cited on pages 83, 168).

[162] Xu Zhang et al. 'Large-scale 3D printing by a team of mobile robots'. en. In: *Automation in Construction* 95 (Nov. 2018), pp. 98–106. DOI: 10.1016/j.autcon.2018.08.004. (Visited on 01/27/2023) (cited on page 85).

[163] Johannes Pankert and Marco Hutter. 'Perceptive Model Predictive Control for Continuous Mobile Manipulation'. In: *IEEE Robotics and Automation Letters* 5.4 (Oct. 2020), pp. 6177–6184. DOI: 10.1109/LRA.2020.3010721. (Visited on 01/27/2023) (cited on page 85).

[164] Pok Yin Leung et al. 'Automatic Assembly of Jointed Timber Structure using Distributed Robotic Clamps'. en. In: *PROJECTIONS – Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design*. Vol. 1. Accepted: 2022-06-17T10:29:40Z. Association for Computer Aided Architectural Design Research in Asia, 2021, pp. 583–592. DOI: 10.3929/ethz-b-000481928. (Visited on 09/06/2022) (cited on page 98).

[165] Hans Jakob Wagner et al. 'Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood Pavilion'. en. In: *Construction Robotics* 4.3 (Dec. 2020), pp. 187–204. DOI: 10.1007/s41693-020-00038-5. (Visited on 09/06/2022) (cited on page 98).

[166] Tobias Bonwetsch, Fabio Gramazio, and Matthias Kohler. 'Digitally fabricating non-standardised brick walls'. In: *ManuBuild, 1st International Conference*. Rotterdam: D. M. Sharp, 2007, pp. 191–196. (Visited on 08/21/2019) (cited on pages 98, 167).

[167] Terry Knight. 'Shapes and Other Things'. en. In: *Nexus Network Journal* 17.3 (Dec. 2015), pp. 963–980. DOI: 10.1007/s00004-015-0267-3. (Visited on 11/19/2022) (cited on page 100).

[168] Daniela Mitterberger. 'Augmented human, extended machine: extended reality systems for robotic fabrication in architecture, engineering, and construction'. en. In: *XRDS: Crossroads, The ACM Magazine for Students* 29.1 (Sept. 2022), pp. 48–53. DOI: 10.1145/3558196. (Visited on 07/11/2023) (cited on page 100).

[169] Kathrin Dörfler, Florian Rist, and Romana Rust. 'Interlacing'. In: *Rob | Arch 2012*. Ed. by Sigrid Brell-Çokcan and Johannes Braumann. Vienna: Springer Vienna, 2013, pp. 82–91. DOI: 10.1007/978-3-7091-1465-0_7. (Visited on 08/22/2019) (cited on pages 100, 153).

[170] Ankit R. Patel et al. 'Vitality of Robotics in Healthcare Industry: An Internet of Things (IoT) Perspective'. en. In: *Internet of Things and Big Data Technologies for Next Generation Healthcare*. Ed. by Chintan Bhatt, Nilanjan Dey, and Amira S. Ashour. Studies in Big Data. Cham: Springer International Publishing, 2017, pp. 91–109. DOI: 10.1007/978-3-319-49736-5_5. (Visited on 09/06/2022) (cited on page 100).

[171] Anika Fiebich, Nhung Nguyen, and Sarah Schwarzkopf. 'Cooperation with robots? A two-dimensional approach'. In: *Collective Agency and Cooperation in Natural and Artificial Systems: Explanation, Implementation and Simulation* (2015). ISBN: 9783319155159, pp. 25–43. DOI: 10.1007/978-3-319-15515-9_2 (cited on page 100).

[172] Felix Amtsberg et al. 'iHRC: An AR-based interface for intuitive, interactive and coordinated task sharing between humans and robots in building construction'. In: *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*. Ed. by Chen Feng et al. ISSN: 2413-5844. Dubai, UAE: International Association for Automation and Robotics in Construction (IAARC), Nov. 2021, pp. 25–32. DOI: 10.22260/ISARC2021/0006 (cited on pages 100, 153).

[173] Christopher Crick et al. 'Rosbridge: ROS for non-ROS users'. In: *Springer Tracts in Advanced Robotics*. Vol. 100. ISSN: 1610742X. Springer Verlag, 2017, pp. 493–504. DOI: 10.1007/978-3-319-29363-9_28 (cited on page 109).

[174] Malcolm Mccullough and G. Mclaren. *Abstracting Craft: The Practiced Digital Hand*. Vol. 11. Publication Title: Journal of Design History Issue: 1 ISSN: 0952-4649. Cambridge: MIT Press, Jan. 1998 (cited on page 115).

