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EDITORIAL

Editorial CpA #6: Human-Robot Interaction for Carbon-free Architecture

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Abstract

The Spool CpA #6 issue on Human-Robot Interaction for Carbon-free Architecture reviews current tendencies in autonomous construction and human-robotic interaction in architecture. It aims at affirming and/or challenging research agendas in the domain of architectural robots and attempts to answer questions about (i) the fundamental framing of post-carbon autonomous construction, (ii) the interdependencies between machines, humans, and materials, and (iii) the different imple-mentation timeframes ranging from continuous transformation to leapfrogging.

Editorial

The Architecture, Engineering and Construction (AEC) industry is facing a threefold challenge in-volving the (i) digital transformation of all design and planning processes, (ii) automation of construction processes, and (iii) reconsideration of energy, process, and material use. This challenge involves issues of productivity, scalability, safety, labour skill shift, and environmental impact. There is a particular urgency in transferring effective solutions from research to building practice to meet significant carbon reduction goals by 2040.

These questions are addressed by various contributors from TU Delft, Leibniz University Hannover, and the University of Sydney by discussing themes ranging from numerical simulations to experi-mental studies involving mobile and miniaturized robotic approaches, human-robot collaboration, and various robotic building systems.

While Boyle is presenting coordination strategies for swarms of autonomous construction robots using an open-source simulation of abstracted termite-like swarm construction, Sardenberg et al. introduce continuously reconfigurable interlocking modular discrete structures that are assembled by mobile robots. Both explore opportunities in the field of collective robotic construction (CRC) using robots designed in tandem with specific materials and/or building blocks.

On a different trajectory, three contributions focus on approaches using industrial robots for im-plementing various tasks extending from domestic environments to workshop and fabrication sce-narios. Reinhardt and Masuda explore action packages, robot motion, and Human-Robot Collabora-tion (HRC) in domestic environments, while Bier et al. and Aslaminezhad et al. are advancing archi-tectural design to production methodologies based on computational and robotic techniques for architectural applications ranging from smaller to larger scale interventions.

All applications aim to meet current requirements and affordances while integrating sustainable and adaptive functionalities, which is further reflected in the concluding 'Dialog on Architecture' discussing applications presented during the Human-Robot Interaction for Carbon-free Architecture symposium in 2022.

DOI

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An interactive simulation of control and coordination strategies for swarms of autonomous construction robots

Towards a post-carbon re-imagining of the interplay between natural and built environments, facilitated by bio-inspired robotic technology

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Abstract

There is an established idea – found in science fiction, architectural studios, and scientific papers alike – of stainable buildings crafted from bio-based materials, colonized by plant and animal life, and blending seamlessly into the natural surroundings. Such buildings might one day be built, maintained and remodelled by swarms of autonomous robots, allowing them to evolve in response to the changing needs of their inhabitants. Inspired by that vision, this paper contributes to the field of swarm intelligence with a focus on robotic construction and human-swarm interaction. Along with a short literature review on robotic building, swarm intelligence and biocompatible building materials, the paper presents an open-source simulation of abstracted termite-like swarm construction. The focus is mainly on human-swarm interaction, specifically how to influence the emergent behaviour of an autonomous swarm in order to elicit a desired outcome while retaining the robustness and adaptability of a self-organized system. The simulator is used to demonstrate a set of four autonomous swarm behaviours that are representative of construction tasks.

Keywords
Swarm robotics, robotic additive manufacturing, emergent behaviour, computational modelling, termites

DOI

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1 Context

The mainstream construction industry is recognised as being unsustainable, leading to a growing interest in 'green building'. In the short to medium term, the most achievable approaches include the introduction of more sustainable materials, more efficient use of materials, and an emphasis on circularity of material use (Munaro et al., 2020). But other emerging technologies like additive manufacturing (Paolini et al., 2019), robotics and artificial intelligence (Debrah et al., 2022) also have potential to contribute in the longer term. Within robotics, an interesting emerging approach is the use of multi-robot teams or swarms (Dias et al., 2021; Petersen et al., 2019), which gain efficiency through parallelism and robustness through redundancy and self-organisation.

Combining all the above-mentioned approaches, one can envision a future in which buildings are constructed by autonomous robots from natural materials, becoming habitats for plant and animal life and utilizing the associated natural processes to help keep them cool and improve air quality. Construction, maintenance, remodelling and extension could be continuously performed by swarms of robots, influenced by the evolving needs of the building and its inhabitants. As suggested by Wiesenhuetter et al. (2016), the conventional perspective of buildings progressing linearly through design, construction, use and demolition phases could be reframed as an ongoing evolution in which design, construction and use occur simultaneously.

As a step in that direction, this paper starts by briefly reviewing a selection of prior work in the domains of robotic building, swarm intelligence and environmentally friendly materials. It then goes on to present an original contribution in the form of an interactive swarm building simulation, which is used to demonstrate a number of interesting mechanisms for human-guided swarm coordination.

2 Related work: Robot Building

A substantial body of prior work on robotic building exists, much of which is framed in a construction industry context. For a more thorough treatment of that field than space allows here, the reader is referred to Xu et al. (Xu et al., 2022) and Petersen et al. (Petersen et al., 2019). The use of robotics in construction can be divided into two main classes of approach, namely robotic assembly and robotic additive manufacturing (AM). Examples of robotic assembly include Bier et al. (Bier et al., 2020), which presents a `design to robotic production and assembly' approach, including a large-scale physical prototype made of wooden beams and robotically milled panels, connected by 3D printed nodes. Similarly, Chiang et al. (Chiang et al., 2018) considers computational design, fabrication and robotic assembly as a single scheme. A segment of a larger freeform structure is robotically assembled by stacking rectangular beams, with the assembly sequence optimised to ensure that the partially built structure is stable. At smaller scale, the TERMES project set out to develop `robotic termites' (Werfel et al., 2014). The system consists of a swarm of mobile robots that build structures from pre-manufactured, roughly cuboid blocks whose geometry facilitates alignment and interlocking. Each robot is capable of carrying and placing one block at a time. The system has a centralised controller (Deng et al., 2019) that uses an offline `compiler' to pre-processes the desired structure and derive an optimal assembly sequence. Once the sequence of block placements is determined the individual robots execute it autonomously through decentralized control. In a similar vein, Allwright et al. (2014, 2019) present a multi-robot construction system that builds structures from pre-manufactured cubes. These robots cannot climb the structure, and instead have a crane-like mechanism that allows them to stack blocks up to three high. The control strategy is abstractly but strongly bio-inspired, in that it is fully decentralized and uses behavioural rules for individual robots combined with stigmergy (indirect coordination via changes to and sensing of the environment, which in termites is believed to be mediated in part by pheromones). The building blocks contain microcontrollers and multicolour LEDs, allowing them to display different colours under different conditions in lieu of a pheromone signal. Finally, flying robots have also been developed for building structures. Compared to ground robots they have the significant advantage of being able to move in 3D, but the disadvantage of lower payload capacity and greater energy expenditure. Augugliaro et al. (2013) use a quadcopter carrying a spool of rope to build tensile structures by wrapping the rope around anchor points, while Willmann et al. (2012) use a team of four quadcopters to build a 6m tall tower out of lightweight rectangular blocks.

Examples of robotic AM include Oskam et al. (2022), which presents the computational design and robotic AM (using a bio-based material) to produce 'plantetoids' intended as habitats for animal and plant life. Tiryaki et al. (2019), Sustarevas et al. (2018) and Rivera et al. (2021) all present different variants on the concept of a conventional mobile robot platform carrying an industrial robot arm equipped with a material extruder. To varying degrees, they couple the kinematics of the mobile base with those of the arm, enlarging the build space beyond that of the arm alone. Zhang et al. (2018) further considers a 'team' of two robots and addresses the control and sequencing challenges associated with them collaborating to build a single structure. Finally, Zhang et al. (2022) presents an impressive 'Aerial-AM' system consisting of 'BuilDrones' and 'ScanDrones'. The former are multirotor UAVs equipped with a lightweight actuated arm (for fine position control) and extruder, which deposits a lightweight cementous-polymeric composite. The latter are UAVs equipped with 3D scanners to monitor print quality and correct for deviations. The system is demonstrated printing simple structures like a cylindrical tower.

3 Related work: Swarm Intelligence in Architectural Design

The field of swarm intelligence explores the underlying mechanisms and applications of self-organizing multi-agent systems. It is inspired by the behaviour and organizing principles of biological swarms, as described in the seminal book by Bonabeau et al. (1999). Swarm robotics embodies swarm intelligence in physical agents (sometimes simulated 'physical agents'), and Dias et al. (2021) provides a good review of this topic. Swarm intelligence concepts have been applied to good effect for developing optimization algorithms (Tang et al., 2021) for various applications including architectural design. Buus (2006) adapts earlier models of termite-inspired building to elicit design of 'human-like architecture', which they characterize by key features like straight walls, right angled corners and openings for doors and windows. Von Mammen & Jacob (2008) use artificial evolution to tune the behaviour of an abstract swarm model inspired by bird flocking to create 'architectural idea models'. The focus is on form, not physics, and the resulting 3D structures have striking and unconventional shapes. Wiesenhuetter et al. (2016) discusses the role of swarm intelligence in architecture, and argues that it could be used as a tool for optimizing a design based on one or more specific metrics, or as a means of creating adaptive structures that respond to environmental or other changes. Finally, Agirbas (2019) uses the software combination of Grasshopper and Rhino, along with an add-on called Locust which implements a swarm-based optimisation algorithm, to design Non-Euclidian geometries for a building façade that are optimised to give desired lighting conditions in the building.

4 Related work: Materials

Materials are not the focus of this paper, but a few potential examples are provided here. Humans have made buildings from `rammed earth' (compressed sand, gravel, silt and clay) for thousands of years, and the fact that some of these buildings still stand is testament to the quality of this material. Another interesting approach is the use of microbially-induced calcite precipitation, in which ureolytic (Farrugia et al., 2019) or photosynthetic (Heveran et al., 2020) bacteria create biominerals (usually CaCO3), between grains of sand or soil, thereby increasing stiffness and strength. One could also potentially use living materials as explored in Camere & Karana (2018). The most plausible example they discuss is mycelium, which can be grown in various different organic substrates (including waste plant matter) and forms a solid network within that bulk material as it grows. Heinrich et al. (2019) discusses the possibility of creating `living buildings' by integrating biological organisms into automated construction tasks. They suggest using a combination of static scaffolds, biological organisms and manual manipulation (which could be performed by robots) to shape the growth of the biological elements as desired.

5 Innovations

The key benefits of swarms, namely robustness, flexibility and scalability (Dias et al., 2021) are due in large part to the use of distributed, self-organizing control strategies. But this approach also makes it hard to 'design' a desired group level behaviour, because that behaviour emerges through the interaction of the agents rather than being explicitly programmed. In the context of swarm construction, it is similarly challenging to develop control and coordination strategies that lead to the swarm following the specification for a structure that the human operator wants them to build. When developing control strategies for swarms, engineers often take inspiration from biological phenomena like ant foraging or termite nest construction, but these natural systems certainly don't support external user input! The goal of swarm engineering is to develop approaches for designing desired swarm behaviour, which often involves abstracting and modifying biological mechanisms (Brambilla et al., 2013).

The work presented here falls under the swarm engineering umbrella but focusses mainly on human-swarm interaction, motivated by the question: How can a human 'conductor' influence the emergent behaviour of an autonomous swarm in order to elicit a desired outcome while retaining the robustness and adaptability of a self-organized system?

To that end, an interactive simulator was developed (see Methods) and a set of agent behaviours were implemented (see Results). The novelty of the work lies in how the biological concepts of stigmergic and template-based building (Perna & Theraulaz, 2017) were abstracted and applied. Combining various technologically feasible sensory modalities with user-input, the swarm performs several representative construction tasks.

6 Results

In line with most agent-based simulations, the model is an abstraction and simplification of actual swarm robotic construction. Its purpose is to develop and test organizational principles that could be translated to real robot builder swarms. Each experiment demonstrates a distinct mechanism that enables a group of agents, with only local sensing and decentralized control, to coordinate their efforts, generate large-scale structure, perform tasks that would be useful in a real construction context, and respond to human input. More details on the behaviours used in each of these experiments is provided in Methods.

6.1 Terrain levelling

This experiment, illustrated in Figure 1, represents a pre-construction phase where uneven terrain must be levelled before it can be built on.

In the simulation, agents can perceive a 3D depth map of their immediate surroundings. They assess the terrain's curvature at their current location (refer to Methods). If they identify a mound, they are inclined to collect material, while if they are in a depression, they might deposit material. In both scenarios, the likelihood of action aligns approximately with the local curvature, i.e., they're more likely to add or remove material if the mound or depression is more pronounced. Gradually, the terrain becomes progressively flatter. This mechanism is loosely inspired by research showing that local surface curvature influences soil displacement by termites (Calovi et al., 2019).

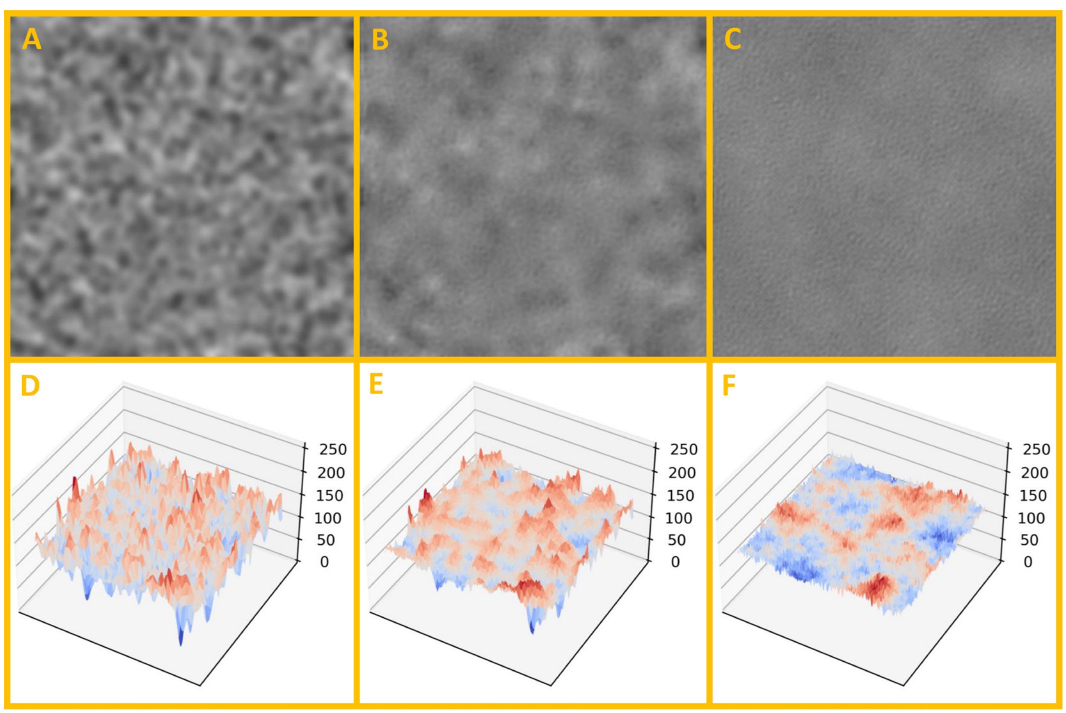

FIGURE 1 Initially random, lumpy terrain become increasingly smooth as the swarm fills depressions and excavates mounds. Panels A – C and D – F show the same snapshots in time (t = 0s, t = 30s and t = 180s), with the top row showing the 2D greyscale representation from the simulator itself (where lighter colours correspond to higher elevation), and the bottom row showing the same data as a 3D mesh plot.

6.2 Building a large-scale structure

This experiment, illustrated in Figure 2, represents the initial phase of constructing a building within a 'footprint' defined by a human architect. It addresses the challenge: how do small individual agents, relying on local sensing, ensure the large-scale geometric accuracy of their build? The mechanism deployed here mirrors the termite's 'Royal Chamber' construction, known to be facilitated by a queen-specific pheromone (Bonabeau et al., 1998).

The simulation employs a pheromone map (as described in Methods), which could be physically realized using a detectable chemical like ethanol, signal-emitting beacons (e.g., radiofrequency or audio), or GPS. In the experiment, the user designs the 'building footprint' via the software's UI. This design is translated into a 'blueprint pheromone' template, exhibiting a blurry transition between 'build' and 'no build' zones, representative of chemical diffusion or sensor uncertainty.

Agents conduct a random walk, stochastically depositing or picking up material based on sensed pheromone concentration (see Methods). Over time, a 'building' forms according to the plan. Despite the template's blurry boundaries and stochastic deposition, the structure emerges with defined edges due to the convergence of many random events on the probabilistically expected value.

