Rethinking Digital A collaborative machines and

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and Kathrin Dörfler

construction
future of humans, craft

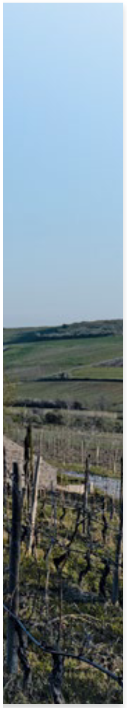
Gramazio Kohler Research and the Technical University of Munich (TUM) Professorship of Digital Fabrication, Tie a Knot, 2022

Tie a Knot examines the potential of 'open-ended design' in a digital fabrication workflow. Humans can adjust the design of the structure on the fly, enabling a fast and intuitive interaction with a computational setup.

Gramazio Kohler Research,
Augmented Bricklaying,
Kitrvs winery,
Kitros, Greece,
2019

above: The geometry of the façade evokes the illusion of three-dimensional waves, computationally designed to gracefully symbolise the fluidity of wine, as well as mirroring the meandering contours of the nearby valley. Every brick, individually positioned and rotated, owes its precision to the augmented-reality (AR) system, enabling bricklayers to execute their craft with high accuracy and differentiation.

right: A camera sensor is capable of registering and tracking the exact location of bricks in 3D space. This spatial information is directly translated into craft-specific visual instructions – in this case, where and with how much force to tap a brick into its exact location.



The vast majority of construction industry processes are labour intensive, and often fraught with errors due to non-exact assembly tolerances and dimensions. Digital fabrication can mitigate or remove the potential of these anomalies occurring by negating or reducing human site-participation. But there is another side to the digital fabrication coin – the transition to more automated processes will liberate humans to become more collaborative and creative with machines both virtual and actual. **Daniela Mitterberger**, an Assistant Professor at Princeton University School of Architecture, and **Kathrin Dörfler**, Assistant Professor of Digital Fabrication at the Department of Architecture at the Technical University of Munich, highlight the evolving advantages of these new relationships.

The construction sector is on the verge of a transformation, driven by the possibilities of digital fabrication. They create aspirations for a future where fully automated construction processes replace manual labour, enhancing precision and quality in construction workflows. Yet these aspirations often overlook the technology's potential to empower human skills and foster meaningful collaboration between humans and machines.

Conventional narratives surrounding human–machine interaction often operate under the assumption that increasing machine autonomy leads to decreased human involvement. Research efforts frequently reflect this bias, aiming to minimise human intervention through ever more autonomous machines, but a compelling alternative also exists – a positive correlation between autonomy and collaboration. To achieve such a synergy, we require highly autonomous machines capable of comprehending and adapting to their surroundings.[1] Such robots, devices and algorithms are the foundation for interactive digital workflows that augment human actions and expand creative possibilities for shaping the built environment. By enabling machines to learn from the vast repository of human knowledge while fostering natural human–robot interaction, we could augment human skills and find novel and unexpected ways to seamlessly integrate human craft into digital construction processes.

A reimagined relationship between builders, materials, tools and technologies could help to realise what the interdisciplinary theorist María Puig de la Bellacasa calls technoscientific futurity,[2] which would facilitate a sustainable building future. This futurity does not overlook the contextual aspects of construction labour, physical exertion and cultural dependencies. Rather, in that setting, builders and craftspeople exemplify new ways of relating to materials, tools, buildings and architecture, that are enabled by emerging technology but that also cultivate the sociocultural dimensions of craft.

Presented here are four distinct architectural projects and experiments involving Gramazio Kohler Research and the Technical University of Munich (TUM) Professorship of Digital Fabrication, separately or in collaboration, all of which illustrate this new relationship between craft and digital construction technology, with each project exploring how to effectively centre builders and craftspeople within digitally supported building workflows. The projects consistently incentivise human engagement and present diverse opportunities for collaboration between human and computational intelligence.