[175] COMPAS. *Compas - Frame*. Nov. 2022. URL: https://compas.dev/compas/dev/api/generated/compas.geometry.Frame.html (visited on 10/11/2022) (cited on page 116).

[176] Garvin Goepel. 'Augmented Construction'. In: *ACADIA 19:UBIQUITY AND AUTONOMY [Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-0-578-59179-7] (The University of Texas at Austin School of Architecture, Austin, Texas 21-26 October, 2019) pp. 430-437*. ACADIA, 2019. (Visited on 01/15/2022) (cited on page 124).

[177] Alireza Fazel and Abbasali Izadi. 'An interactive augmented reality tool for constructing free-form modular surfaces'. In: *Automation in Construction* 85.October 2016 (2018). Publisher: Elsevier, pp. 135–145. DOI: 10.1016/j.autcon.2017.10.015 (cited on page 124).

[178] Andreas Dietze, Yvonne Jung, and Paul Grimm. 'Supporting Web-based Collaboration for Construction Site Monitoring'. en. In: *The 26th International Conference on 3D Web Technology*. Pisa Italy: ACM, Nov. 2021, pp. 1–8. DOI: 10.1145/3485444.3495180. (Visited on 01/27/2023) (cited on page 124).

[179] Yifan Liu et al. 'Evaluating the Impact of Virtual Reality on Design Review Meetings'. en. In: *Journal of Computing in Civil Engineering* 34.1 (Jan. 2020), p. 04019045. DOI: 10.1061/(ASCE)CP.1943-5487.0000856. (Visited on 01/27/2023) (cited on page 124).

[180] Reza Zaker and Eloi Coloma. 'Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study'. en. In: *Visualization in Engineering* 6.1 (Dec. 2018), p. 4. DOI: 10.1186/s40327-018-0065-6. (Visited on 01/27/2023) (cited on page 124).

[181] Bernardo Marques et al. 'An Ontology for Evaluation of Remote Collaboration using Augmented Reality'. en. In: (2021). Publisher: European Society for Socially Embedded Technologies (EUSSET). DOI: 10.18420/ECSCW2021_P04. (Visited on 01/27/2023) (cited on page 124).

[182] Xiangyu Wang and Jerry Jen-Hung Tsai, eds. *Collaborative Design in Virtual Environments*. en. Dordrecht: Springer Netherlands, 2011. (Visited on 01/27/2023) (cited on page 124).

[183] Steve Benford et al. 'Collaborative virtual environments'. en. In: *Communications of the ACM* 44.7 (July 2001), pp. 79–85. DOI: 10.1145/379300.379322. (Visited on 01/27/2023) (cited on page 124).

[184] Andrew McGrath and Wolfgang Prinz. 'All That Is Solid Melts Into Software'. en. In: *Collaborative Virtual Environments*. Ed. by Dan Diaper et al. Series Title: Computer Supported Cooperative Work. London: Springer London, 2001, pp. 99–114. DOI: 10.1007/978-1-4471-0685-2_6. (Visited on 01/14/2022) (cited on page 124).

[185] Elizabeth F Churchill and Dave Snowdon. 'Collaborative virtual environments: an introductory review of issues and systems'. In: *virtual reality* 3.1 (1998). Publisher: Springer, pp. 3–15 (cited on page 124).

[186] Jeronimo Gustavo Grandi, Henrique Galvan Debarba, and Anderson Maciel. 'Characterizing Asymmetric Collaborative Interactions in Virtual and Augmented Realities'. In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. Osaka, Japan: IEEE, Mar. 2019, pp. 127–135. DOI: 10.1109/VR.2019.8798080. (Visited on 01/27/2023) (cited on page 124).

[187] Thammathip Piumsomboon et al. 'CoVAR: a collaborative virtual and augmented reality system for remote collaboration'. en. In: *SIGGRAPH Asia 2017 Emerging Technologies*. Bangkok Thailand: ACM, Nov. 2017, pp. 1–2. DOI: 10/gf2bqk. (Visited on 01/13/2022) (cited on page 124).

[188] Hikaru Ibayashi et al. 'Dollhouse VR: a multi-view, multi-user collaborative design workspace with VR technology'. In: *SIGGRAPH Asia 2015 Emerging Technologies*. SA '15. New York, NY, USA: Association for Computing Machinery, Nov. 2015, pp. 1–2. DOI: 10.1145/2818466.2818480. (Visited on 03/16/2022) (cited on page 125).

[189] Jan Gugenheimer et al. 'ShareVR: Enabling Co-Located Experiences for Virtual Reality between HMD and Non-HMD Users'. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. New York, NY, USA: Association for Computing Machinery, May 2017, pp. 4021–4033. DOI: 10.1145/3025453.3025683. (Visited on 03/16/2022) (cited on page 125).