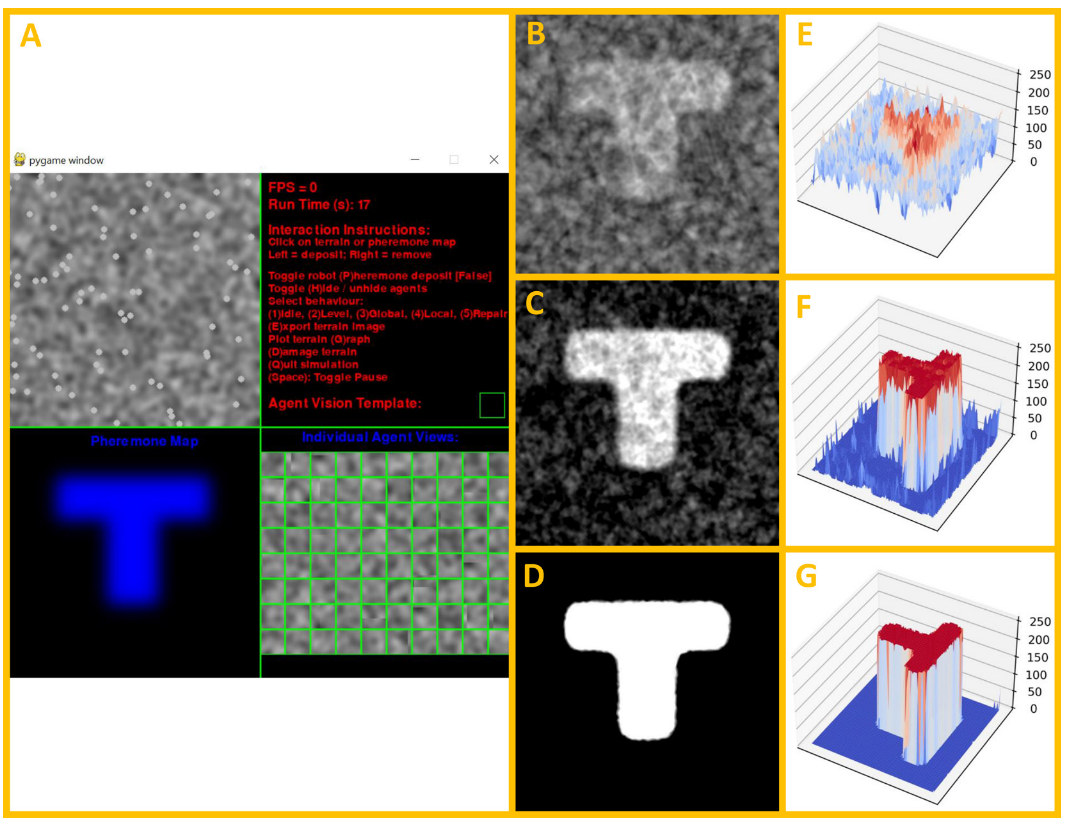

FIGURE 2 A 'building' defined by a blueprint pheromone template is constructed on initially random terrain. Panel A shows a screenshot of the simulator (top left, initial agent positions and terrain map; bottom left, pheromone template; top right, user instructions; bottom right, individual agent views). Panels B – D and E – G show the same snapshots in time (t =3 0s, t = 60s and t = 180s), with the left column showing the 2D greyscale representation from the simulator itself (where lighter colours correspond to higher elevation), and the right column showing the same data as a 3D mesh plot.

While the emergence of the building's flat top and surrounding ground appears as a simulation artefact due to a numerical range limit on the terrain map, in a physical setting, equipping robots with an altitude sensor to control the build and excavation heights would offer a practical way to achieve the same result.

6.3 Creating small-scale features

These experiments, illustrated in Figure 3 – 5, represent a later construction phase where small scale features must be added to a larger structure (like surface texture, ventilation holes or windows), or a repeating pattern needs to be applied across a large area (such as constructing support pillars, digging holes for plants, or creating drainage channels).

In this behavioural state, agents 'see' their surroundings (i.e., obtain a 3D depth map) and compare that view to a small-scale 'vision template' (inset in panel A of each figure), designed by the human user using the software's UI and representing the desired appearance of an equivalent small area. The agents perform a random walk and continually compare their observable area to the 'vision template'. They also 'envision' the outcome of adding or removing material and compare these two hypothetical cases to the 'vision template' as well (see Methods). If such actions improve the match to the template, they are executed. Gradually, the desired repeating pattern, albeit with some variability, manifests across the entire terrain map.

This variability results from stochastic agent behaviour and their localized, rather than global, perception. The degree of variability partially depends on the template's nature. Figure 3 shows a template representing an isolated feature surrounded by empty space (e.g., a pillar). Here, sensing range and template provide sufficient information for approximate pillar spacing but not for precise alignment. Figure 4 depicts a continuous feature template (e.g., rows of trenches), providing better alignment information. However, errors can still occur, primarily when agents independently initiate the pattern in different areas during early construction stages. Figure 5 depicts an experiment using the same template as in Figure 4, but this time the agents were initialised clustered in the middle of the world, and the human user guided the swarm by placing pheromone. This more methodical construction approach reduces improves overall pattern alignment[1].

1 Another repeat of the experiment shown in Figure 5, with user guidance of the swarm, is shown in Supplementary Video 1 (https://youtu.be/p9uJOsB9LCg).

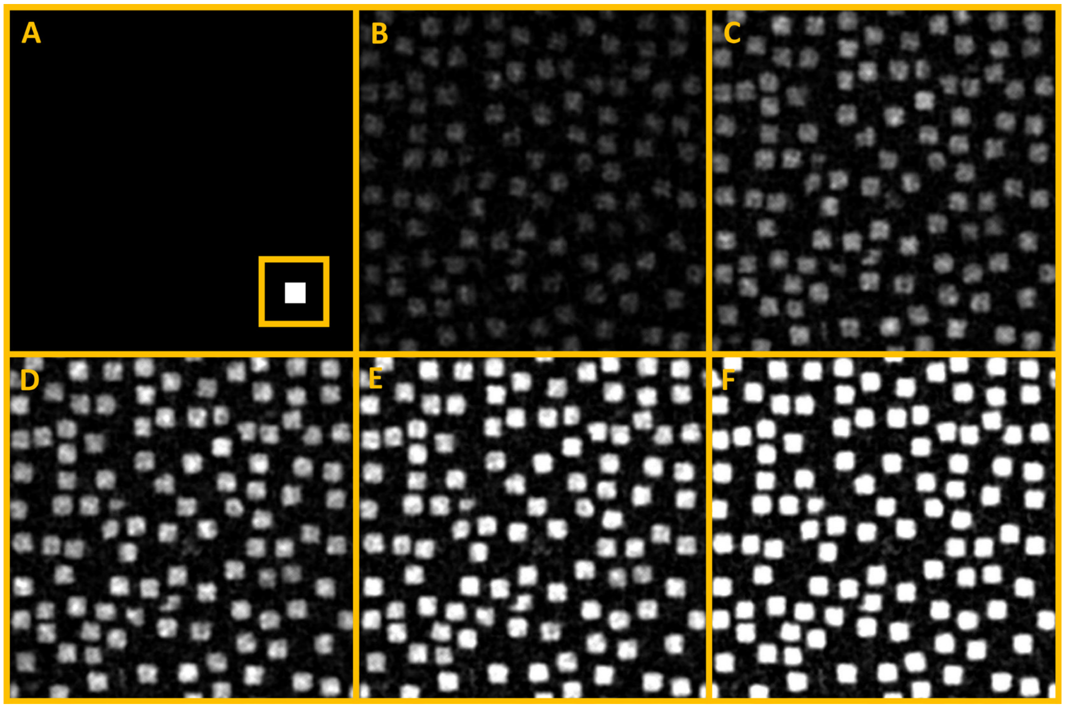

FIGURE 3 Construction of 'pillars' based on a local vision template (inset in Panel A). Panels A to F show snapshots of the construction process in increments of 30s.

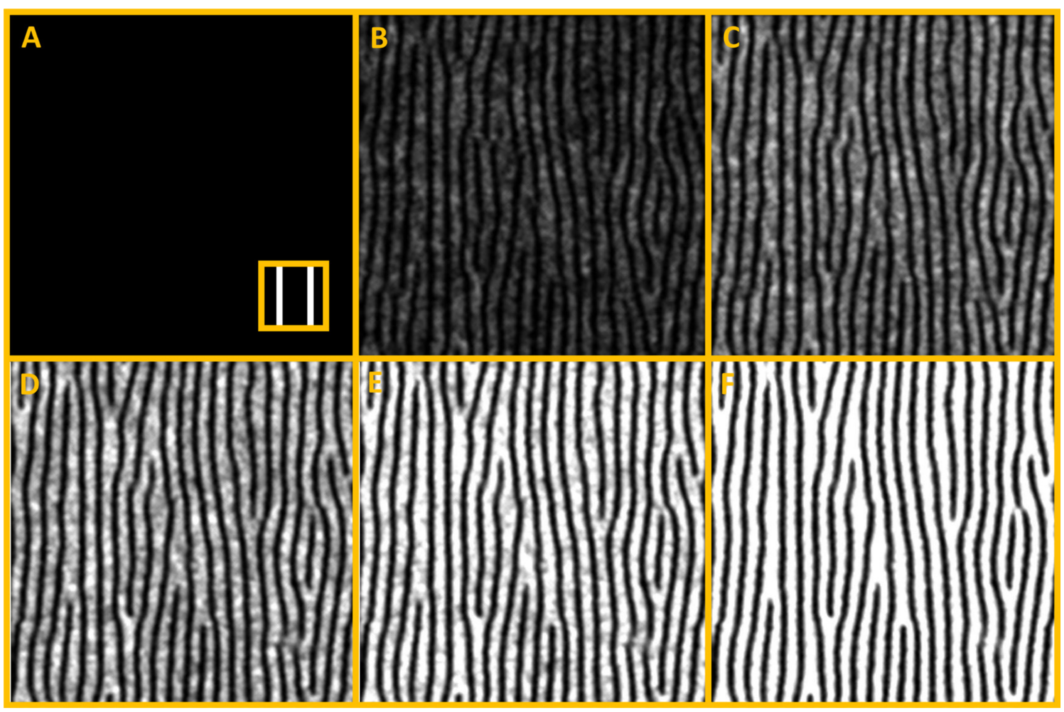

FIGURE 4 Construction of 'trenches' based on a local vision template (inset in Panel A). Panels A to F show snapshots of the construction process in increments of 30s.

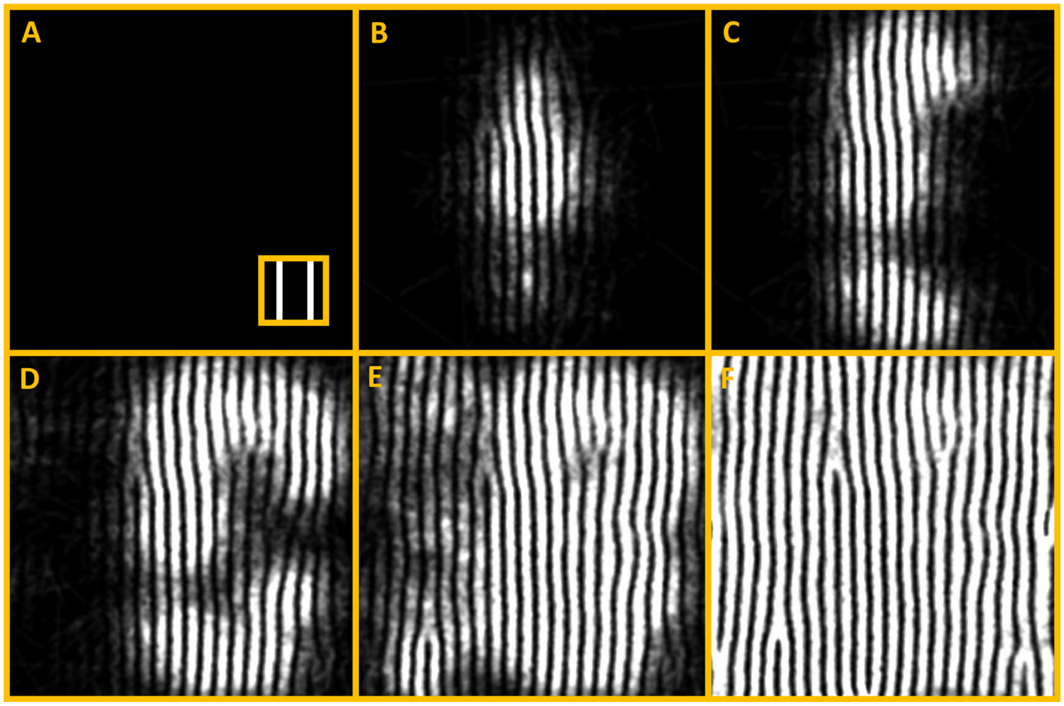

FIGURE 5 Construction of 'trenches' based on a local vision template (inset in Panel A), with the building activity of the swarm guided by a human overseer. Panels A to F show snapshots of the construction at 0s, 30s, 60s, 90s, 150s and 240s. Note how construction progresses through space as the swarm moves.

6.4 Repairing a damaged structure based on local curvature sensing

This experiment, illustrated in Figure 6, is a simplified representation of a post-construction phase where agents maintain an existing building. The concept involves agents initially exploring the intact structure with local sensing to learn what 'normal' looks like. Here, that involves memorizing the structure's maximum (most positive) and minimum (most negative) curvature. In a real-world application, training a neural network to recognize a range of 'normal' local features through computer vision techniques would enable a more complex version of this.

Once familiar with the intact structure, the agents are switched to 'maintenance mode'. They start investigating the structure for anomalies that diverge from their learned experience. In this simulation, anomalies are characterized by local curvature surpassing previously encountered limits. 'Damage' to the structure, represented by random lumps and pits, can be introduced by the user. On detecting these anomalies, agents add or remove material to 'repair' the structure.

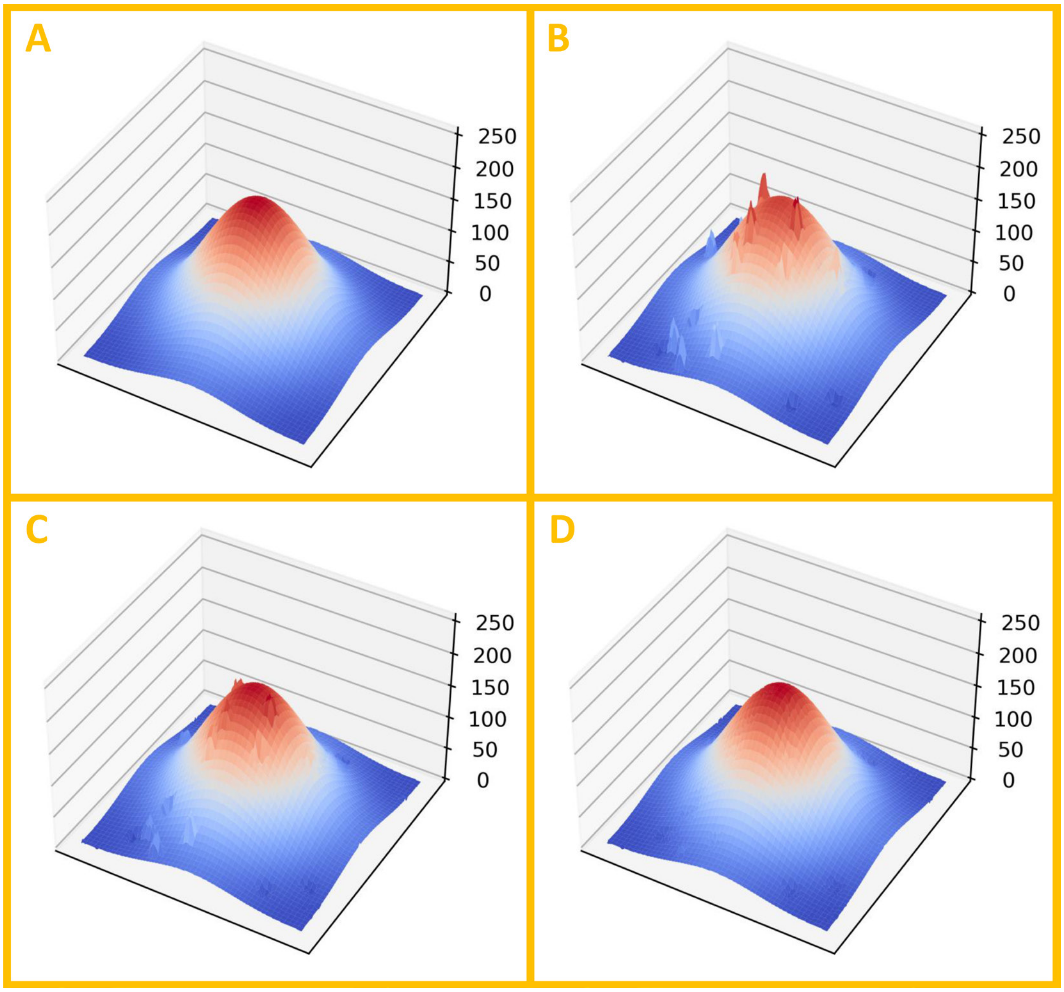

FIGURE 6 Repair of a damaged structure by the swarm. In this case only 3D mesh plots are shown, because these provide a better visualisation. A) The original, undamaged structure, which the swarm 'learns' the features of. B) Damage is introduced, in the form of localised lumps and holes in the surface. C) The swarm has begun recognising these anomalies and repairing them. D) Repair complete.

7 Conclusions

This work presents promising algorithms that combine sensing and user input to achieve human-directed construction by a simulated robot swarm. A user-defined global spatial template encoded in the intensity of a detectable quantity (e.g., chemical concentration, light intensity, electromagnetic field), sampled locally by the agents and used to modulate the probability of picking up or depositing material, was shown to successfully impose large-scale structure. Short-range sensing of 3D shape around the agent (achievable with laser scanning, time-of-flight cameras or structured light sensors) compared to a 'desired' local shape (learned or user-specified) and used to influence pickup and deposit probabilities was also shown to be effective. As agents move through space, continuously applying these 'local templates', order can be imposed at scales much larger than the sensing radius.

For readers who want to explore these behaviours, experiment with modifications, or create new behaviours, the expandable open-source simulator (GitHub link in Methods) is complex enough to yield intriguing insights while remaining accessible to those with only intermediate Python programming skills.