Digitally Augmented Craftspeople

Craft, in its essence, is the skilful manual creation of objects, embodying artistic creativity and personal engagement. Craftspeople engage with physical materials, tools and processes, where tacit knowledge, an experiential understanding, is acquired and cultivated over long periods of time. This type of knowledge forms the core of what sociologist Richard Sennett discusses in his 2008 book *The Craftsman*, where he explores the concept of material awareness and how craftspeople gradually 'become the thing on which they are working'.[3] Merging craft sensibilities and practices with computational strategies and new making technologies therefore requires a fostering of active human engagement with the very materials in question.[4]

Augmented Bricklaying (2019) is a building project commissioned by Gramazio Kohler Research, in which the traditional craft of masonry was digitally enhanced for the assembly of the intricate, geometrically differentiated brickwork façade of the Kitrvs winery in Greece.[5] The project employed an ecosystem of digital tools, including visual sensors and augmented-reality (AR) interfaces, to elevate the expertise of masons in brickwork. A custom-developed AR guidance system enabled local Greek bricklayers to carry out a millimetre-precise assembly of 225 square metres (2,422 square feet) of fair-faced brick façade according to a 3D model, consisting of 13,596 individually rotated and tilted bricks. These digital tools inherently build on traditional masonry skills and principles, particularly the tacit knowledge of handling mortar and mortar joints, the dexterity required for bricklaying, and the flexibility and adaptability to handle malleable materials. In return, the intricate human craft skills are enhanced by the AR visual guidance system providing real-time three-dimensional accuracy and a direct link to the digital model, guiding the brick-and-mortar placement. To date, it is the largest project that has been built on site using an AR interface, merging digital technology with traditional artisanship in an entirely new construction process.

The Augmented Bricklaying guidance system combines a sensor system integrating an object-based tracking feature with a visualisation setup providing a craft-specific user interface. The sensor system facilitated highly accurate real-time tracking of individual objects, specifically bricks, in three-dimensional space.[6] Leveraging this spatial information – the precise locations of the bricks – the craft-specific user interface provided detailed visual guidance for specific masonry actions in real time. This involved guiding various bricklaying activities, such as carefully knocking the brick into the mortar at intended precise locations or applying mortar, using real-time visual cues derived from a digital model.

These dynamically generated instructions enabled the bricklayers to intuitively understand where to place the bricks in 3D space in correlation with a computer model.

The augmentation system was developed in collaboration with experienced bricklayers and proved exceptionally interactive and intuitive after an initial learning phase. When used in the real construction-site environment, it seamlessly establishes a direct link between the digital design environment, the skilled masons and the digital construction process. As a result, the system and the architectural outcome of this façade achieved a level of precision that surpasses conventional AR representations and is comparable to production by digitally controlled machines, but with a distinct and unmistakable human touch.

New Robot Collaborators

Along with elevating skills, there is also a need to mitigate physical challenges for builders and fabricators while keeping them cognitively engaged. With this concern in mind, the TUM Professorship of Digital Fabrication project Diversifying Construction (2023) looked into enhancing craftspeople through robots, exploring how robots can best support and collaborate with craftspeople skilled in masonry and bricklaying in the process of brickwork construction.[7] The aim was to have craftspeople and robots share tasks, combining their complementary abilities – human cognitive skills, versatility, fine motor skills and the robot's precision and endurance. The research further explored how such a sensible task distribution could contribute to the physical relief of construction labourers while retaining their physical engagement, tactile sense of the physical construction environment, decision-making and agency.