[190] Ohan Oda et al. 'Virtual Replicas for Remote Assistance in Virtual and Augmented Reality'. In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15. New York, NY, USA: Association for Computing Machinery, Nov. 2015, pp. 405–415. DOI: 10.1145/2807442.2807497. (Visited on 03/16/2022) (cited on page 125).

[191] Daniela Mitterberger et al. 'Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-site Robotic Plastering'. In: *CHI Conference on Human Factors in Computing Systems*. CHI '22. New York, NY, USA: Association for Computing Machinery, Apr. 2022, pp. 1–18. DOI: 10.1145/3491102.3501842. (Visited on 05/02/2022) (cited on page 125).

[192] Eric Rosen et al. 'Communicating Robot Arm Motion Intent Through Mixed Reality Head-Mounted Displays'. en. In: *Robotics Research*. Ed. by Nancy M. Amato et al. Springer Proceedings in Advanced Robotics. Cham: Springer International Publishing, 2020, pp. 301–316. DOI: 10.1007/978-3-030-28619-4_26 (cited on page 144).

[193] J. M. Huang, S. K. Ong, and A. Y. C. Nee. 'Real-time finite element structural analysis in augmented reality'. en. In: *Advances in Engineering Software* 87 (Sept. 2015), pp. 43–56. DOI: 10.1016/j.advengsoft.2015.04.014. (Visited on 12/15/2022) (cited on page 144).

[194] *Litho*. URL: https://www.litho.cc/ (visited on 01/23/2023) (cited on page 145).

[195] Facebook. *Inside Facebook Reality Labs: Wrist-based interaction for the next computing platform*. URL: https://tech.facebook.com/reality-labs/2021/3/inside-facebook-reality-labs-wrist-based-interaction-for-the-next-computing-platform/ (visited on 01/23/2023) (cited on page 145).

[196] Pauline Maurice et al. 'Human movement and ergonomics: An industry-oriented dataset for collaborative robotics'. en. In: *The International Journal of Robotics Research* 38.14 (Dec. 2019), pp. 1529–1537. DOI: 10.1177/0278364919882089. (Visited on 01/27/2023) (cited on page 146).

[197] *AnDy - suit*. URL: https://andy-project.eu/ (visited on 01/27/2023) (cited on page 146).

[198] Inés Ariza et al. 'In place detailing: Combining 3D printing and robotic assembly'. In: *Recalibration on Imprecision and Infidelity - Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture, ACADIA 2018*. Issue: October. 2018, pp. 312–321 (cited on page 151).

[199] Harald Kloft et al. 'Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP)'. en. In: *Cement and Concrete Research* 134 (Aug. 2020), p. 106078. DOI: 10.1016/j.cemconres.2020.106078. (Visited on 02/21/2023) (cited on page 151).

[200] Apolinarska, Aleksandra Anna, Bärtschi, Ralph, and Furrer, Reto. *Advances in Architectural Geometry 2015 - Mastering the Sequential Roof: Computational Methods for Integrating Design, Structural Analysis, and Robotic Fabrication*. en. vdf Hochschulverlag AG an der ETH Zürich, 2016. (Visited on 02/06/2023) (cited on page 151).

[201] Patrik Lindenfors. *For Whose Benefit?: The Biological and Cultural Evolution of Human Cooperation*. en. Cham: Springer International Publishing, 2017. (Visited on 02/06/2023) (cited on page 153).

[202] David C. Queller. 'Cooperators Since Life Began *The Major Transitions in Evolution.* John Maynard Smith , Eors Szathmary'. en. In: *The Quarterly Review of Biology* 72.2 (June 1997), pp. 184–188. DOI: 10.1086/419766. (Visited on 02/06/2023) (cited on page 153).

[203] Mica R. Endsley, Betty Bolte, and Debra G. Jones. *Designing for Situation Awareness: An Approach to User-Centered Design*. London: CRC Press, July 2003 (cited on page 154).

[204] Scott A. Green et al. 'Human-Robot Collaboration: A Literature Review and Augmented Reality Approach in Design'. en. In: *International Journal of Advanced Robotic Systems* 5.1 (Mar. 2008). Publisher: SAGE Publications, p. 1. DOI: 10.5772/5664. (Visited on 10/24/2022) (cited on page 154).

[205] Jane Shi and Roland Menassa. 'Transitional or partnership human and robot collaboration for automotive assembly'. In: *Proceedings of the 10th Performance Metrics for Intelligent Systems Workshop*. PerMIS '10. New York, NY, USA: Association for Computing Machinery, Sept. 2010, pp. 187–194. DOI: 10.1145/2377576.2377611. (Visited on 10/24/2022) (cited on page 155).