8 Methods

This paper provides only a concise description of the implementation due to space limitations. For further details, consult the source code[2]. The simulation is built in Python (3.11.3) and uses several standard libraries along with **numpy**, **scipy**, **matplotlib** and **pygame** (which you will need). It runs in real time, offering user control over various simulation features and behaviours. Numerical constants in the code can be easily modified. The presented experiments utilized the provided values. Individual components of the software are described below, and a high-level overview of the architecture is shown in Figure 7.

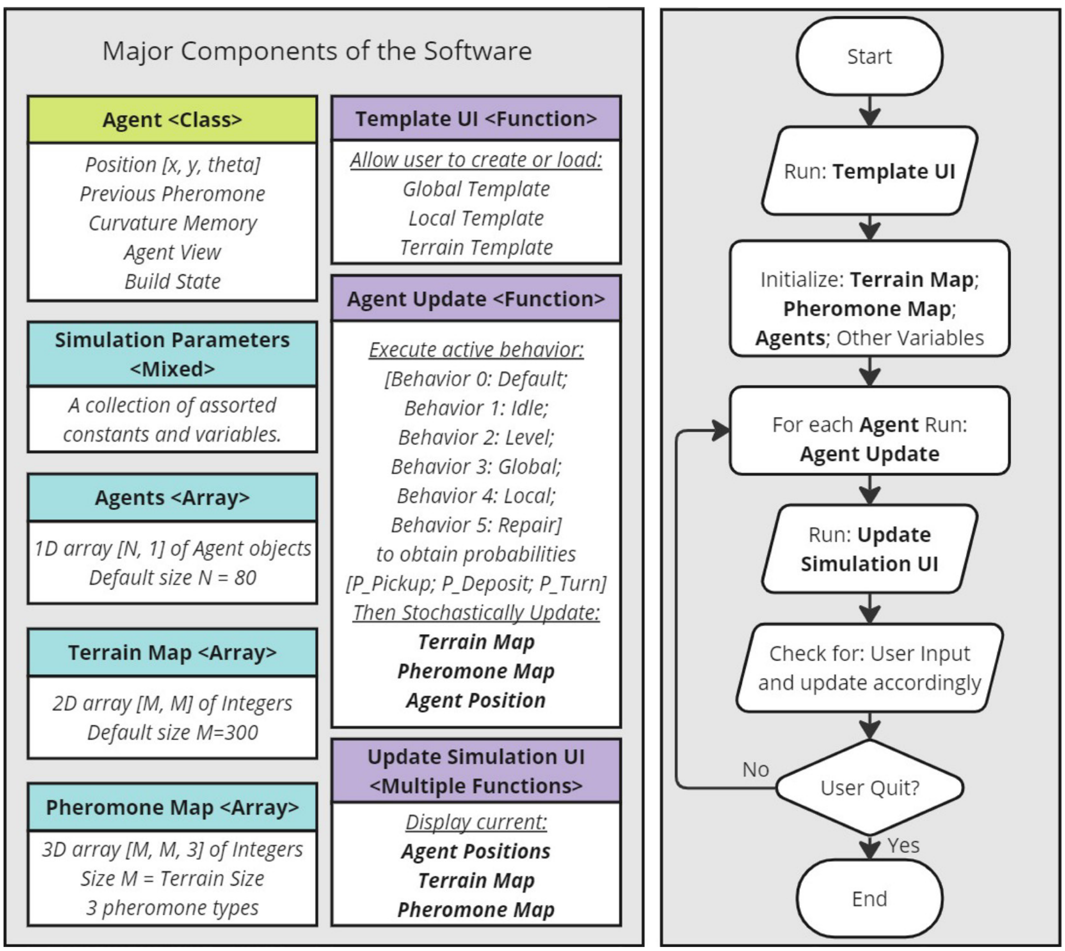

FIGURE 7 Main software components (left) and high-level program flow (right) of the simulator.

2 https://github.com/DrJordanBoyle/Spool_Builder_Swarm_Simulator/tree/main

8.1 World

The *world* is defined by a *terrain map* and a *pheromone map*, which are square grids of square cells. The size of the *world* is specified by a parameter *width* (*width* = 300 here). Cells of the *terrain map* each store one integer in the range [0 – 255], where this value represents the amount of material (i.e. 'height' of the terrain) in that cell. During the simulation the evolving *terrain map* is visualised as a 2D greyscale image where black = 0 and white = 255. At any time, the user can export a snapshot of this 2D image or generate a 3D mesh plot using Python's **matplotlib** library (if you are running the code in an IDE that supports this, like 'Spyder').

Cells of the *pheromone map* each store three integers in the range [0 – 65,535] representing the concentrations of three different pheromone types. When developing the simulation, it was found that the pheromones benefitted from a higher resolution representation than the terrain, hence the different scale.

The boundaries of the world can either be *reflecting* (as if enclosed by a wall) or *wrapping* (as if the world was toroidal), as selected by the user.

8.1.1 World: Initial conditions

The user can select between three options for the initial conditions of *terrain map: empty* (no initial terrain); *random* ('lumpy' terrain created through a combination of random number generation and Gaussian smoothing); *template based* (created by smoothing a binary template drawn by the user and then converting this to terrain values). The user can also choose to create a *blueprint pheromone* template (see Agent Behaviours). Finally, the user can choose whether *agents* are initialised *spread out* (at random positions in the *world*) or not (all grouped in the centre).

8.1.2 World: Updates

The *terrain map* and *pheromone map* are both modified during simulations. *Agents* can *pickup* or *deposit* terrain. When they do so, they decrease or increase (respectively) values of the *terrain map* in a rounded 'blob' (height = 5 terrain units; radius = 5 cells) centred on their current position. The resulting terrain values are clipped to the range [0 – 255] which is admittedly unrealistic but necessary for practical reasons.

The three pheromone types are used differently in the current implementation, though the same capabilities exist for all of them. *Terrain pheromone* is actually only used transiently as a computationally convenient way to achieve *template-based* initialisation of *terrain map*, so it won't be discussed further here. *Blueprint pheromone* underlies one of the agent behaviours described later. It is user generated (through the UI) and the associated parameters have been set such that it does not change while the simulation runs. *Build pheromone* is more complex. If the *agents deposit pheromone* option is active, then whenever an *agent picks up* or *deposits* material, it also adds a circular 'cloud' (peak value at centre = 20 pheromone units; drops off linearly to zero over a radius of 50 cells) of *build pheromone* to the *pheromone map* centred on its current location. In addition, the concentration of *build pheromone* in each cell decays every time step, reducing by an amount proportional to the current concentration. As such, it will gradually disappear in any given location if not replenished. Finally, one of the ways the user can influence the behaviour of the swarm is by manually adding (peak value at centre ≈ 16,000; drops off linearly to zero over a radius of 100 cells) or removing (set = 0 within radius of 100 cells) *build pheromone* from a specific area by left or right clicking with the mouse.

8.2 Agents

The simulator supports an arbitrary number of *agents* (representing robots). The value of N=80 used here was found to be the maximum number for which the desired frame rate of 30FPS could be consistently achieved on the author's laptop. Agents are stored as an array of instances of an *AGENT* class. *Agent* state is represented by set of class variables:

$$position = \{(x, y) \in \mathbb{R}\}$$

$$orientation = \{\theta \in \mathbb{R}\}$$

$$build\ state = \{idle, level, global, local, repair\}$$

$$previous\ pheromone = \{(Ph_{build}, Ph_{blueprint}, Ph_{terrain}) \in \mathbb{Z}\}$$

$$curvature\ memory = \{(max, min) \in \mathbb{R}\}$$

$$agent\ view = \left\{ \left[\begin{matrix} t_{1,1} & \cdots & t_{1,N} \\ \vdots & \ddots & \vdots \\ t_{M,1} & \cdots & t_{M,N} \end{matrix}\right] \middle| t_{i,j} \in \mathbb{Z} \right\}$$

The software limits x,y to the range [0 → width] and θ to the range [0 → 2π]. The size of *agent view* is also a parameter that could be changed, but M=N=30 is what the author has always used.

8.2.1 Behaviour 0: Default

This is the default behaviour, and is always active. *Agents* perform a random walk, biased by *build pheromone* and may *pickup* or *deposit* material. First the change in *build pheromone* concentration since the last time step is computed:

$$\Delta Ph_{build} = sense(Ph_{build}) - previous\ pheromone(Ph_{build})$$

Then the turn probability of reorienting is computed based on that change:

$$P_{turn} \begin{cases} 0.2, & \Delta Ph_{build} \leq -5 \\ 0.002, & \Delta Ph_{build} \geq 5 \\ 0.02, & otherwise \end{cases}$$

Then a random number, *X*, is generated from a uniform distribution in the range [0→1] and compared to the turn probability to determine whether the agent reorients. If it does, a turn angle is drawn from a normal distribution with $\mu = \pi$ and $\sigma = \frac{\pi}{4}$ such that:

$$\theta = \begin{cases} \theta + \Delta\theta, & X < P_{turn} \\ \theta, & otherwise \end{cases}$$

Then the *agent* updates its position based on its speed and orientation:

$$x = x + Speed \times \Delta t \times \cos\theta$$

$$y = y + Speed \times \Delta t \times \sin\theta$$

Where *Speed=100 cells/sec* and $\Delta t = \frac{1}{30}$

Finally, two random numbers U and V are generated from a uniform distribution in the range [0→1] and compared to probabilities P_{pickup} and $P_{deposit}$ to determine whether the *agent* executes a *pickup* and *deposit* of material (as described in World: Updates). By default, these probabilities are both zero, but they can be modified by other behaviours, of which exactly one is always active (selected by the user through the UI).

8.2.2 Behaviour 1: Idle

This is a minimal overlay on top of Behaviour 0, during which $P_{pickup}=0$ and $P_{deposit}=0$. The only addition is that *agents* constantly monitor the local terrain curvature, which is obtained by computing the Laplacian of *agent view*:

$$\boldsymbol{\mathcal{L}} = \nabla^2(agent\ view)$$

And then taking the average of the four elements in the 'middle' of the matrix (which correspond roughly to the *agent's* current position). Assuming the size of *agent view* is 30x30 as used here:

$$Curv = \left(\mathcal{L}_{14,14} + \mathcal{L}_{14,15} + \mathcal{L}_{15,14} + \mathcal{L}_{15,15}\right)/4$$

Finally, this value is compared to the current *max* and *min* values of *curvature memory* and these are updated if necessary:

$$max = \begin{cases} Curv, & Curv > max \\ max, & otherwise \end{cases}$$

$$min = \begin{cases} Curv, & Curv < min \\ min, & otherwise \end{cases}$$

8.2.3 Behaviour 2: Level

First, each *agent* computes the local terrain curvature Curv based on *agent view* as described in Behaviour 1. Then, probabilities P_{pickup} and $P_{deposit}$ are calculated as follows:

$$P_{pickup} = \begin{cases} Curv, & Curv > 0 \\ 0, & otherwise \end{cases}$$

$$P_{deposit} = \begin{cases} 0, & Curv > 0 \\ -Curv, & otherwise \end{cases}$$

8.2.4 Behaviour 3: Global

Each *agent* senses the value of *blueprint pheromone* at its current location and normalises it to the range [0 → 1] by dividing by the maximum possible pheromone value of 65,535. This value is then passed through a sigmoid function:

$$Ph_{norm} = sense(Ph_{blueprint})/65{,}535$$

$$Ph_{sigmoid} = \frac{1}{1 + e^{(-\sigma(Ph_{norm}-\mu))}}$$

Where values of σ=*50* and μ=0.4 are used here. Finally, the probabilities P_{pickup} and $P_{deposit}$ are calculated as follows:

$$P_{deposit} = Ph_{sigmoid}$$

$$P_{pickup} = 1 - P_{deposit}$$

8.2.5 Behaviour 4: Local

Each *agent* samples a local portion of *terrain map*, centred on its current location *(x, y)* to obtain *agent view* which is an *MxN* (30x30) matrix. It then creates two copies of this matrix, which are modified by performing a *pickup* and *deposit* in exactly the same way as is done when modifying *terrain map*. This yields two additional matrices *pickup view* and *deposit view*. Each of these three matrices becomes a *sample* for comparison with the user-generated *view template*. This is achieved using forward and inverse Fast Fourier Transforms from the **numpy.fft** library as follows:

$$templateFFT = FFT2(view\ template)$$

$$sampleFFT = FFT2(sample)$$

$$correlation = iFFT2(conjugate(templateFFT) * sampleFFT)$$

$$match = \max\left(abs(correlation)\right)$$

Note that the match is quantified based on the maximum absolute value within the correlation matrix, which makes the process insensitive to any spatial offset between the sample and template as desired. After doing this for *agent view*, *pickup view* and *deposit view* to obtain *match*, *pickup match* and *deposit match*, the probabilities are calculated as follows:

$$P_{pickup} = \begin{cases} 1, & pickup\ match > deposit\ match\ AND\ pickup\ match > match \\ 0, & otherwise \end{cases}$$

$$P_{deposit} = \begin{cases} 1, & deposit\ match > pickup\ match\ AND\ deposit\ match > match \\ 0, & otherwise \end{cases}$$

8.2.6 Behaviour 5: Repair

Each agent computes the local terrain curvature *Curv* as per the method described in Behaviour 1, and compares this to the *max* and *min* curvatures learned while executing Behaviour 1. The probabilities P_{pickup} and $P_{deposit}$ are calculated as follows:

$$P_{pickup} = \begin{cases} 2 \times (Curv - 1.1 \times max), & Curv > 1.1 \times max \\ 0, & otherwise \end{cases}$$

$$P_{deposit} = \begin{cases} -2 \times (Curv - 1.1 \times max), & Curv < 1.1 \times min \\ 0, & otherwise \end{cases}$$

User Interface

Upon launching the program, a pre-simulation menu is displayed which allows for the creation or loading of Global (for Behaviour 3), Local (for Behaviour 4) and Terrain (for *template-based* world initialisation) templates, as well as selection of some initial conditions.

Once choices are confirmed, the main screen appears, with the simulation initially paused to allow the user to change settings before agents start moving. This screen is subdivided into four windows: Top left shows the *agents* (they can be hidden to see the terrain better) and current *terrain map*; Bottom left (separate for visual clarity) shows the current *pheromone map* (*build pheromone*: Red, *blueprint pheromone*: Blue, *terrain pheromone*, Green). Top right shows the FPS currently being achieved (this is capped at the target of 30FPS) and simulation time, along with user instructions and some *agent* status information. Bottom right shows a grid of the *agent view* for all *agents* (if a behaviour that uses these is active).

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The migrating walls

Continuously reconfigurable interlocking modular discrete structures assembled by mobile robots

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Abstract

This paper presents a comparison of different workflows for mobile robotic fabrication using modular building blocks. Different localization, locomotion, and interlocking building systems strategies are tested and compared. The work is influenced by related research into ecosystems of building parts, design software, and builder robots to digitize the construction work. For localization, it compares LIDARs, reacTIVision, and ArUco markers. As a mobile platform, a MIR100 robot platform, a 3.3 m linear axis, and a manual trolly are used. Interlocking components such as wood slates, custom-made bricks, and interlocking wood building blocks are used. The research is in the field of collective robotic construction (CRC) using bespoke robots designed in tandem with specific discrete building blocks.

Keywords

Localization, interlocking parts, mobile robots, mobile platforms, discrete architecture, autonomous construction, computer vision, collective robotic construction

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1 Introduction

Migrating Walls is a series of six prototypes to foster a vision of continuously reconfiguring buildings. The research aims to develop small-scale mobile autonomous builders that transform building blocks of architectural construction and extend the workspace of robotic systems on-site construction. Dry joint interlocking building blocks allow architectural constructions to be assembled, disassembled, and reassembled using discrete connection logic. Such continuous reconfigurability enables buildings to adapt to different uses across their life cycle. Even when a building becomes obsolete, the interlocking building blocks can be used in new buildings. Six prototype structures were developed in combination with robotic systems and custom-made interlocking building blocks to evaluate the feasibility of using robots for continuous reconfigurable architectural construction. The focus of these prototypes lies in (A) robot localization, (B) integration in a CAD environment of robotic arm inverse kinematics and mobile platform communication, and (C) interlocking systems design. The strategy was to learn from current commercially available tools and libraries, apply them in a design-build educational context, and extrapolate findings into the future.

Although architecture has changed widely since the 1990s through the digitalization of practice, the most fundamental transformation of it is still to come with the automation of construction (Skibniewski & Garcia de Soto, 2020). The opportunity for this change lies in fundamentally rethinking building materials and construction processes and thus arriving at robotic procedures where materials can be reconfigured in long-term cycles.

2 Context and state-of-the-art

A significant part of research on mobile robots in architecture focuses on using conventional general-purpose robotic arms or task-specific automated machines and applying them to current construction practices and established building products (Bock, 2007). That allowed the first implementations of robotics in applications of the current construction industry. However, human and robot builders afford different capabilities, and a robot-enabled construction site gives way to rethink building products in number, scale, weight, and connection logic. The construction site could be envisioned as an ecosystem of building blocks, robotic builders, and design software. We believe that such a novel construction ecosystem of integrated new building products and robot technology can lead to discoveries that significantly enhance the sustainability of the construction sector (Pan et al., 2018).

Central to this exploration is the concept of “discrete interlocking blocks” in architecture, which uses modular units that connect mechanically in pre-defined ways by dry joint interlocking. Compared to bespoke building elements at its extreme in parametric design, the discrete interlocking system facilitates faster production through mass production of blocks and precise specification. It also offers crucial features such as flexibility, mobility, expandability, and modularity, making it particularly suitable for future construction projects, primarily when used with mobile robots.