Designed to work safely alongside humans in shared workspaces, collaborative robots are built with lightweight materials, designed with rounded shapes and incorporate sensory systems for measuring and limiting force when needed. For this research project, a distinct workflow was set up between a skilled mason and a collaborative robot, intended to take turns performing physical tasks necessary to construct a brickwork structure. The bricks are assembled into their precise locations according to a given digital model by the robot, relieving the mason from measurement operations and repetitive lifting and assembly tasks. Manual application is used for the mortar, the malleable material that ensures the brick bond, accommodates material inaccuracies and enables the force transmission between the bricks. The bricklayer places the mortar beds, gently knocks bricks into them, cleans the mortar joints and triggers successive robot tasks.

left: The bricklayer is checking whether the brick is levelled correctly after the robot has placed it. Here, the transdisciplinary research approach – the testing and evaluation procedures with professionals – generated a spectrum of imaginations for how a collaborative robot might, or might not, be appropriately used, and whether or not it proves useful in certain tasks and scenarios.

Technical University of Munich (TUM) Professorship of Digital Fabrication, Diversifying Construction, 2023
left: The workflow tested with a professional bricklayer was concerned with the deliberate distribution of tasks, with the collaborating robot placing bricks based on a digital design model, and the bricklayer handling mortar application, refining brick placement, cleaning mortar joints and triggering robot tasks.

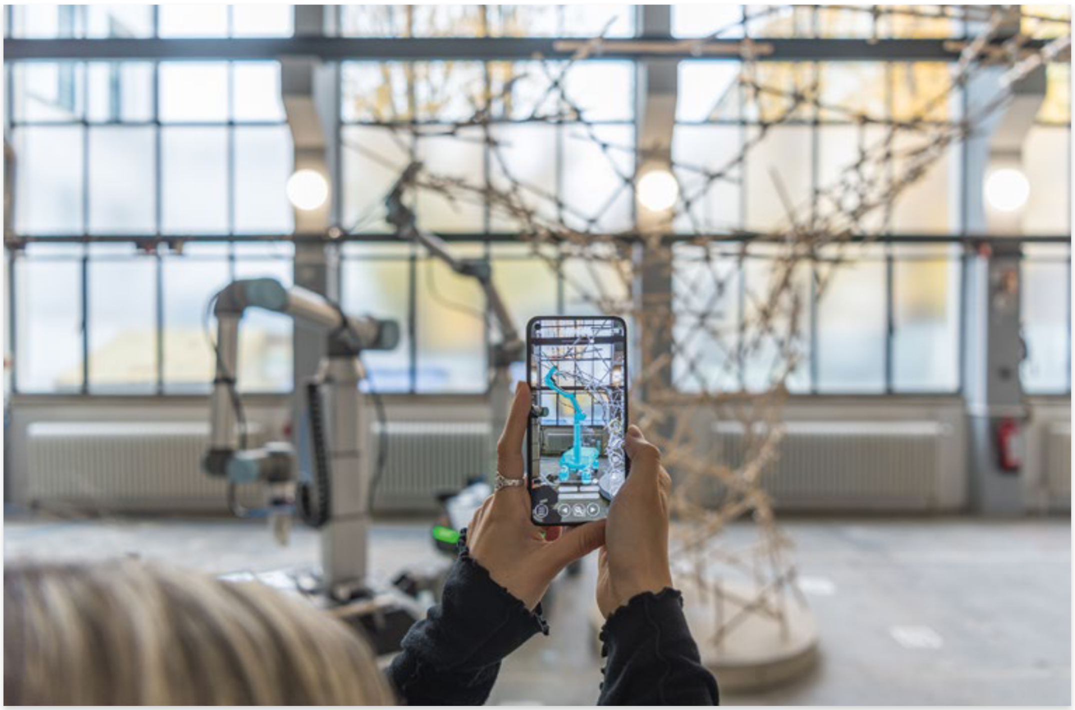
Gramazio Kohler Research and the Technical University of Munich (TUM) Professorship of Digital Fabrication, Tie a Knot, 2022
above: The Tie a Knot project provides a cooperative workspace for two mobile robots and two humans. While robots are used to place precise elements and stabilise the structure, humans are used to tie rope joints and assemble intricate wooden elements.