[206] Nicole C. Karafyllis, ed. *Biofakte: Versuch über den Menschen zwischen Artefakt und Lebewesen*. OCLC: ocm61714530. Paderborn: Mentis, 2003 (cited on page 157).

[207] Jens Hauser. 'Art Between Synthetic Biology and Biohacking: Searching for Media Adequacy in the Epistemological Turn.' In: *Leonardo Electronic Almanac 22* 1 (2017) (cited on page 157).

[208] Eduard Georges Groutars et al. 'Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Color Interfaces'. en. In: *CHI Conference on Human Factors in Computing Systems*. New Orleans LA USA: ACM, Apr. 2022, pp. 1–19. DOI: 10.1145/3491102.3517713. (Visited on 08/05/2022) (cited on page 157).

[209] Humberto R. Maturana and Francisco J. Varela. *Autopoiesis and Cognition: The Realization of the Living*. en. Vol. 42. Boston Studies in the Philosophy and History of Science. Dordrecht: Springer Netherlands, 1980. (Visited on 08/05/2022) (cited on page 160).

[210] Philip Beesley et al., eds. *Hylozoic ground: liminal responsive architecture: Philip Beesley*. First edition. OCLC: ocn640342655. Cambridge, Ont.: Riverside Architectural Press, 2010 (cited on page 160).

[211] Karen Michelle Barad. *Meeting the universe halfway: quantum physics and the entanglement of matter and meaning*. OCLC: ocm71189745. Durham: Duke University Press, 2007 (cited on page 160).

[212] Jens Hauser and Lucie Strecker. 'On Microperformativity'. en. In: *Performance Research* 25.3 (Apr. 2020), pp. 1–7. DOI: 10.1080/13528165.2020.1807739. (Visited on 08/05/2022) (cited on page 160).

[213] Gary Charness, Uri Gneezy, and Michael A. Kuhn. 'Experimental methods: Between-subject and within-subject design'. en. In: *Journal of Economic Behavior & Organization* 81.1 (Jan. 2012), pp. 1–8. DOI: 10.1016/j.jebo.2011.08.009. (Visited on 02/06/2023) (cited on pages 168, 170).

[214] David Lindlbauer et al. 'Influence of Display Transparency on Background Awareness and Task Performance'. en. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. San Jose California USA: ACM, May 2016, pp. 1705–1716. DOI: 10.1145/2858036.2858453. (Visited on 02/06/2023) (cited on page 171).

[215] Harry Braverman. *Labor and monopoly capital: the degradation of work in the twentieth century*. eng. 25th anniversary ed. OCLC: 823170284. New York: Monthly Review Press, 1998 (cited on page 195).

[216] Richard Sennett. *The craftsman*. Tech. rep. Publication Title: Opera News Volume: 73 Issue: 3 ISSN: 00303607. 2008, p. 38 (cited on page 195).

[217] John Beebe and Ernst Falzeder, eds. *The question of psychological types: the correspondence of C. G. Jung and Hans Schmid-Guisan, 1915-1916*. Philemon series. Princeton: Princeton University Press, 2013 (cited on page 196).

[218] Joseph Beuys et al. *Joseph Beuys - Intuition! Dimensionen des Frühwerks von Joseph Beuys, 1946-1961 = dimensions of the early work of Joseph Beuys, 1946-1961*. eng ger. Ed. by Susanne Figner. First edition. Schriftenreihe Museum Kurhaus Kleve - Ewald-Mataré-Sammlung Nr. 82. Göttingen: Steidl, 2022 (cited on page 196).

[219] Glenn Adamson, ed. *The craft reader*. eng. London New York Oxford New Delhi Sydney: Bloomsbury Visual Arts, 2018 (cited on page 196).

[220] Benjamin B. Beck. *Animal tool behavior: the use and manufacture of tools by animals*. Garland series in ethology. New York: Garland STPM Pub, 1980 (cited on page 197).

[221] Robert W. Shumaker, Kristina R. Walkup, and Benjamin B. Beck. *Animal tool behavior: the use and manufacture of tools by animals*. Rev. and updated ed. OCLC: ocn637707314. Baltimore: Johns Hopkins University Press, 2011 (cited on page 197).