Furthermore, interlocking blocks represent a sustainable approach to digital architecture compared to complex and less universally applicable alternatives that rely on numerous variations of elements for specific forms and functions (Anastasiades et al., 2020).

2.1 Interlocking blocks

There are many precedents in applying interlocking blocks in architecture. Some of the oldest structures applying closely fitted stones in masonry can be found in Inca architecture (Tessmann, 2012). More recently, while the construction industry has been rethinking its practice to respond to the climate crisis, the interest in interlocking parts has resurfaced. After many decades of research around sustainable construction shifting to CO2-neutral materials and energy-efficient forms of buildings, the interest has moved to two ancient concepts that 20th Century Modernism has forgotten:

- The reuse of entire buildings for other uses, which was rebranded as retrofit, and
- The reuse of building parts in the same or other buildings, which was known as spolia and rebranded as circular construction.

Many young practitioners are dedicated to applying strategies for disassembling and reassembling building parts into new wholes, such as Kevin Kimwelle in Port Elizabeth (Berger, 2022), Arquivo in Salvador (*Arquivo – simplificando o reuso de materiais,* n.d.), Certain Measures in Berlin and Boston (*Certain Measures*, n.d.), Rotor DC in Brussels (*Rotor Deconstruction – Reuse of Building Materials Made Easy,* n.d.), Collectif Saga in Nantes (*Ca Gaze ?*, n.d.) and Norell/Rohde in Stockholm (Norell et al., 2020). This strategy has also been named Design for Deconstruction (DfD), and a recent study looked at 130 industry practitioners of it and listed five factors for its success: “stringent legislation and policy,” “design process and competency for deconstruction,” “design for material recovery,” “design for material reuse,” and “design for building flexibility” (Akinade et al., 2017).

The computational design research community has been developing tools and methods to empower architects to design and build employing reused or repurposed building materials and scaling up the productivity of this practice. Some examples are robots and computer vision applied to reused brick-laying (Fingrut & Leung, 2022), robotically assembling interlocking parts (Mangliár & Hudert, 2022), 3D scanning and reassembly of roof structures (Batalle Garcia et al., 2021), NFT tracking of building components on the blockchain (Dounas et al., 2021), the concept of digital materials (Popescu, 2008), and machine-learning for automated arrangement of parts (Huang, 2021).

A current research agenda in computational design places reusing building elements at its heart under the name of discrete architecture. In opposition to the aesthetics of continuous fluid surfaces from the 1990s blobs to the 2000s and 2010s NURBS surfaces, it offers the visual complexity of “aggregations” of many standard building parts. Discrete architecture inverts the part to whole logic of continuous smooth architecture (Sardenberg & Becker, 2022). In the paradigm of Parametricism (Schumacher, 2012), a continuous surface, or the whole, defines the form of individual bespoke parts. In discrete architecture, this is inverted, and the parts are standard, autonomous, and assembled in incomplete wholes or aggregations. Therefore, the introduction of interlocking parts in digital design is not only a matter of tectonic logic but also a new aesthetics.

The aesthetics and tectonics of many discrete parts avoid the problem of the reuse of bespoke parts in digital architecture. A bespoke building part cannot be reused because it is custom-tailored for a specific location and performance. On the other hand, discrete parts are generic elements that can perform multiple roles in the same or other buildings (Retsin, 2016). This vision of discrete parts allows robotics to fabricate and assemble the parts *in situ* (de Paula, 2023). Mobile robots are necessary to build autonomously on-site full-scale structures, and their localization on the worksite is a critical problem.

2.2 Mobile robots and their localization

The early days of applying robots in the construction site can be traced back to Japan in the 1970ies. To avoid dangerous, dirty, and heavy work for humans, robots have been seen as a replacement able to work 24/7 (Yoshida, 2006). The approach was to adapt off-the-shelf industrial robotic arms for construction tasks, such as applying fire-proofing spray to steel structures. When combined with mobile platforms, robotic arms can build complete architectural elements such as walls on site.

A vital issue of mobile robots is their localization. Localization is never a trivial problem, especially on the construction site. Multiple actors (human and non-human) constantly move during construction, and mobile robots must be aware of them. Because construction is the creation of environments, the environment itself is (hopefully) in constant change until completion, complicating methods that compare the robot's sensor reading to an ideal static environment. Because of the transformation while building, any tentative keeping direct sights on all rooms with external static localization devices such as total stations or cameras for visual tracking is impossible.

An example of a mobile robot in construction is the "In Situ Fabricator" from ETH Zurich. It is an ABB IRB 4600 robotic arm assembled on a robotic mobile platform that performs brick-laying and mesh welding. The In Situ Fabricator utilizes a point cloud scanner and cameras pointing to AprilTag markers to achieve a precision of less than 5mm (Giftthaler et al., 2017).

Another example of in-situ robotic construction is 3D printing using a robotic arm and a mobile platform. The challenge is to have precise accuracy so each layer of deposited material is adequately aligned. Lachmayer et al. combined an UR10e robotic arm with a Robotnik RB-VOGUI+ (Lachmayer et al., 2022). Requiring a precision of less than 3.5mm, they utilized a 3D scanner to localize the platform to within ≈±10mm precision and then used a Keyence LJ-V7200 2D laser profile scanner with an accuracy of about 20 μm to scan only the work area. Comparing the current point cloud to the previous one allowed them to locate the Tool Center Point (TCP) within the 3.5mm precision required.

In traditional construction, having multiple builders allows time efficiency. The same may be achieved in a digitalized worksite by having multiple robotic builders. This emerging field of research is named collective robotic construction.

2.3 Collective robotic construction

The approach of having many robots operating parallelly in the construction site is called collective robotic construction (CRC) and describes embodied, autonomous, multi-robot systems. CRC focuses on multi-robot autonomous systems, building more extensive structures than each robot, and involves bio-inspired robotics, building design, and self-organizing systems to achieve scalable, robust, and efficient parallel construction (Petersen et al., 2019). Some examples are drone addictive manufacturing (Zhang et al., 2022), passive blocks picked, carried, and placed by small robots (Petersen et al., 2011), specialized small robots for concrete printing ("Minibuilders - Institute for Advanced Architecture of Cataloni," n.d.), filament weaving with small robots (Yablonina & Menges, 2019), rotating joints to pick and place wood slats (Leder et al., 2019), robots building in outer space (Dunker et al., 2009), and robotically pre-assembling architectural elements that are further assembled by other larger robots (Abdel-Rahman et al., 2022).

The application of robotic arms in building construction has focused on building complex and precise bespoke building elements. This application has led to outstanding formal exploration and high-performance building elements (Menges & Knippers, 2020). However, the scalability of the results beyond the reach of the robotic system has been a challenge. Moreover, the sustainability of the elements produced has been questioned because of a high degree of specialization.

Applying small mobile robots on site is a way to respond to the above-mentioned scalability issue. When multiple small robots can pick and place blocks inside a construction, they are called mobile robotic assemblers or relative robotic assemblers. These relative robots can be manufactured cheaply since they do not need highly precise localization sensors. They take their precision from locally aligning with the discrete blocks already placed in the assembly at every step. This process enables a virtually infinite working volume, allowing the construction of full-scale buildings. Relative robots are designed to fit the discrete blocks precisely, limiting motions to discrete steps from one block to the next, correcting their position step by step, and placing or removing neighboring blocks before moving on. Therefore, relative robots minimize the accumulation of global localization errors by setting the reference to be relative to the robot instead of the structure (Carney & Jenett, 2016). An example of applying relative robots on the architectural scale is Ivo Tedbury's *semblr* (Claypool, 2018; Tedbury, 2018; Tedbury & Vaughan, 2019).

3 Methods

This research focuses on developing a mobile robotic system capable of assembling, disassembling, and reassembling interlocking elements on the construction site. To achieve this, we designed robotic systems utilizing commercially available hardware. Critical gaps of knowledge that were addressed were:

- Localization of the system;
- Communication between the design software, the robotic arm, and the robotic platform;
- The interlocking parts.

The method to develop knowledge and test the feasibility of the robotic systems was to build prototypes during semester-long seminars introducing robotics to Bachelor and Master students of architecture.

Each robotic setup was tested by placing its corresponding interlocking part on the floor four times to test the precision of the localization system. The precision was calculated by approximating the largest distance between the center of each placed part and the average center of all placed parts (Figure 1). Moreover, the robotic systems were tested by assembling, disassembling, and reassembling walls.

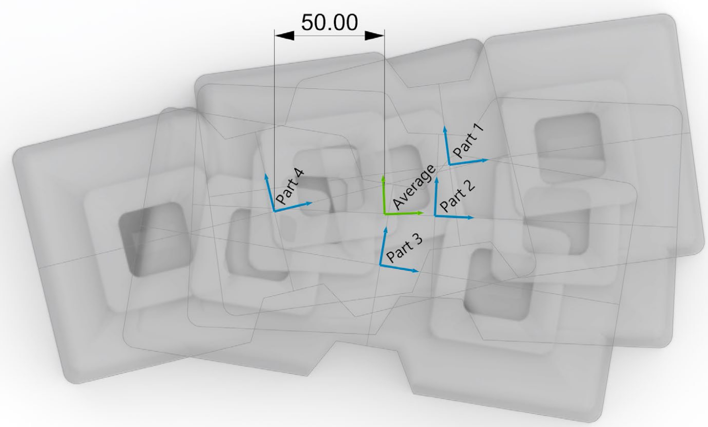

FIGURE 1 Diagram of the method for precision measuring. Authors, 2023.

4 Experiments

Each of the following six prototypes explored a different localization method (from Lidar to computer vision), mobility solutions (mobile platform, human-robot interaction, and a linear axis), building components (timber slats, custom bricks, and interlocking blocks), and design methodologies (parametric variation, sequential placing, and stochastic aggregation). Combining these characteristics resulted in different aesthetics, resolution, and precision.

The name Migrating Walls derives from the concept of architectural elements that are continuously assembled, disassembled, and reassembled. In the context of walls, it migrates by repeatedly moving its parts or blocks by a robot. Therefore, there is no final construction, allowing a building to adapt to the change in needs of its inhabitants continuously. The design involved defining possible states of the wall with possible locations for the parts or blocks. The robot program's role was to constantly track the current arrangement of parts and blocks and decide which to disassemble and where to reassemble. This scenario demonstrates the continuous transformation of architectural constructions over time. In real life, the time scale of such transformation will be very different, including more prolonged periods of no change, local changes, repairs, and cyclical changes during the seasons.

4.1 Prototype I

The first prototype design was a parametrically composed wall of identical timber slats. Its goal was to kickstart the development of a mobile robot capable of building a 1:1 scale architectural prototype and disassembling and reassembling it somewhere else, overcoming the limitations of the work area of immobile robots.

FIGURE 2 MiRo in front of wood slats wall. Authors, 2023.

To realize it, an *assemblage* named MiRo was built (Figure 2). MiRo was assembled using a MIR100 mobile platform and a UR5 robotic arm with a Robotiq 2-finger gripper. It was entirely controlled by a Grasshopper definition where the UR5 was programmed using the plug-in Robots (visose, 2015/2023), while MIR was controlled by custom components that communicate REST commands via HTTP. MiRo localization relied on MIR's standard pair of LIDARs that informed the Grasshopper definition about its position. This location was used to define what slats were inside the UR5 range. The definition used this location to create a program for the UR5 to pick the slats from its back and place them in their final position.

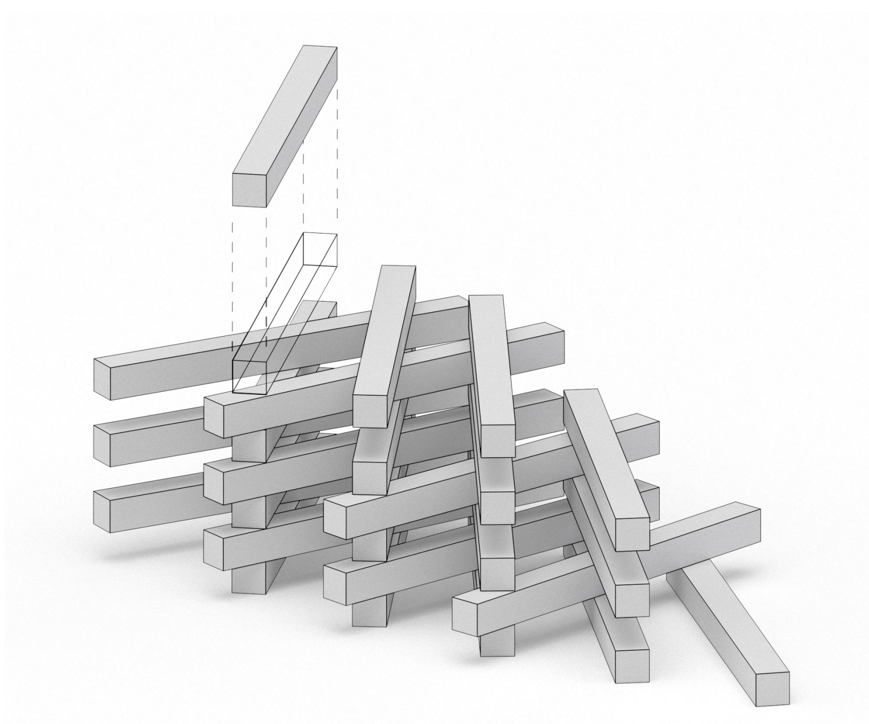

FIGURE 3 Logic of piling of the wooden slat structure. Authors, 2023.

Because the placement relied on MIR's localization system, the precision of the TCP in our tests was ≈±50mm, although MIR-100 position tolerance is documented as ±26mm in its data sheet (*Mobile Robot from Mobile Industrial Robots - MiR100*, n.d.).

Therefore, the design required much space between each part (Figure 3), not allowing it to be made of interlocking parts. Picking from the built structure to place somewhere else was impossible, which made the structure assembled permanent. Because this robotic system did not allow the interlocking or disassembling of building parts, a design strategy of parametric and smooth variation of angles across parts was adopted (Figure 3).

FIGURE 4 Video demonstrating MiRo assembling the first prototype. Authors, 2023. Video with link https://www.igd.uni-hannover.de/en/dma/projects/migrating-wall#c97835.

4.2 Prototype II

An aluminum profile structure on wheels replaced MIR as the mobile solution for the second prototype (Figure 7). The reason for doing so in the first place was a defect in our MIR platform, which allowed us to explore how a person could interact with the UR5 to expand its reachability, an approach already explored for robotic wire-cutting (Becker et al., 2020). The goal of this prototype was to expand the worksite of a robotic arm by collaborating with a person and enabling the robot to assemble, disassemble, and reassemble a structure more extensive than the work area of the UR5.

Assisted by Microsoft HoloLens 2's augmented reality goggles running Fologram (Jahn, 2022), people placed markers on the floor following the grid established by the floor tiles for accuracy. The goal was to move the robot close enough to its target position, assisted by AR. Attached to the two-fingers gripper, a Microsoft Azure Kinect camera looked perpendicular to the floor for reacTIVision fiducial markers (Kaltenbrunner & Bencina, 2007). The reacTIVision system was developed to interpret the angle and position of elements on a table. It was adapted to read fiducial markers on the floor and stipulate the camera's location and, therefore, the robotic system's location.

This prototype introduced interlocking bricks as building blocks (Figure 5). The bricks were designed inspired by LEGO®'s interlocking capabilities, and they featured reentrances on their larger side so they could be carried by a two-finger gripper and properly placed side by side. Moreover, they could connect from the bottom to the top with a slight chamfer to facilitate connection and diminish imprecisions. There were also two holes across the brick, allowing post-tension elements to be installed among many bricks vertically. These bricks were cast on 3D-printed molds using wood chips and plaster as the matrix. They were lightweight because of this combination.

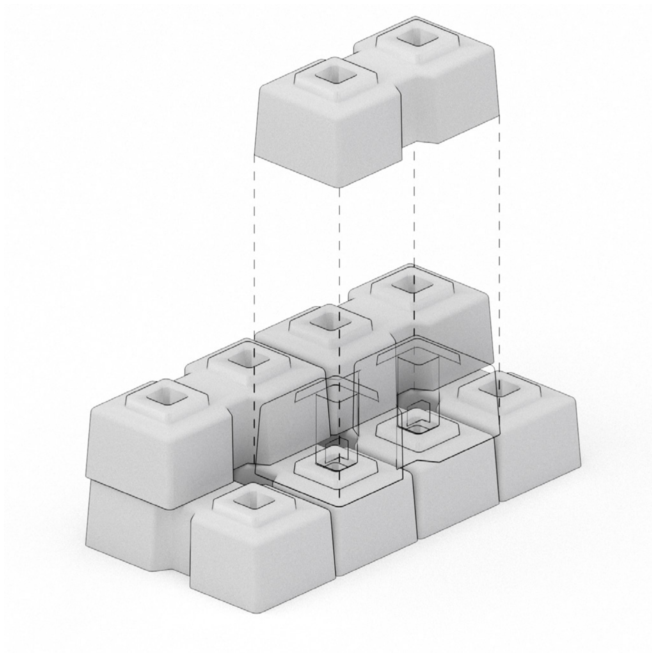

FIGURE 5 Custom-made interlocking brick. Authors, 2023.

FIGURE 6 The UR5 with a Robotiq 2-finger gripper placing the custom-made bricks. Authors, 2023.