Gramazio Kohler Research and the Technical University of Munich (TUM) Professorship of Digital Fabrication, Collaborative Augmented Assembly, 2023
opposite: The project uses a phone-based augmented-reality app to enable intuitive task sharing between humans and robots.

The Human Element in Hybrid Construction

Preserving the multifaceted nuances of construction also involves integrating low-tech manual operations with high-tech digital fabrication processes – a concept examined through the collaborative project Tie a Knot (2022).[8] This project provides a cooperative workflow in which two mobile robots and two humans collectively assemble an intricate timber structure within a shared digital-physical workspace. The design encompassed a spatial reciprocal frame structure made of cylindrical wooden rods positioned in 3D space, supported only by mutual interlocking and tied together by knots with a soft rope.

In this context, robots carry out the precise placement and temporary stabilisation of the timber rods, crucial for high spatial accuracy. Simultaneously, humans undertake the intricate crafting of traditional rope joints, which demands a high level of dexterity.

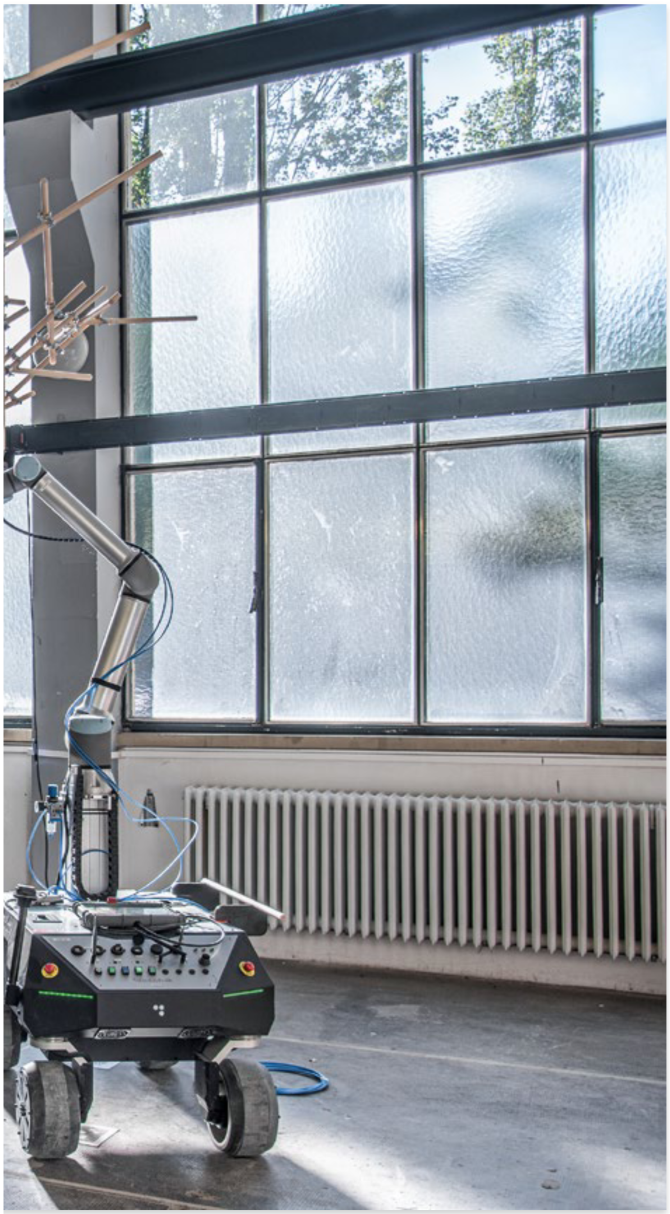


Increasing creative engagement, humans were able to initiate assembly cycles, and these cycles were subsequently brought to completion with the support of robots. The system, set up with utmost flexibility and adaptability, allows humans to manually position timber rods at locations of their choice without a predefined design. Manually placed elements are digitally recorded and integrated into the digital model, based on which robot actions are generated adaptively. As such, the experimental study presents a fascinating human–machine cooperation, facilitating creative design choices and the act of manually joining elements as part of robotic assembly procedures. Here is where the exploration goes beyond mere technical functionalities, investigating pathways into synergistic human–robot cooperation and thereby offering valuable insights for the future integration of such hybrid workflows in the construction domain.