Glossary

A

AEC architecture, engineering and construction. 3–5, 9, 13, 18, 21, 23, 24, 29, 42, 64, 65, 85, 97–99, 124, 125, 137, 140, 142, 143, 151

API application programming interface. 18, 45

AR augmented reality. 5, 11, 17, 18, 20, 24–26, 29, 38, 39, 42–50, 52–56, 60, 65, 66, 68, 69, 78, 86, 89, 94, 98, 100, 103, 105, 108–111, 113–116, 120, 121, 125, 133, 138–140, 144, 145, 153, 167, 168, 170, 174, 175, 198–200

C

craftsperson Craftsperson is a human worker who skillfully manipulates the tools and materials of a craft or trade. In a text from the "International Molders Journal", craftsmanship is described as something additional to manual skill and dexterity[215]. It is the intimate knowledge of the character and usage of the tools, the materials, and the process of craft instilled by experience and tradition. This knowledge enables the craftsperson to intuitively understand a process and constantly overcome new fabrication difficulties, whether they be tool-based, material-based, or related to work conditions. Furthermore, there is a distinction between "craft knowledge" and "craft skill". Craft skill relates to specific pieces of practical knowledge within a craft. In contrast, craft knowledge is the tacit knowledge that craftspeople develop through experience, the process of reflection, and practical problem-solving while executing their craft (refer to [52, 216]). 13, 15, 16, 22, 23

CSCW computer-supported cooperative work. 124

CVE collaborative virtual environment. 124, 125

D

device A device is a machine or tool used for a specific task and mostly describes a piece of mechanical or electronic equipment such as desktops, laptops, tablets, smartphones, etc. 11, 16–18, 20

E

ERC extended reality collaboration. 123–126, 131, 132

F

feedback Feedback refers to the transmission of information from the receiver of a message back to the sender of that message. 4, 20, 22–24

H

HCI human-computer interaction. 4, 18

HMC human-machine collaboration. 4, 5, 18, 29, 137

HMD head-mounted display. 18, 24, 29, 31, 53, 68, 125, 139

HMD-AR head-mounted augmented reality device. 48, 139, 140, 144, 167–171, 175, 176, 201

human-instructed machine fabrication Human-instructed machine fabrication refers to a design and fabrication system in which a human offers input, and the machine responds with physical feedback. This system allows for direct adjustment of the physical outcome during manufacturing. 19

I

intuition Intuition is an information processing procedure we can not explicitly decode. Carl Jung describes intuition in 1916 in "Psychological Types" as an "irrational function" and as a "perception via the unconscious". According to Jung, intuition gives outlook and insight, and its process is mostly based on the unconscious. As everyday situations are mostly too complex to decode logically, we outsource the solution to our subconscious. Therefore, intuition aims to reveal ideas, images, solutions, and possibilities to unblock and solve such difficult situations. As Jung describes it, the solution our subconscious provides can come from data and information we receive from the situation itself mixed with experience or from within the human. Nietzsche and Beuys introduce the concept of intuition as a creative means of generating knowledge. According to Beuys, intuition is not confined in the same way that rule-driven, logical reasoning is; rather, it is a method to holistically comprehend the potentials of material, atmospheric, and spiritual worlds. (refer to [217, 218]). 18

IRoP interactive robotic plastering. 63, 65, 67, 69, 70, 76, 78, 81–87, 100, 125, 199

M

machine A machine is a physical system that uses natural, chemical, thermal or electrical power to perform an action, apply forces or control movement. Some sources delineate that a clear difference between tools and machines is that, in the first case, the human is the power source. In the second case, a motive power such as an animal, water, electricity, and so on is used. All machinery consists of three distinct parts, a motor mechanism, a transmitting system, and finally, a tool or working machine (refer to [219]). 3–5, 8–16, 18, 20–26

machine-assisted human fabrication Machine-assisted human fabrication is a system in which a machine gives a user instructions for a given manual manipulation task via an interface. This allows for a direct connection between a digital model and the users, who execute the task manually. 16

MR mixed reality. 5, 18, 125–129, 131, 132, 200, 201

P

PbD programming by demonstration. 67

R

research through design Research through design is a research approach that takes advantage of the unique insights gained through the design practice to provide a better understanding of complex issues in the design field. 29

robot A robot is a machine capable of carrying out a complex series of programmable physical actions. 4, 16, 20, 22

T

tacit knowledge Tacit or implicit knowledge is difficult to transmit, as it can not be verbalised. It can be defined as a skill, talent, idea, or creativity that a person learns over time or inherits. Explicit knowledge, in contrast, is the knowledge that can be logically written down and verbalised (refer to [27]). 3, 5, 8, 13, 15, 23, 24

tool There are physical and digital tools. A physical tool is an external employment of an unattached or manipulable attached environmental object that extends a person's ability to alter features of the environment, change the form, position, or condition of another object, or perform a specific task. The user of the tool holds and directly manipulates the tool during or before its use and changes the direction and orientation of the tool (refer to [220, 221]). A digital tool describes software, programs and applications that can be used with digital devices (computers, mobile devices, etc.) and provides multisensory stimuli (audio, visual, tactile, etc.). 9, 11, 14