The tolerance for placing the bricks using reacTiVision was ≈±20mm. Although computer vision improved precision substantially, this localization method was still not precise enough to place a set of bricks, move the robot, and continue appropriately, as was the initial goal. Therefore, only the corners of a planned wall, each consisting of bricks within reach of the robot arm from one location, were placed (Figure 7). Moreover, it was impossible to pick bricks from a previous part of the wall to place somewhere else because of the imprecision in the localization, which made it impossible to reconfigure its parts' position continuously.

FIGURE 7 UR5 with Kinect camera on wheels, reacTIVision markers on the tile grid, and the custom bricks placed in the corners of an unbuilt wall. Authors, 2023.

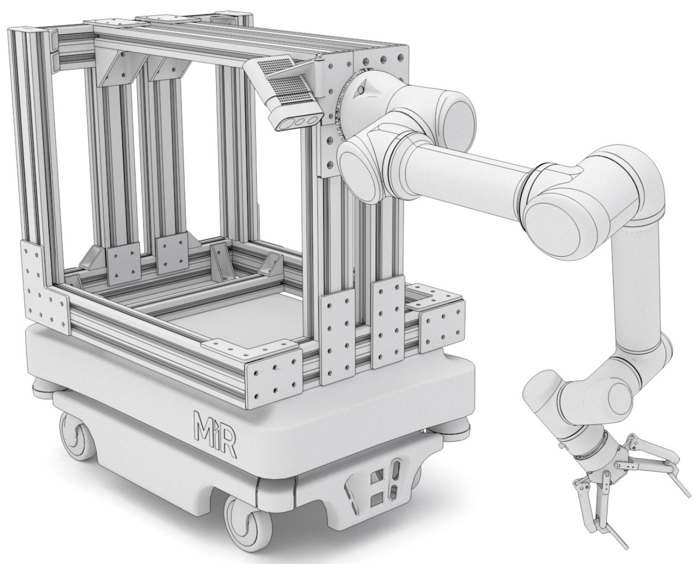

FIGURE 8 MiRo. MIR100 mobile platform with aluminum profiles and UR5 robot. An Azure Kinect camera assembled at 45 degrees close to the robot base. Authors, 2023.

4.3 Prototype III

The goal of the following prototype was to use AruCo markers to improve precision and, therefore, be able to place interlocking parts, disassemble them, and reassemble them. This experiment incorporated the MIR100 platform again as a mobile solution. However, instead of relying on its LIDAR location, a Kinect camera was assembled to MiRo aluminum profiles in a 45-degree position to increase its visibility area and precision (Figure 8).

Instead of adapting reacTIVision markers, a more robust ArUco marker reader was implemented using OpenCV. One hundred stickers with individual ArUco markers were placed on the floor, assisted by the Hololens according to a pre-defined model. There was no need for high precision on the markers' placement because a Leica BLK360 was used to scan the room from two distinct positions to produce a point cloud with the precise location of the markers (Figure 9).

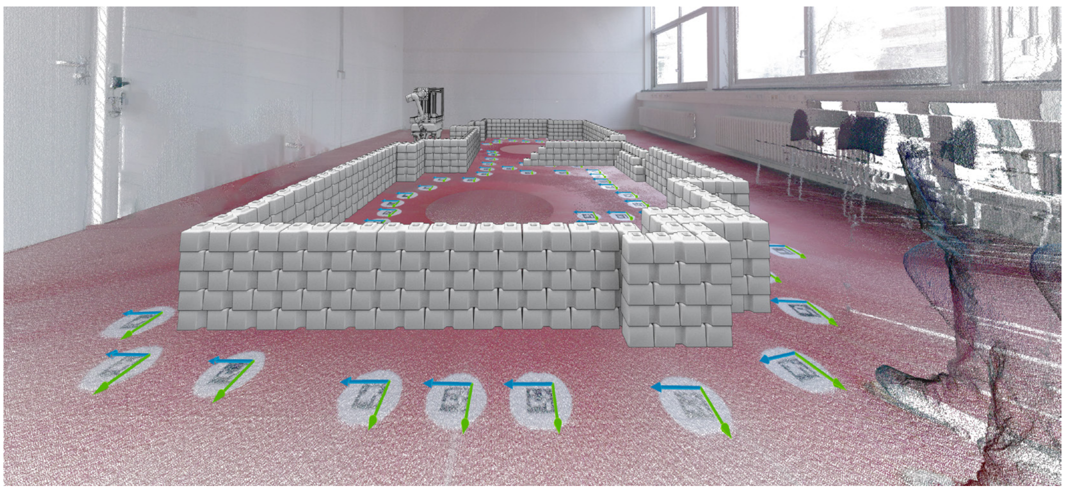

FIGURE 9 Wall with 450 possible positions for the bricks. In the background is the point cloud with the ArUco markers and the X and Y directions of each (blue and green). Authors, 2023.

The Galapagos genetic algorithm was set to precisely locate the planes in the digital model to correctly correspond to their location in the point cloud, allowing each plane to move and rotate to fit each marker better. Such a localization solution allowed many bricks to be placed correctly, with around 20% colliding during placement (Figure 10). This prototype is the first where the concept of migrating the wall succeeded. It was possible to pick bricks from one side of the structure and move it further, allowing the wall to reconfigure continuously.

It was noticeable that approaching a new position from the same direction as in the previous placement cycle increased the precision. The tolerance was calculated to be around ≈±10mm. A possible reason for this inaccuracy could be the complex translation from the picture plane captured by the Kinect camera into the robot system's location and/or the inaccurate localization of the markers through the point cloud scan. This inaccuracy could be better corrected in three ways:

1. Better calibrating the CV system to correct the distortion caused by the camera lenses.
2. Better measuring the matrix transformation from the UR5 base to the camera sensor.
3. Better modeling of the light rays' behavior through the camera's lenses.

FIGURE 10 The wall assembled by MiRo with the ArUco code markers on stickers on the floor. Authors, 2023.

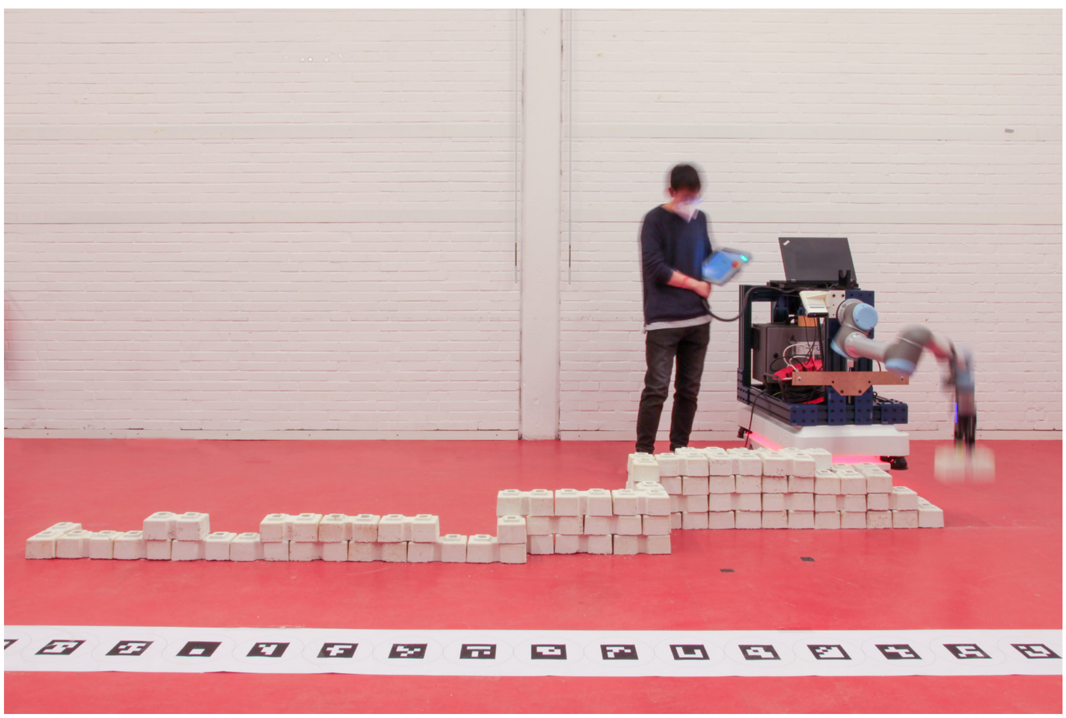

FIGURE 11 The wall assembled by MiRo with the QR code markers on a banner on the floor. Authors, 2023.

4.4 Prototype IV

The following experiment used a single printed QR code banner to replace the sticker markers and point cloud scan (Figure 11). The goal was to locate better the causes of the imprecision in the previous prototype and further decrease the tolerance. This linear location of the markers on the banner implied a wall redesign to follow this constraint. Moreover, MiRo only approached the markers from one direction (with its back facing one wall while the UR5 faces the banner). Many more bricks were correctly placed in this setup, and the tolerance was ≈±5mm. We suppose that the print's better accuracy than creating a point cloud and finding the planes on it increased precision. Also, approaching the markers from the same direction minimizes possible imprecision of the aluminum frame's assembly that would cause a wrong matrix transformation from the camera sensor to the UR5 base.

4.5 Prototype V

The fifth prototype was a small portion of a trade fair pavilion. Its goal was to introduce a new interlocking system and test and improve the repeatability of the disassembling and reassembling loop. The assembly system comprised an interlocking wood block named H-Block that allows connections along several axes (Figure 12). The pavilion was built using 2000 H-Blocks manually with the assistance of Augmented Reality using HoloLens 2 and Fologram. The location of each block was defined using the discrete assembly plug-in WASP (Rossi, 2017/2023). Because it was in the context of a fair demonstrator and we were only interested in repeatability, MiRo continuously reassembled only three H-Blocks in this prototype to present a vision of how robots could assemble interlocking structures.

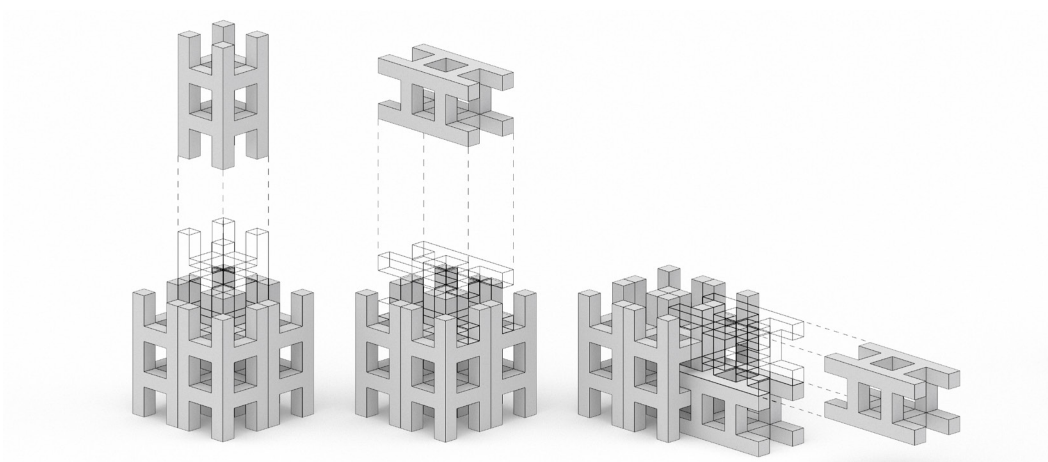

FIGURE 12 Drawing of possible H-Block assemble positions. Authors, 2023.

The pavilion design contained two stations (Figure 13). The prototype demonstrated the possibility of continuously assembling and disassembling the H-Blocks. MiRo recursively drove to one of the sides of station 1 to place three blocks from its back, drove to the other side of station 1 to pick these blocks, and repeated it on the other station (Figure 14). Because of the tolerance of ≈±5mm, the blocks assembled and disassembled by MiRo were chamfered (Figure 15). After fine-tuning the stations in the 3D model by moving it a few millimeters on the digital model to better correspond to the physical one, picking and placing were successfully repeated dozens of times without failures.

FIGURE 13 MiRo assembling the H-Blocks on-site. In the right image, both material stations are identified. Authors, 2023.

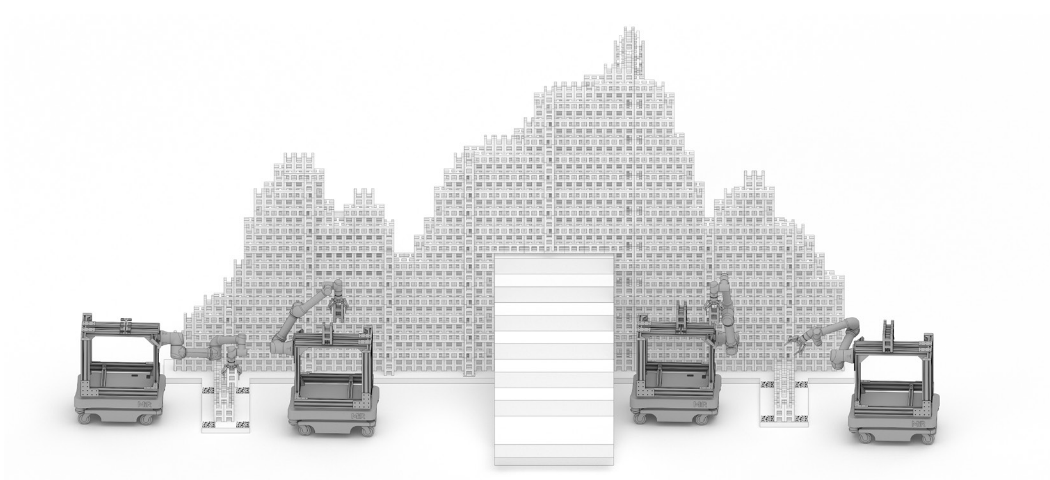

FIGURE 14 The four possible locations where MiRo loaded or unloaded H-Blocks. From left to right: Loading from platform 1 to its back; Unloading to platform 1; Loading from platform 2; Unloading to platform 2. Authors, 2023.

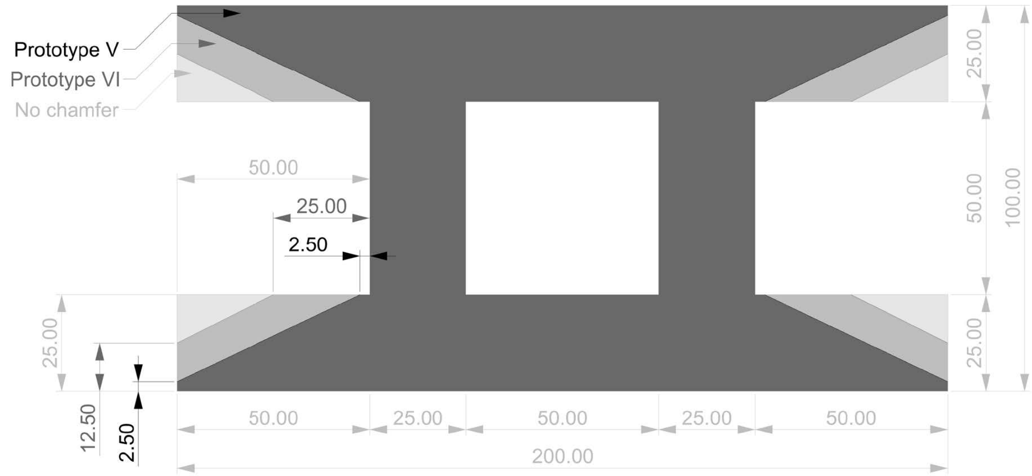

FIGURE 15 Dimensions in millimeters of the H-Blocks with varying hatches according to the tolerance of each prototype. Blocks are chamfered only on one side, both sides, or neither, according to their position in the prototype. Authors, 2023.

4.6 Prototype VI

The sixth prototype aimed to compare the precision of the MiRo mobile robot to an immobile robot. It approached the robotic assembly of H-Blocks interlocking structures without complete locomotion to compare its precision to the previous locomotion systems. It explored how a UR5e robotic arm extended by a Vention 3.3m linear axis could pre-assemble beams to be used on the construction site (Figure 16). Such a setup could be placed outside or inside the construction site, producing elements like beams to be installed on-site by humans or other robots. In the context of the research about robotic localization, this prototype functions as a control to compare its precision to the mobile solutions and delimit what challenges are posed to mobile robots or robotic construction in general.

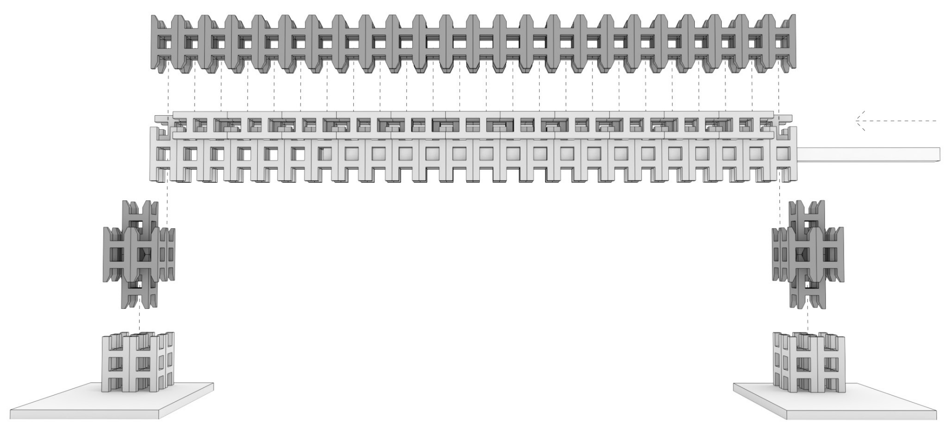

FIGURE 16 Diagram of beam assembly. In darker gray, parts were assembled by the UR5e, and in brighter gray, parts were assembled by people. Authors, 2023.