Building upon this concept, another collaborative Gramazio Kohler – TUM project, Collaborative Augmented Assembly (2023), introduces a phone-based mobile AR for humans to interface and seamlessly communicate with their robot collaborators during building construction. The custom-made AR app offers a simple interface for humans, allowing for real-time interaction between a 3D design model and the collaborating robots. It relies on cloud-based communication for information exchange among various mobile devices and robots. As the assembly unfolds, humans can utilise the AR app to preview robot motions, initiate robot actions and obtain detailed and spatially precise assembly instructions for the manual placement of timber rods and the placement of their mechanical connectors. Here again, robotic precision is utilised to place timber rods at strategically important locations. Human workers also play a crucial role, manually placing metal joints that require tightening, which adds a tactile dimension to the assembly process.

Gramazio Kohler Research and the Technical University of Munich (TUM) Professorship of Digital Fabrication, Collaborative Augmented Assembly, 2023

Collaborative Augmented Assembly supports cooperative human–robot fabrication of self-supporting structures.



Collaborative Narratives for Digital Construction

The outcomes of these experiments suggest that there may be room for achieving new processes of collaboration within the bounds of automation narratives for digital construction. While certain aspects of these workflows, such as flexible task distribution and communication fluidity, will require further development and in-depth research, such technological advancements could effectively be harnessed to facilitate future collaborations between humans and machines that improve working conditions, foster human engagement and increase the interactivity of machines. Such collaborations can preserve the multifaceted nuances of construction labour, which encompass cultural heritage, knowledge preservation, human–tool relationships and various individualised craft skills influenced by geographical context, class or gender, while capitalising on technological possibilities such as skill elevation, increased precision, improved repeatability or reduced physical exertion. ⌂

Notes

1. See Jenay M Beer, Arthur Fisk and Wendy Anne Rogers, 'Toward a Framework for Levels of Robot Autonomy in Human-Robot Interaction', *Journal of Human-Robot Interaction* 3 (2), 2014, pp 74–99.
2. See María Puig de la Bellacasa, *Matters of Care: Speculative Ethics in More than Human Worlds*, University of Minnesota Press (Minneapolis, MN), 2017.
3. See Richard Sennett, *The Craftsman*, Yale University Press (New Haven, CT), 2008, p 174.
4. See Terry Knight, 'Craft, Performance, and Grammars', in Ji-Hyun Lee (ed), *Computational Studies on Cultural Variation and Heredity*, Springer (Singapore), 2018, pp 205–24.
5. See Daniela Mitterberger *et al*, 'Augmented Bricklaying: Human–Machine Interaction for In Situ Assembly of Complex Brickwork using Object-Aware Augmented Reality', *Construction Robotics* 4 (3–4), 2020, pp 151–61.
6. See Timothy Sandy and Jonas Buchli, 'Object-Based Visual-Inertial Tracking for Additive Fabrication' *IEEE Robotics and Automation Letters* 3 (3), 2018, pp 1,370–77.
7. See Lidia Atanasova and Kathrin Dörfler, 'Diversifying Construction', in Anh-Link Ngo *et al* (eds), *ARCH+: The Great Repair – Politics of the Repair Society*, ARCH+ (Berlin), 2023, pp 170–71.
8. See Daniela Mitterberger *et al*, 'Tie a Knot: Human–Robot Cooperative Workflow for Assembling Wooden Structures using Rope Joints', *Construction Robotics* 6 (3–4), 2022, pp 277–92.