U

UI user interface. 18–20, 22, 24, 25, 39, 42, 45, 47, 48, 51, 52, 54, 64, 66, 76–78, 89, 129, 138, 141, 145, 198

user interface In computing, an interface is a shared boundary of two or more individual computer systems or components that exchange information. The interaction can be between software, hardware, sensor systems, humans, other biological systems, and any combination thereof. This interface can be a hardware device such as a touchscreen, which can send and receive data as an interface, or a mouse or microphone, which can send data to the desired system. Some interfaces can translate data into a readable format so the user can understand the data. The user interface is specifically for humans to interact with machines and includes many different modes of interaction, such as visual, audible, positional, or movement-based interaction. Any interaction applies as long as it transfers data between a user and a computer system. 12

V

VR virtual reality. 5, 11, 74, 120, 121, 125–133, 139, 140, 200, 201

X

XR extended reality. 5, 22, 24, 29, 31, 102, 129, 138, 141, 144

List of Figures

1.1 Examples of embodied cognition, tacit knowledge and dexterity of humans . . . 9
1.2 Examples of reproducibility, precision and physical strength of machines 9
1.3 Stelarc's *Third Hand* is an art piece where electrical signals of other muscle groups, such as the abdominal and leg muscles, control the motions of the third artificial hand. © Simon Hunter 10
1.4 Wendy Carlos at her Moog Electronic Music Synthesiser (1969). Left is an 8-track recorder that tapes directly from the Synthesiser's output, and above the Synthesiser keyboards are the circuits, which can be interconnected to generate tones with desired qualities. [46] 12
1.5 Tyrolian Krampus mask by Franz Oberschneider © Wanderhotels 14
1.6 Examples of physical augmentation for more precise manual fabrication 17
1.7 Examples of human cognitive augmentation to support complex manual fabrication 17
1.8 Examples of interactive fabrication projects using physical objects and spatial input as a tangible UI 19
1.9 Examples of different interactive fabrication processes 19
1.10 Diagram visualising the applied methodology. 28

2.1 Diagram visualising the four research streams: (a) digital twin, (b) visual feedback system, (c) cooperative building workflows, (d) interaction modalities 30
2.2 Process digital twins have the potential to synchronise the design and fabrication space. 30
2.3 On-body and on-environment augmentation 32

3.1 Diagram visualising the applied methodology for Augmented Bricklaying: (a) context-aware computational model, (b) screen-based AR, (c) manual fabrication, (d) object tracking 38
3.2 Katerini Winery (2019): biggest brick-structure constructed to date using augmented reality guidance 43
3.3 Gantenbein winery facade (2006): fully robotically fabricated winery 44
3.4 Custom-built AR setup: operator, bricklayer, handheld camera and IMU (1), portable sensory-input device (2), WIFI connection (3), calculation laptop (4), debugging and visualisation laptop (5), mounted screen (6) 46
3.5 Full setup in operation: The bricklayer adjusts the bricks whilst the operator registers the current brick in relation to the neighbouring bricks and global objects of reference (concrete frame, struts) 47
3.6 Craft-specific UI: arrows indicate location and strength of the knocking to reposition the bricks (2). Bricks are indicated according to layer and brick-index per layer (1). Symbols show the mortar amount per brick (3). Frame rate is indicated in the corner of the screen, informing the operator about light conditions (4) 48
3.7 Diagram and pictures of the on-site setup 49
3.8 Design articulation of Kitrus winery 50
3.9 Global objects of reference (green) need to be precisely measured and digitised beforehand 51