Because of the better precision of the linear axis, the chamfer required to assemble the interlocking blocks was less pronounced than for the mobile solution (Figure 15). However, they were still necessary because the robot lacks the real-time feedback a person has to place the building blocks into position intuitively, which could be added by a force feedback loop. The tolerance of the system was around 0.5mm. The high degree of precision in the robotic system led to questions regarding other variables in the construction process, such as the accurate placement of the structure's foundation or the tolerances within the building blocks themselves.

This prototype was a beam supported by two columns. The stations from the prototype V were adapted to be used. In the prototype V, the material station consisted of 16 H-Blocks screwed from below on a HDF board. The blocks were visually aligned to a print. Because of the larger chamfer, the imprecision of the stations was well compensated. However, on prototype VI, the chamfer was smaller than the one used on prototype V. Therefore, the first layer of H-Blocks needed more precise alignment, achieved using a laser-cut rigid template glued to the HDF board.

After robotically placing the H-Blocks for the columns, a 2m long wood profile with H-Blocks was manually connected to them to guarantee more structural rigidity, and more blocks were assembled on top of it.

Unfortunately, many blocks could not be placed despite the robot system's high accuracy. The reason for that was the tightness of the H-Block's interlocking system, which is undoubtedly necessary for the system's stability but often requires more force than a UR5e robot can apply safely. In prototype V, there was always a gap between each part placed and the next. In prototype VI, they were placed side-by-side, which required more force from the UR5e. That was compensated by a person rubber hammering the parts that were not ideally placed. Moreover, there is a slight difference in tolerance between each interlocking component, and some are harder to interlock than others.

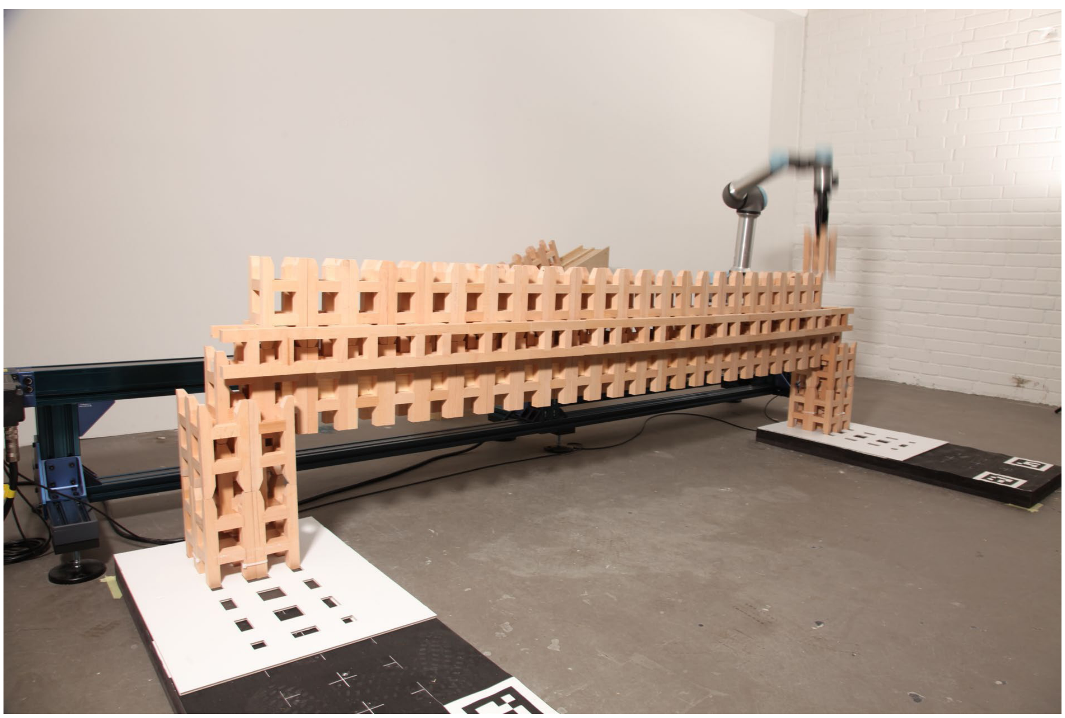

FIGURE 17 Beam comprised of H-Blocks assembled by a UR5e robot on top of an external linear axis. Authors, 2023.

5 Results

There are substantial improvements in MiRo, its localization, and the building parts from the first prototypes to the last one. These can be classified as:

- Changes in design strategies;
- Building parts;
- Localization;
- Mobile solutions;

Each of these, in combination with each other, resulted in different precisions, as described in Table 1:

Prototype	I	II	III	IV	V	VI
Design strategy	A parametric wall made of repeated slats	Wall modeled using custom interlocking bricks	Wall modeled using custom interlocking bricks	Wall modeled using custom interlocking bricks	Stochastic aggregation using custom interlocking blocks	Beam modeled using custom interlocking blocks
Building part	Wood slats	Custom bricks.	Custom bricks	Custom bricks	H-Blocks	H-Blocks
Localization	MIR Lidars	reacTIVision (computer vision)	QR Codes + Point Cloud + computer vision	Printed QR Codes Banner + computer vision	Printed QR Codes + computer vision	Linear axis' position output
Mobile solution	MIR100	AR-assisted human	MIR100	MIR100	MIR100	Vention linear axis
Tolerance	≈±50mm	≈±20mm	≈±10mm	≈±5mm	≈±5mm	≈±0.5mm

TABLE 1 Comparative table of design strategies, building blocks, and localization systems.

Ahead, we describe the aspects of each of these classifications.

5.1 Design strategies

Each building technique is tightly related to a design technique and vice-versa. Because of the requirement of large tolerances between the building parts caused by the imprecision of MIR Lidars on the prototype I, using interlocking parts like Kunic et al. was impossible (Kunic et al., 2021). Therefore, a design strategy of parametric smooth variation of each slat's placement angles was adopted. That allowed each slat to be adequately supported by at least two other slats and avoided collision with neighbors. Moreover, the imperfection in placement was not visually perceived in the overall view of the construction. That strategy prioritizes the definition of a whole, subdivided to specify each part's location and angle. The initial aim was to build a wall section on one side of the room and disassemble and reassemble it on the other side. Because of the low precision of the localization system, it was impossible to disassemble and reassemble it.

The introduction of interlocking custom bricks on prototypes II, III, and IV afforded another design strategy. Because the brick bond has a vital role in the stability of walls and because they only connect at two points and four angles, there was no need for programming the overall form, and the designers defined the overall possible location of each brick by using LEGO® bricks and then manually 3D modeled it. The model contained all possible positions a brick could occupy on the wall, and an algorithm to keep track of the current state of the construction with the placed bricks was developed. This algorithm contained a rule to define from what positions MiRo should pick bricks and where they should be placed according to UR5's reachability of MiRo's current location.

A faster design strategy was necessary because of the scale of the fair pavilion where prototype V was introduced. WASP plug-in for Grasshopper was used to define how the H-Blocks can be connected. The designers were tasked to use the H-Blocks to accommodate a few functional requirements, such as a bar and bleachers, and they defined meshes using VR and Rhinoceros that were further filled with H-Blocks following its connection rules into a stochastic aggregation. In this strategy, the parts are prioritized, and the whole is defined by how these parts connect. Moreover, the whole can always be regenerated in new variations, never complete.

Because of the simplicity of the prototype VI arrangement, it was modeled as a finalized object to be built step-by-step by the robotic system.

5.2 Building parts

Three building parts were used to construct the six prototypes. Wooden slats were initially employed for ease of production. Although they could be reused in new building elements, applying them to elements not only on compression, such as beams, was impossible. Therefore, an interest in interlocking building parts surfaced.

The following building part was the custom-designed bricks that could be interlocked and, therefore, be assembled and disassembled continuously and have structural properties, behaving as larger wholes. However, casting them took many weeks because each brick had to wait 30 minutes to set, and only four molds were printed. Because of its complexity, assembling and disassembling the mold took much time (Figure 18). We also speculated about using mycelium to cast it, but it would require many more molds and an even longer time to set. We concluded that the molds were too complex and time-consuming to produce, be assembled for casting, and disassembled for demolding.

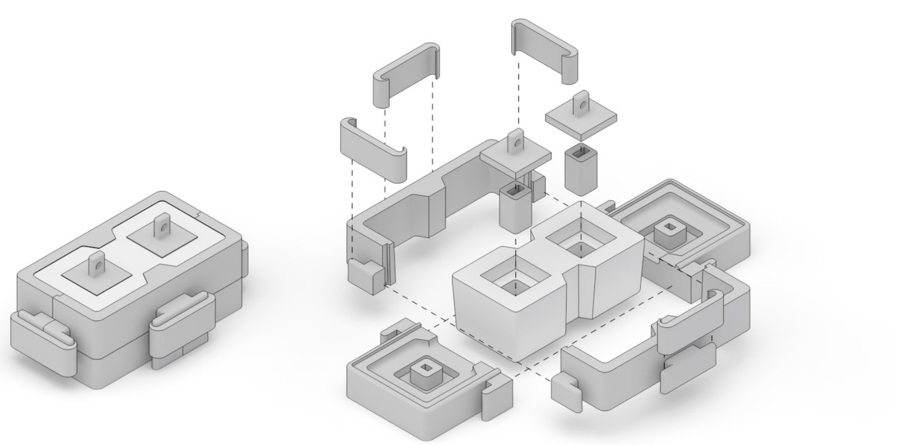

FIGURE 18 Custom brick and its mold with 12 parts.

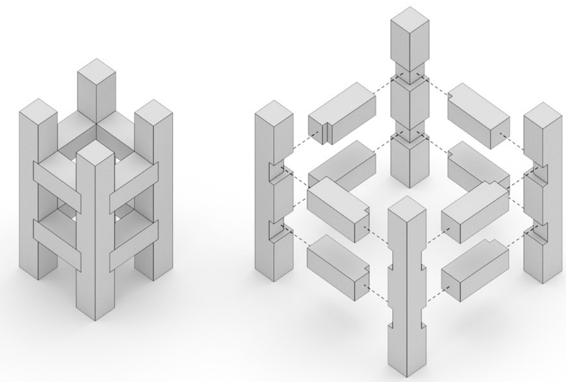

FIGURE 19 H-Block and its constituent parts.

Finally, the H-Block was adopted to respond to scalability, production speed, and precision. It was made of machined wooden slats with only two types of components glued together (Figure 17). We produced 2300 H-Blocks. It took 40 hours to manually machine all parts and 115 hours to glue them together.

The H-Blocks were not identical in their dimensions and tolerances, even when machined and glued following the same processes. This imprecision made some of them easier or harder to assemble and disassemble. Therefore, many H-Blocks with less chamfering in prototype VI could not be assembled entirely by the UR5e, requiring a person to rubber-hammer it into position. That problem could be solved by changing the H-Block tolerances to make it less tight, which could turn its assemblies less structurally robust, or by using a robotic arm capable of a heavier workload in comparison with the UR5 and UR5e used that are only capable of handling 5kg.

Placing the blocks directly on the floor without any board as a foundation worked successfully.

5.3 Localization

We were not interested in external tracking systems like total stations, HTC Vive tracking, or external camera tracking because they cannot completely cover a construction site. Therefore, we focused on internal tracking. The first two prototypes, which relied on MIR LIDAR and ReacTIVision, could not continuously assemble and disassemble discrete parts. Localization of mobile robots was substantially improved on MiRo in the following prototypes when we implemented a Kinect camera looking at ArUco markers on the floor. This setup required a laptop running OpenCV inside Grasshopper and streaming each plane identification and orientation via UDP using MIR's wireless network to a laptop operated by the designers.

This setup had the advantage of running the CPU-consuming computer vision algorithm on a dedicated machine. However, this machine on board of MiRo consumed valuable battery from MIR. A dedicated device for OpenCV, such as nVidia Jetson, can be a more efficient solution for capturing an image from a camera, recognizing fiducial markers, and streaming their localization to the network.

Using ArUco markers raises the problem of ensuring that their position in the physical world and the digital model are consistent. We tried to achieve it through the point cloud capture of the physical markers and fitting the digital model planes to it by running a genetic algorithm. That was not able to allow complete repeatability. Maybe the point cloud should be more precise since we used the lowest number of points allowed by the Leica BLK360 to keep our models lighter (it was still a 3.6GB Rhino Model). A better method for fitting the digital planes on the 3D model could also be developed to improve precision. These problems were overcome when we used a printed banner where one could rely entirely on its dimensions. Also, we always approached the planes from the same direction.

We could only achieve total repeatability when we fine-tuned each target location and repeated the picking and placing on the same material stations on prototype V. This approach very much limits the extendability of MiRo to the number of targets that an operator can pre-adjust manually. Prototype VI´s robotic system relied on the step count of the linear axis and was, therefore, much more precise than any other solution tested. However, it cannot be considered a mobile robot.

5.4 Mobile Solutions

The experiments here presented introduced MIR and AR-assisted human placement. MIR100 is suitable for placing building parts as long as it does not require much strength. Because it is on four unmotorized and two motorized wheels, MIR may move when the UR5 applies strong forces. When designing such robotic assemblies, one should remember where to distribute loads: finding a sweet spot where the robotic arm is on its periphery to take better advantage of its reachability, but it may displace the center of gravity far away from the MIR´s center.

The application of the UR5 placed by a human utilizing AR is interesting to keep a human in the loop that can keep track of the work done by the robot while achieving other tasks. That solution also introduced wheels that could be locked in position so the robotic system does not move while operating.

Rhino and Grasshopper were critical intermediaries between all actors involved in the prototypes. It was used to design the prototypes utilizing strategies such as 3D and parametric modeling, stochastic rule-based aggregations, and VR. Moreover, it supported our custom-made OpenCV component to read the fiducial markers and remap them on the digital model. We also experienced the digital model overlaid on the physical reality using Fologram. It allowed us to communicate with MIR and the linear axis the targets for its movements via REST commands sent via HTTP and to create the programs for the UR5 and UR5e. Finally, it also kept track of each device’s current position and construction status.

6 Discussion and future research

This research proposes to achieve scalability by building full-scale architectural elements on-site using mobile robots. The lessons learned with MiRo and the six prototypes should be applied to building more miniature robots in the future that are well-integrated with building blocks especially suited to robotic construction. The problem of precision in localization needs to be addressed to achieve the buildability of interlocking parts with robots. The interlocking building blocks system locally corrects each block's position due to their characteristic of connecting only in particular ways. However, to correctly connect them, the assembler –a human or a machine – must place new blocks in a certain way. This connection can be achieved by increasing the precision of the TCP global location, adopting blocks that correct their positions – using, e.g., chamfers – or iteratively adjusting the TCP location using the feedback of sensors.

Most conventional building elements' dimensions respond to a human worker's capability to carry them or to the length of trucks. The application of robots has responded to the use of these building elements whose scale relates to humans or trucks. However, robotics in construction can be better implemented when it is part of an ecosystem of (1) standardized interlocking smaller and lighter building parts, (2) custom, simple, cheap, and small robots, and (3) a specific digital design environment able to manage millions of building parts.

This research is part of developing such material, machine, and software ecosystems. Some developments in parallel with MiRo that point to its future developments are the BrickrBot 0.1 and 1.0, which can climb and place LEGO bricks (Figure 17 and Figure 18). These prototypes of robots take a different approach to localization. They rely on discrete movements embedded in the building part, which is LEGO® bricks. Because LEGO® bricks can only be assembled at specific distances, the BrickrBot uses this limitation to relocate itself within the system at each step, gaining precision from the system instead of precise motor control. This local positioning methodology could be combined with ArUco fiducial markers to achieve high precision global position.

For further development of the H-Block ecosystem, robots like the BrickrBot should be designed to operate tightly with the H-Block to move around, climb, carry, assemble, and disassemble it. The inability to carry more than one of the blocks can be counter-weighted by having many of these robots working parallelly.

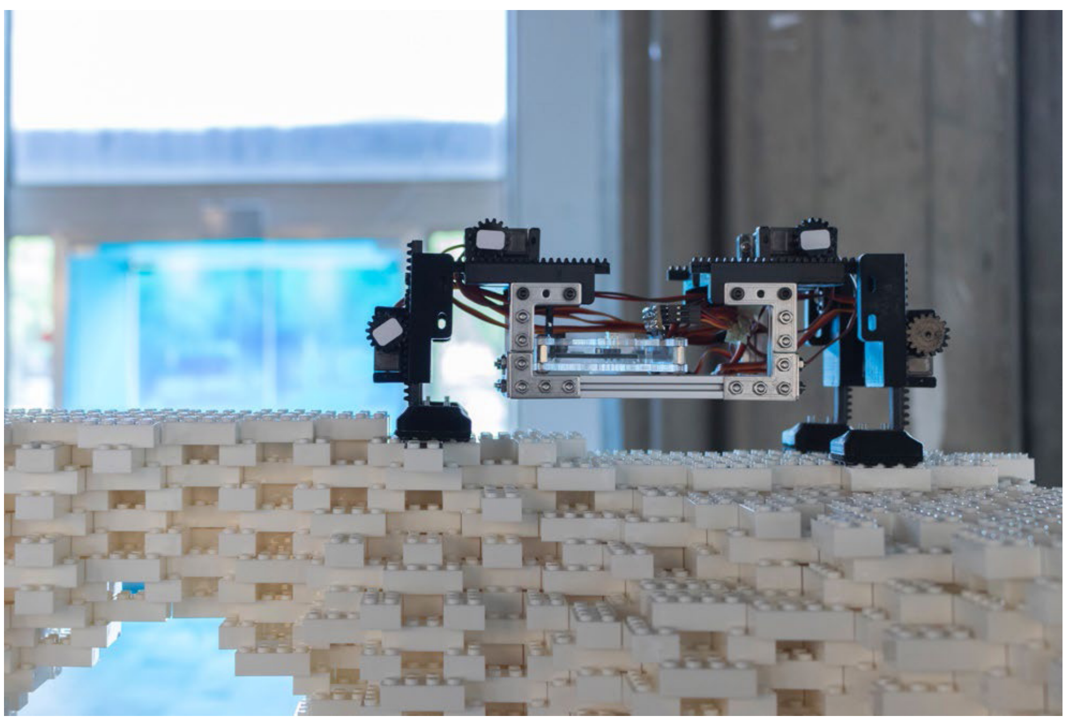

FIGURE 20 BrickrBot 0.1 climbing a wall made of LEGO® bricks. Authors, 2023.