3.10 User performance analysis and learning curve 52
3.11 Kitrus winery façade: The individual rotation of each brick correlates to the amount of mortar underneath 53
3.12 The design of the semi-transparent façade reflects the idea of a constantly changing pattern resembling the shimmering light of liquid 55
3.13 Design adjustments are made on-site to update the digital model to inform the AR interface. 56
3.14 Augmented Bricklaying setup with one operator and one mason. 56
3.15 Masons are evaluating the recently finished wall element. 57
3.16 The finished building has a changing shadow pattern on the facade depending on lighting conditions. 57
3.17 Diagram visualising the applied methodology for Interactive Robotic Plastering: (a) context-aware and interactive computational model, (b) projection-based AR, (c) robotic fabrication, (d) controller tracking and surface scanning 60
3.18 Left: (1) Manual spraying of the material (2) and smoothing, levelling or shaping with additional tools. Right: Robotic Plaster Spraying, an adaptive thin-layer printing technique, builds a volumetric formation without any additional formwork or support structures. 68
3.19 The design and fabrication workflow designed around three key modes. 69
3.20 System architecture: computational setup (1a, b), the user interaction-tracking system with projection mapping (2a-d), robotic fabrication setup (3a-d) 70
3.21 (A) Selection of filter (B) localisation (C) designing, adjusting the design (D) robotic spraying. 71
3.22 User interaction-tracking system including visualisation computer (1a), *ROS* master (1b), *VIVE* tracking system (2a), controller (2b), projection mapping (2c), projector (2d); Right: Robotic fabrication setup including *UR10* robotic arm (3a), spray gun (3b), controller box (3c), pump (3d), external axis (3e). 73
3.23 Translation of human input to robotic trajectories via interpolation and remapping of gesture input data to fabrication output data: $P \to T$; $D \to E_d$; $V_h \to V$ 74
3.24 The remapping of the distance value D translates into specific plaster effects as a smaller D results in a smaller E_d leading to a carving effect. 75
3.25 Screen recordings of the different interaction modes: Localize (Step 1); Design (Step 2); Adjust (Step 3). 76
3.26 On-site projection mapping of Design step (Step 2): Interface shows fabrication parameters such as information on current (1) interaction mode, (2) robot reach from a stationary position, (3) distance of frames to the wall surface, and (4) the number of sprayed layers. 77
3.27 Audio-visual guided fabrication workflow. 78
3.28 Experimental setup showing the design and fabrication routine. 79
3.29 Different filter systems and their distinct translation of human input to machine output. 80
3.30 Interior space fabricated solely by using *IRoP*. 81
3.31 Results of user-study 1: designer and user-study 2: skilled worker. 84
3.32 Wall detail showing the aesthetic qualities of *IRoP* 87
3.33 Details of the wall elements showcasing results of micro-gestures. 88

3.34 Diagram visualising the applied methodology for *Tie a Knot*: (a) context-aware and interactive computational model, (b) phone-based AR, (c) manual and robotic fabrication, (d) object tracking and manual probing 94
3.35 Cooperative assembly scenario by human-robot teams 99
3.36 Overview cooperative assembly cycle, consisting of five main components (A) interactive design, (B) robotic assembly, (C) manual assembly, (D) rope jointing, (E) tracking of elements 101
3.37 Proof-of-concept prototype to test the system's design principles and workflow. . 102
3.38 Turn-taking task distribution between humans and robots 103
3.39 Reciprocal space frame structure from interlocking struts, referred to as Y-triplet. 104
3.40 *God's Eye* rope joint. 104
3.41 System walkthrough: (A) interactive design, (B) robotic, (C) manual, and (D) rope joint placement (E1) tracking with the phone, (E2) tracking with the robot 106
3.42 The user interface of the interactive design model provides input controls for selecting a starting element for a new triplet and defining the triplet's rotation angle via a number slider 107
3.43 Time-lapse recordings of assembly and disassembly of the experimental prototype. 108
3.44 Hardware setup of the system. (A) Linux computer, (B) CAD computer, (C) mobile AR device, (D) QR-codes, (E) adjustable 3D printed feet, (F) zip-ties, (G) wooden struts, (H) wool, (I) robot 1, (J) robot 2, (K) mobile platform, (L) timber strut pick-up station, (M) pneumatic parallel gripper with custom 3D printed gripper fingers, and (N) measured-in fix points (QR codes). 110
3.45 Communication workflow diagram showing the system setup consisting of 1) a computer with a CAD design environment, 2) a mobile AR app, and 3) a robotic unit 111
3.46 Screenshot of the digital model showing in blue the robotically placed elements and in yellow the manually placed elements 112
3.47 Different tracking results of manually placed elements: orange: tracked with the AR-capable phone, red: tracked with the robot. 113
3.48 The colour gradient (red for translation (a) and blue for rotation (b)) visualises the deviation between the tracking results of the AR app with those from the measurement executed with the robot. 114
3.49 Diagram visualising the applied methodology for Extended Reality Collaboration: (a) context-aware, interactive and collaborative computational model, (b) AR Headset, VR Headset, (c) manual fabrication, (d) controller tracking, hand tracking and spatial tracking 120
3.50 User scenario showing the on- and off-site scenario with two distinct stakeholders 126
3.51 System walkthrough. 127
3.52 3D sketch and annotation feature. On the left is a first-person view of the MR-User watching the VR-User sketch. On the right side is a third-person view of the MR and VR-User drawing collaboratively within the VR space. 128
3.53 Collaborative design on-the-fly feature. On the left is a first-person view of a hologram of the design on the installation site. On the right side is a third-person camera view of the MR and VR-User discussing the design in VR. 128
3.54 A menu informing the MR-User about fabrication parameters and the holographic 3D model supporting fabrication. 128