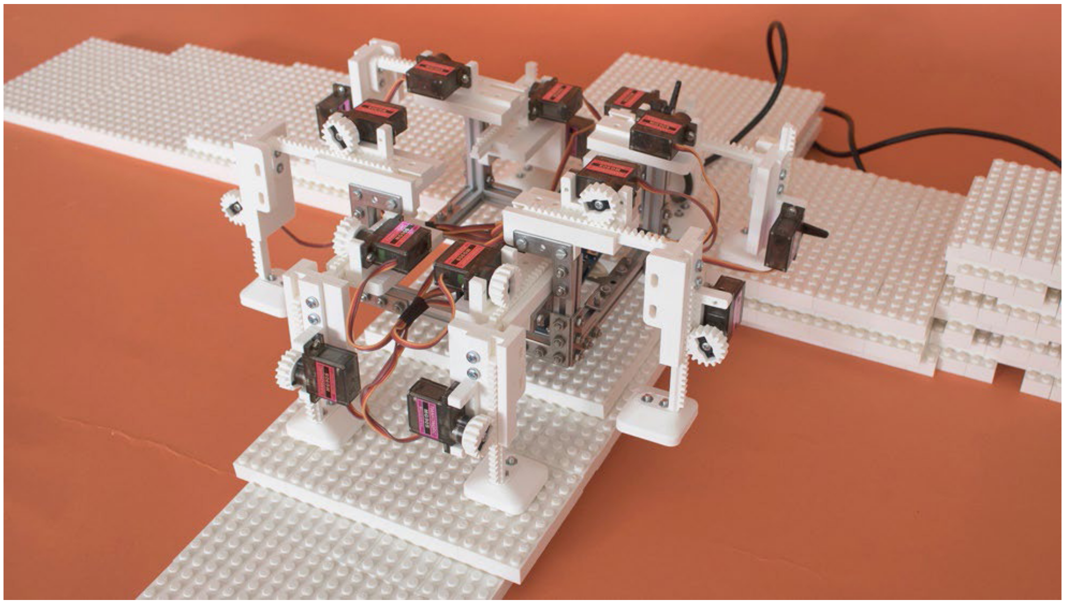

FIGURE 21 8-legged wall climbing BrickrBot 1.0. Authors, 2023.

To be able to build whole buildings using interlocking parts and small robots requires novel design approaches. Currently, CAD software operates on a high degree of abstraction: A wall, for example, is represented by a polyline on a 2D drawing or a solid on a 3D model. However, such a construction paradigm proposed here requires it to be represented and modeled as a collection of interlocking parts. Moreover, current software can only manage tens of thousands of geometric entities. In the case of building architecture with the scale of the proposed parts, this is a considerable limitation. Using Virtual Reality goggles in gaming engines has proven to be a proper environment for assembling discrete parts (Drude et al., 2020).

Finally, building at this scale allows a degree of resolution uncommon in the history of architecture. Some precedents are Brick Expressionism in Germany and the Netherlands, some details of the Peter Zumthor's Kolumba Museum, Kengo Kuma and Associates' revival of Japanese interlocking wood details like Sunny Hills Minami-Aoyama (Arlet, 2021), and Atsushi Kitagawara Architects' Japanese pavilion at Expo 2015. Such approaches will need a new wave of aesthetic experimentation to explore the formal possibilities within these systems.

7 Conclusions

There is a potential for digitization of the construction site offered by rethinking construction as an ecosystem of building parts, design software, and mobile robots. Interlocking parts allow a more ecologically responsible building system due to its ability to be assembled, disassembled, and reassembled. Localization systems can implement global fiducial markers combined with restrains within the building blocks to allow interlocking parts to be assembled by mobile robots. Building with small parts requires developing a swarm of small robots fully integrated into the building parts for localization error correction using the relative robots approach. Finally, new design software is necessary to design in such a paradigm.

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Therblig to Robot

Action Packages, Robot Motion and Human-Robot Collaboration in Domestic Environments

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Abstract

Industrial robotic arms commonly require specialist knowledge for machine functions. Specifically, training cobots for work sequences is time consuming and complex when task complexity increases, such as through differentiation in tool adaptations or work processes. This research explores robot versatility for a context of domestic environments (such as a kitchen/workshop), where work processes are approached as a hybrid scenario, with setup for integration of a tool variety whereby human-robot teams collaborate. The paper discusses a) novel workflows based on a palette of work tools adopted for robot tooling to translate manual human tasks to human-robot tasks; b) an initial script series for work processes that represents modelling, planning, simulation, and implementation; c) a framework for task division through action sets based on Therbligs that supports users; and d) an empirical evaluation of the approach through a series of user studies. In a post-carbon context, previously autonomous robots are required to become more versatile in terms of productivity, scalability, safety and skill criteria and environmental impact. This research extends beyond traditional kitchens to include workshop and fabrication scenarios characterised by the complexity and variability of task applications, guided by detailed action packages that explore robotic work for modular components or fluid and liquid materials; heat and assembly-based processing; and bridges from food preparation to fabrication and manufacturing tasks.

Keywords

Human-robot teaming, human-robot collaboration, robot programming, task allocation, Therbligs, kitchen, workshop

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1 Introduction

At present, industrial robotic arms in construction and manufacturing settings are commonly programmed to function autonomously, exhibiting precision, speed and accuracy (Javaid et al., 2021). To overcome work restrictions that arise by placing robots in secure settings, a shift to more customizable products, use of wider tool range or more intuitive work processes with robots and collaborative robots is desirable but challenging. The forthcoming advancement in both personal and industrial robotics involves transitioning robots from seclusion to cooperative engagements, where they can work alongside co-workers or users (Hjorth & Chrysostomou, 2022). Integrating robots into real-time scenarios and the unregulated and multi-criteria context of construction sites demands significant engineering to ensure that human operators can proficiently leverage the capabilities of robotic resources (Melenbrink et al., 2020).

Collaborative robots in contrast offer alternatives and novel pathways for work, collaborative work, manufacturing and interaction between man and machine beyond restricted environments (Michaelis et al., 2020). Yet despite advancements in skill acquisition and execution, robots applications are challenged in reaching their maximum potential when taken out of the usually well-regulated laboratory environment. Reprogramming industrial robotic arms is expensive as this requires specialist knowledge. Training cobots for work sequences is time consuming and complex when task complexity increases. However, improvements can be made by enabling untrained workers to operate within a framework of work sequences and robot action packages, such as by providing a basic set of work sequences and task sets that can be adopted.

This research explores a six-axis industrial robotic arm for collaborative task division and framework with personalised space of multiple users where sequences of preparation of food are considered, ingredients and menu set into shared workspace and processes. It focuses on interaction between human and industrial robotic arm and action packages for robotic work processes in a kitchen/workshop. A user study is performed to explore the adaptation for tools, robot programming and framework for differentiated tasks and a changing knowledge base. The domestic environment serves as a context for investigation into work processes, varied materials, tool applications, action sets and tasks, and movement sequences for production whereby standard domestic utensils are adopted from kitchen and workshop to test viability for subtractive, additive, forming and assembly methods. In workshop scenarios or construction sites, specialist knowledge must be translated to robotic processes; and actions defined for human or robot, or interaction between both. A series of production case studies (Figure 1) is presented that analyses manual cooking processes, establishes robotic programming and human-robot joint action planning, and uses Therbligs to refine subtasks for division of work between human and robot. The aim is here to go beyond robotic automation and instead better understand the potential of human-robot interaction; application of skills and best practice for man and machine; and providing a platform for innovation with tools and methods (work sequences and motions).

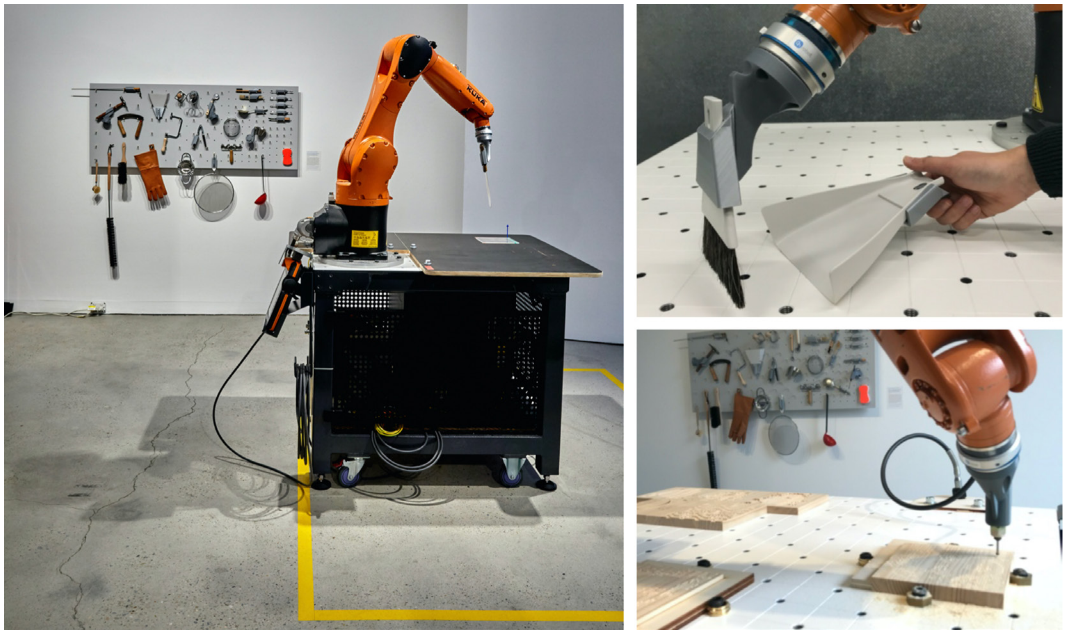


FIGURE 1 Collaborative robot programming with KUKA KR6 robot (left); Action sets in kitchen and workshop - swiping with a broom (left) and subtractive cutting/drilling with a Dremel (right top and bottom) at @SHErobots exhibition, Tin Sheds Gallery, Sydney 2022.

The research addresses a multifaceted set of questions aimed at advancing the field of robotic programming and human-robot collaboration. First and foremost, the study seeks to unravel the intricacies of process segmentation and work tasks, with a focus on delineating clear boundaries that enable efficient robotic programming. Investigating the domain of task division between human and robot, the research aims to establish a harmonious collaboration that optimizes the strengths of both entities. Furthermore, it aims to establish seamless linkages between motion and work movements across diverse task sets, emphasizing a holistic perspective in programming. Shifting from a product-oriented to a tool and motion library approach is a central query, intending to streamline the programming process and foster versatility. Creativity and serendipity, often overlooked in rigid programming structures, emerge as vital elements to be explored and incorporated. Additionally, the research seeks to enhance robot adaptability for non-skilled users, promoting accessibility and usability. Overcoming acceptance barriers constitutes a crucial aspect, acknowledging the need for societal integration of advanced robotic systems. In addressing these questions, the study aspires to contribute to the evolution of robotics, paving the way for more intuitive, adaptable, and widely accepted robotic technologies.

In the following, section 2 provides a summary of related work and gives a short introduction for principles, setup and framework. Section 3 introduces a case study for interaction and learning works and describes experiments, where the novel method of this work is tested in a user study. Section 4 discusses results and limitations. Section 5 offers a conclusion and outline of future work.

2 Background and Related Works

This section provides an overview of systems of cobots (2.1); current applications of kitchen robots (2.2); robot motion interfaces (2.3); and task allocation in Human-Robot teams: by using Therbligs to identify action sets and task division (2.4).

2.1 Collaborative Robots

Cobots are designed to allow humans and robots working together side-by-side, in direct physical interaction with a human user and within a shared workspace (Colgate et al., 1996). Cobots are often employed with the objective to increase workplace flexibility and productivity. A move from a manual to a flexible, robotic, human-involving workplace requires understanding and informed decision making on the side of the worker about what manual work can be handed over to a collaborative robot. In this context, the evolving role of robots as co-workers and collaborators, particularly with the introduction of collaborative robots, or cobots, is important. This introduction of robots in relationship to a human co-worker challenges established social, ethical, and cultural norms that either facilitate or impede their integration. Hence, this research seeks to explore methods of introducing cobots while respecting the significance of human presence in various contexts. For example, there exists a potential for cobots to mitigate musculoskeletal disorders (MSD) by assuming human movements such as lifting, pushing, pulling, and tugging, aiming to prevent MSD and reduce health-related compensation claims in fields like construction and fabrication. The research also delves into the development of training and engagement protocols for human-robot interaction (HRI), addressing the challenge of training robots for multiple movements in diverse settings, including construction. Additionally, the study explores the feasibility of cobots as collaborators in various contexts, ranging from construction sites to public or domestic applications, and evaluates the adaptation of hardware, particularly end effectors, to accommodate the diverse tool requirements of different work scenarios. Better insights are required into the effective integration of cobots, considering both the physical aspects of human-robot collaboration and the broader socio-cultural implications.

The collaborative nature, the ability to learn, and the guarantee of a safe co-existence of collaborative robots and humans in the shared workspace represent an essential change in the use of robots. The flexibility of decision-making between manual and robotic processing enables the technological upgrade of a manually managed workplace (Gajšek et al., 2020). Human-robot teaming, where humans and robots collaboratively perform parts of the task that they are best suited to perform, holds considerable promise for improving industrial work, but significant hurdles still remain in capitalizing on that promise (El Zaatari et al., 2019). While recent studies explore Semantic Recognition of Human Gestures for human-robot interaction (Lin et al., 2013), there remains a discrepancy between the traditional robot programming approaches used by developers and engineers who integrate robots into industrial environments and the needs of collaborative interaction design, the task of specifying collaborative tasks requires a different approach than what is afforded by standard non-interactive robot programming approaches. Schoen et al outlined four key technical challenges involved in human-robot teaming: (1) representation: representing work for both human interpretation and robot execution; (2) task-skill matching: creating human-robot plans that match task elements with worker skills while achieving task goals; (3) robot programming: implementing task elements for collaborative robots in a way that supports exploration of task plans across robot platforms; and (4) authoring pipeline: facilitating intuitive and effective translation of manual work into human-robot plans (Schoen et al., 2020).

Actions required for work processes can be ordered in a Hierarchical Task Analysis (HTA), including a) top-level actions which refer to object handling or the order in which objects are to be manipulated, and b) bottom-level actions that focus on which actions are required (Winter). Identifying hierarchical structures of work processes including tool requirements, material affordances, and motions by both human and robot agents can be exploited to reduce the total solution space. Consequently, a better understanding of robot actions, task sets and sub-tasks for actions is required for collaborating with a cobot or industrial robotic arm, whereby the potential function is defined over all composite tasks across top-level and bottom level work. It is essential to recognize that a robot's genuine value within household settings extends beyond mere companionship to encompass aspects of "workmanship," as underscored in a survey on the general acceptance of robots (Arras & Cerqui, 2005). Additionally, robots are then also contextualised in atypical environments and tasks (Ito & Nakamura, 2022). This implies that in the context of human-robot collaborations, factors such as interaction, communication, and reciprocal exchange need to be given additional consideration. Is a robot merely an object or perhaps a tool? A tool that itself wields another tool? A mechanical device? Or can it be regarded as a genuine companion? Identifying the distinguishing features that transform a robot into a companion rather than a mere tool poses a pertinent question in this exploration.

2.2 Applications of kitchen robots

While a fully automated yet not fully comprehensive kitchen in the film 'Mon Oncle' (Tati, 1958) delivered surprising effects, recent studies into introducing robots in a domestic or industrial kitchen environment have been developed, with the focus on retrieval of recipes and task automation, often with the limitations of programming robots for specific recipes and high affordances in time and expertise. While early studies consider assistive technologies (Boyer, 2004), industrial domestic robots are often programmed for automation (Junge et al., 2020); provide a consumer robotic kitchen with dual arm system by Moley (Hansman, 2015) or ; or the Samsung robot arm duo 'Botchef' (Techable, 2019), based on chef's methods and techniques captured through a 3D motion tracking system and translated into movement using bespoke algorithms. Both approaches assume automation of processes rather than human-robot interaction or collaboration. Further studies expand these limitations to enable a larger range of production, with a focus on natural or textural language for robot programming and motion planning. 'BakeBot' demonstrates application of textual recipes in a kitchen environment that were prepared by a robotic chef, whereby a dual-arm robot collects recipes online, parses them into a sequence of low-level actions and executes different recipes, within a set scenario with workstation and ingredients laid out, and a repertoire of primitive actions, such as pouring ingredients into a bowl and mixing them (Bollini et al., 2013). Integrating the robot into domestic environments includes research into robotic kitchen counters can be equipped with sensors and actuator for action-adapted assistance (Morishita et al., 2003; Yamazaki et al., 2010), ubiquitous sensing and actuation for Robotics and Autonomous Systems (Rusu et al., 2008), or evaluating the usability and users' acceptance of a kitchen assistant robot in household environments (Pham et al., 2017).