3.55 Fabrication supervision feature. On the left is a first-person view of the MR-User looking at the VR-User. On the right side is a third-person camera view of the MR and VR-User discussing the fabrication in VR. The different coloured elements show the different fabrication sessions. 128
3.56 System architecture 129
3.57 Left: The MR-User interacts via hand tracking (A), gesture tracking (B), menu buttons(C), and voice commands (D). The MR-User sees an info window superimposed over their view (E). Right: The VR-User navigates the space and interacts via controllers (A) using controller buttons (B) and virtual menu buttons (C). The VR-User sees an info screen (D)and moves within a digital twin of the construction site (E). 130
3.58 Various and complex parameters that can be exchanged with the system 130
3.59 Computational attractor-based design logic and remapping values to determine sticky note position, rotation, folding size, and colour 130
3.60 Photograph of the fabrication of the final physical installation. 131
3.61 Photograph of the final physical installation. 133

4.1 Examples of different wearable devices 145

A.1 Sequential Roof (photo by Gramazio Kohler Research). 151
A.2 Spatial Timber Assemblies (photo by Gramazio Kohler Research). 152
A.3 CROW: Collaborative Robotic Workbench (photo by ICD University of Stuttgart). 153
A.4 Lift assist device for rolls of metallic banding (photo by Dalmec). 154

B.1 Responsive environments were reacting to human presence and behaviour. . . . 157
B.2 ECo is an enclosed environment hosting Escherichia Coli bacteria. 158
B.3 SuCr is an enclosed environment hosting Sucrofermentas bacteria and microbial biomass production. 159
B.4 Interaction diagram. 160
B.5 CyA environment with Cyanobacteria reacting to different light stimuli. 162
B.6 Eye-tracking device (prototype 1) detects the gaze direction and position of the visitor. 162
B.7 Image showing a typical interaction of a visitor with the ECo environment. Visualisation projected onto the back wall shows the ego perspective of the visitor. . . . 163
B.8 SuCr enclosed environment and supplementary microbial prototypes. 163

C.1 On the left, participants were presented with the setup before starting. On the right is the desired outcome. 170
C.2 Reaction of the novices to the HMD-AR interface. 171
C.3 Reaction of unassisted and assisted novices to the system. 172
C.4 Final indoor acoustic walls 173
C.5 visualised questionnaires' results. 174
C.6 When asked if the system could be used by novices, this is how the users answered: left side: experienced; right side: untrained and assisted 176

List of Tables

3.1 Table showing the key remapping parameters 75
3.2 Relation between QR Code placement and visibility and drift of the digital model. The QR code dimensions were 12.5cm x 12.5cm. 132

C.1 An example of the questionnaire's item. 169

This dissertation is designed and typeset by the author using LaTeX and printed with OK DigitalDruck AG in Zurich on Rebello matt, 100% FSC recycled paper. All images by the author unless stated otherwise. The cover is designed by Hannes Mitterberger.

Augmented Human and Extended Machine: Adaptive Digital Fabrication and Human-machine Collaboration for Architecture — by Daniela Mitterberger

This research aims to establish adaptive digital fabrication processes that include human-machine collaboration in digital fabrication. In the past two decades, digital fabrication in architecture engineering and construction (AEC) has significantly advanced, enabling more complex, customised, and precise fabrication results. Even though most digital fabrication processes aim for full automation, they still require human participation for either material deposition, quality control, or finishing. While humans are still needed, current digital fabrication processes are not adaptive enough to include humans in the digital control logic. This inflexibility limits the robustness and autonomy of digital fabrication and its applicability in areas that are more difficult to automate, such as on-site fabrication or fabrication with more complex material systems.
Therefore, this doctoral research aims to include human actions and decision-making in digital fabrication processes. This combination of human tacit knowledge and dexterity with the precision and endurance of machines has the potential to increase the productivity, adaptability and robustness of digital fabrication. To facilitate human-machine collaboration, this research establishes more adaptive digital fabrication processes, linking digital models with physical fabrication environments.
For this, digital twins are developed to efficiently control and capture data from the entire fabrication process and all its components. These digital twins are linked with extended-reality interfaces, actuators and tracking systems to inform and track humans and machines during fabrication. The research results are obtained through physical experiments and four proof-of-concept case studies investigating various aspects of human-machine collaboration in architecture and digital fabrication. By solving practical and methodological challenges, this research demonstrates how human-machine collaboration supports a faster and more sustainable integration of digital fabrication in AEC. Furthermore, this thesis illustrates the aesthetic and technological benefits of such collaborative systems, as well as their potential to expand our repertoire of digital fabrication workflows.