While a sequence of tasks was successfully carried out in real space, and the system's performance was simulated to adhere to a broader array of recipes, 'Bakebot' predominantly operates with the primary aim of aiding a human partner who intervenes when faced with unsupported task primitives. These are instances where the robot system requires assistance in executing instructions. Similarly, an exploration of robot motion planning, based on the analysis of online recipes, demonstrated the feasibility of 25 out of 50 recipes by scrutinizing and scripting cooking procedures and cross-referencing them with a motion code database (Inagawa et al., 2021). However, the generation of robot motion through offline teaching using a cooking robot simulator, while successful in reproducing defined motions, relied on fixed action protocols and stationary positions of cookware and ingredients. This approach neglected human interaction, thereby limiting the solution space and hindering the advancement of work process applications or adaptations to material changes. In contrast, the present research delves into the collaborative performance of work processes by human-robot teams, emphasizing the development of a tool archive, action sequences, and task sets to facilitate open-ended applications in the realm of cooking (see Figure 2).

Humans naturally categorize items for storage and handling, and the use of classification techniques employing object features can replicate this organizational process. In the context of human-robot interaction, kitchen objects serve as classification system and a database for investigating danger perception (Leusmann et al., 2023). An additional dimension refers to non-finite materials, such as liquids (Elbrechter et al., 2015). At the core remain user and skill adaptability (Wang et al., 2021), which may include human advice to robots (De Winter et al., 2019). An organizational study on robots' adaptation to domestic environments (Cha et al., 2015) outlines key challenges. Firstly, regarding object-related features, robots need to return items to specific locations without constant detailed instructions from users. Secondly, for effective user adaptation, robots must learn user-related features, including instructions about object locations, spatial arrangements, and user habits. This adaptability is crucial for seamless household operation and assimilating new information. Lastly, in dynamic environments like kitchens, robots must register and implement new data about the surroundings, agents, and objects to adapt their behaviour, necessitating both sensing capacity and machine learning capabilities.

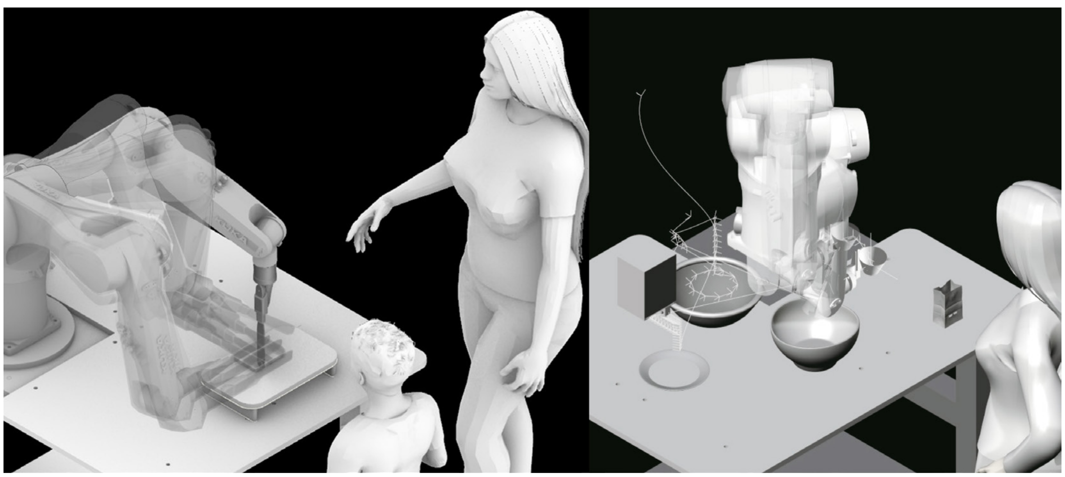


FIGURE 2 Detail of RobotKitchen environment with adapted tools for intuitive human-robot interaction, including cutting (left) and mixing(right), with multiple interactants – collaborative robot arm, two humans – within one workzone.

2.3 Access Points: Robot Motion and Interface(s)

Robot motion programming often demands significant expertise in robotics or coding, presenting a challenge for users and creating barriers to spontaneous or intuitive human-robot collaboration. Effective work processes rely on the ability to plan and visualize robot motion, emphasizing the importance of simple and accessible user interfaces. Common methods include robot motion programming through tools like KUKA prc and ROS, while alternatives involve using a teaching pendant to establish a sequence of points and corresponding angles for the robot arm or employing motion capture systems for hands and arm motions. This research specifically examines robot motion planning within the context of recipe procedures, encompassing operations related to ingredients, movements, tools, and utensils. Human-robot interaction intricately involves explicit information on tool use, toolpath angles, robot trajectory, destination points for material deposition, work plane, and workspace. This complex setup is interconnected through tasks and action sets, requiring differentiation into subsets. To enhance capacities for both the robot and the human, each actant is considered for best practices, with the robot emphasizing precision, consistent quality, repeatability, and handling potentially hazardous tasks, while the human brings advantages such as an unlimited movement range, sensing and locating ability, tolerance compensation, flexible availability, handling complexity, and innovative capacity.

The nature of the tool is questioned—is it an object with associations, or is it an integral part of the robot? Recent research on human-robot collaboration advances the understanding of measures like trust, safety, and effectiveness, predominantly focusing on optimization. However, Leusmann et al. (2023) observe that objects shared in a work process influence these measures and impact human perceptions of danger and safety levels during handling. Their online survey of 153 kitchen objects reveals significant variations in how humans perceive kitchen objects. The object-holder plays a role in danger perception, and prior user knowledge increases the perceived danger when robots handle those objects.

2.4 Task Allocation in Human-Robot Teams

To understand the actions and tasks shared between humans and robots, the study utilizes Therbligs to identify action sets and task allocation, employing Hierarchical Task Analysis (HTA) to model human-robot tasks and pinpoint action sets and sub-tasks distributed between the two entities.

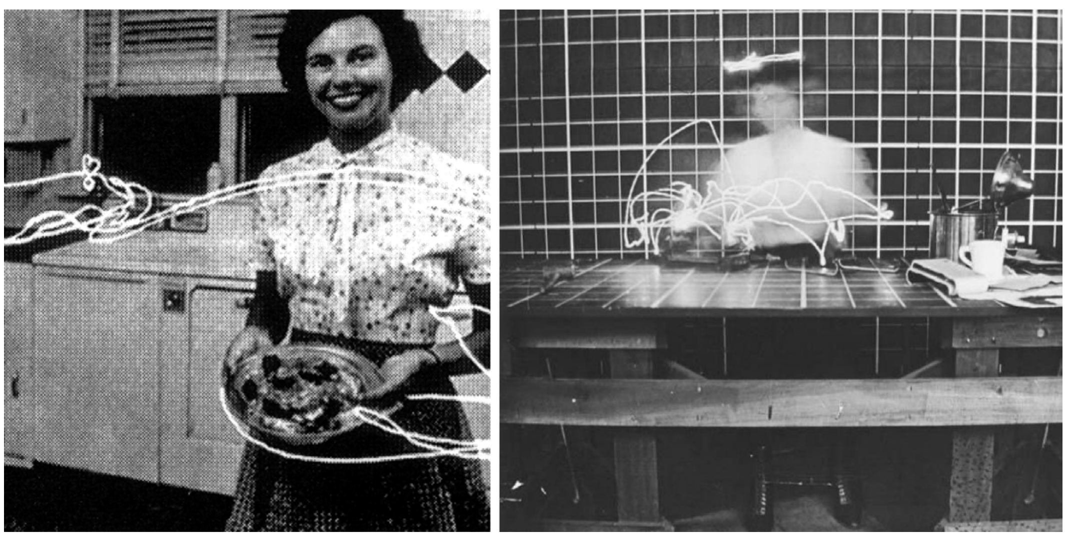


FIGURE 3 Optimisation for kitchen processes around 1960/70 (left), Motion efficiency study by Frank Gilbreth, c. 1914. Collection: National Museum of American History.

The Therbligs, originally developed by industrial analysts Frank and Lillian Gilbreth in 1911, constitute a task assessment system designed for industrial work. This classification system, named after the Gilbreths (spelled backward as "Therbligs"), was created to capture, analyze, and categorize motions that capture human activities during a work task (Gilbreth, 1930). Such motion studies situated in factory environments were later also adopted for optmising space efficiency for kitchen work (Figure 3). Gilbreths' Therbligs can be used to describe any task (Ferguson, 2000), including elemental motions of human-related physical actions, cognitive processes, and behaviours. In turn, these further reverse-engineered to categorize actions and subdivide tasks to achieve results in a work process (Yen, 2011, S. 20). Therbligs contain both data on action and information (Oyekan et al., 2020), as a work agent observes the environment, obtains information, evaluates against an action, and then continues to implement that action as next step. Importantly, the agent in this context can be human or robot, depending on task allocation -and so, full work processes can be segmented in work tasks that are collaboratively shared between human and robot. Recent research (Chen et al., 2021) used Therbligs to analyse user behavior in a kitchen context with observation of actions by the elderly via video documentation, with the aim to optimise kitchen layouts. Their decomposition of continuous actions focuses primarily on spatial setups and movement across U or L shaped kitchen layouts. In addition, an excerpt of seven Therbligs has been adopted as rule-based, compositional, and hierarchical modelling of action used by Dessalen et al. (2023) in a kitchen context.

	Therblig	Description	Agent*
1	Search:	Begins when the eyes and/or the hand start to seek the part and ends when the part is located.	H, C
2	Find:	Momentary mental reaction at end of the search cycle.	H, C
3	Select:	Choosing a particular object among a group of similar objects.	H, C
4	Grasp:	Starts when the active hand grabs the object and ends when the next opera-tion (use or transport loaded) starts.	H, R, C
5	Hold:	Retention of a part after it has been grasped, with no other movement or manipulation of this part taking place.	H, R, C
6	Transport loaded:	Moving a part using a hand motion.	H, R, C
7	Transport Empty:	Moving the unloaded hand.	H, R, C
8	Position:	Placing the part in the proper orienta-tion for performing the motion "use".	H, R, C
9	Assemble:	Joining two parts together.	H, R, C
10	Use:	Manipulating an object in a way it is intended to be manipulated.	H, R, C
11	Disassemble:	Separating parts that where joined.	H, R, C
12	Inspect:	Comparing the object with a predetermined standard.	H, C
13	Preposition:	Replacing an object in the proper orientation for its next "use" (position is performed after).	H, C
14	Release Load:	Releasing the object when it has reached its destination.	H, R, C
15	Unavoidable delay:	Period from the point when a hand is inactive to the point when it becomes active again.	H, R, C
16	Avoidable delay:	Waiting within the agent's control which causes idleness that is not included in the regular work cycle.	H
17	Plan:	Mental function which may occur before one action (deciding which part is going next) or prior to "inspect".	H
18	Rest:	A lack of motion which is only found when the rest is prescribed by the job or taken by the worker.	H

TABLE 1 An overview of the Therbligs and descriptions, and further offers a categorisation for potential human/robot action. Significantly, some Therbligs refer to physical actions are available to both human or robot (as an industrial robotic arms devoid sensors), such as Grasp (4), Transport Loaded (6) or empty (7), Release (14), or Position (8). Others describe cognitive processes that require sensors, such as Search (1), Find (2) or Select (3), or human-focused actions such as Un/Avoidable Delay (15, 16), Plan (17) or Rest (18).

*H (human), R (industrial robotic arm), C (collaborative robot)

3 Case Study: A Robot Kitchen for Reverse Engineering Recipes

The following sections presents integral components of the robotic system, specifically focusing on the Robot Toolbox, Robot Toolpath Library, and Human-Robot Action Sets. The Robot Toolbox serves as a critical aspect, providing endeffector access to industrial robotic arms by employing custom-designed toolholders (Figure 4). These toolholders facilitate the mounting of various work tools, ranging from typical kitchen utensils to workshop tools, offering a versatile foundation for scripting, tooling, and calibrating robot motion sequences. The design includes adaptable features, accommodating a wide array of tools and end effectors, fostering a customizable base that can readily evolve with further additions.

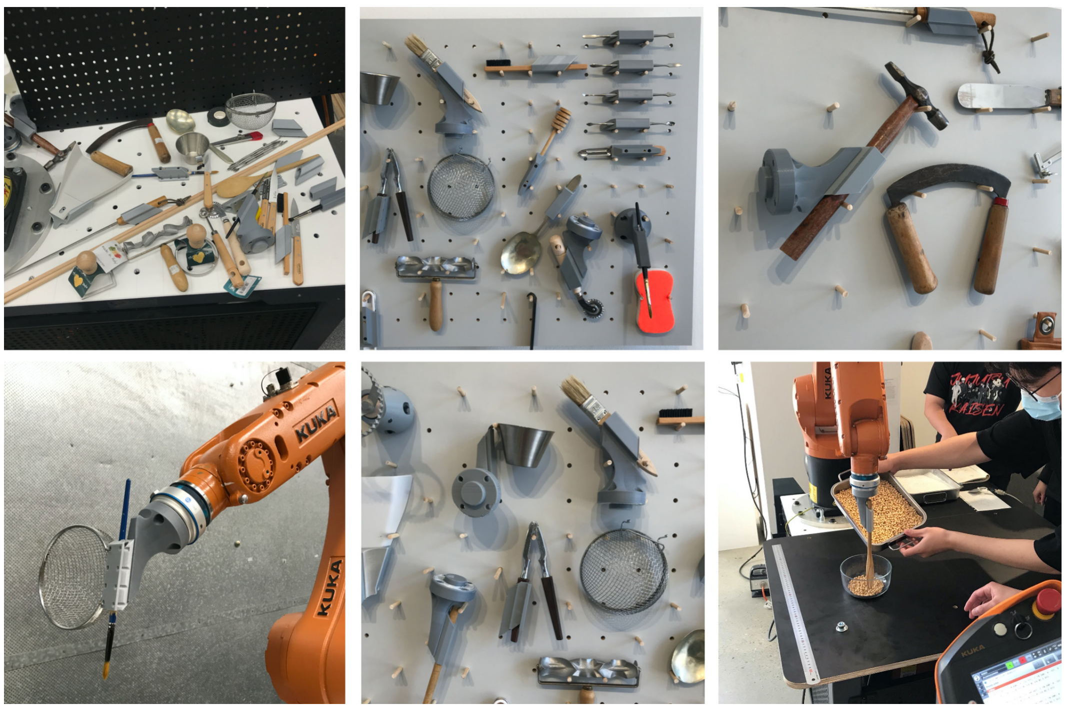


FIGURE 4 Tools adapted as robotic end-effectors across kitchen and workshop, including hammer, stamps, carving knifes, heat resistant glove, measuring cups, or brush, etc. While commonly used in only one context, tools share attributes and can be adopted across applications.

The Robot Toolpath Library is introduced as a pivotal element, enabling users with varying computational design knowledge to program and simulate original motion sequences with chosen tools from the Robot Toolbox. Script Bites, designed for users with a range of expertise from 3D modeling to introductory-level robot programming, offer a user-friendly interface to create and simulate motion sequences for diverse applications. This library encompasses various motions, tools, and robot types, facilitating accessible robot programming without specialized knowledge.

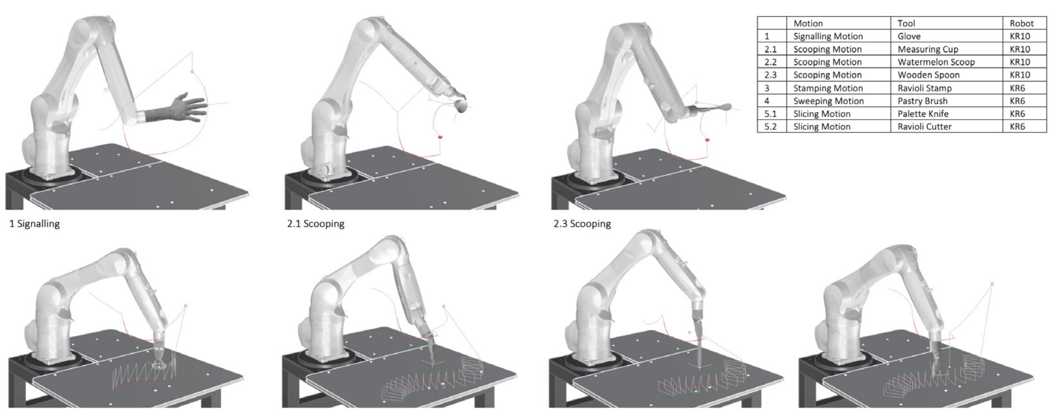
Transitioning to Human-Robot Action Sets, participants are guided to adopt the Therblig framework for food production tasks. The focus is on defining actionable tasks for both the robot (considering factors like toolsets, workplace definition, and reach) and the human (factoring in age, dexterity, and skillsets), along with detailed descriptions of crossovers between both agents. The Therbligs serve as anchor points, facilitating the identification of task divisions, shared tasks, and considerations for interaction and handovers. This framework allows for effective planning of tasks, sequences, and interactions that align with the capacities and restrictions of each agent. The subsequent sections explore these elements in further detail, providing insights into the development and implementation of our integrated human-robot system.

3.1 Robot Toolbox: Providing Endeffector Access

Physical tools were matched with custom designed toolholders as a series of work tools that can be mounted on two industrial six axis robotic arms used for the test series. Figure 4 illustrates an overview of the toolbox that includes typical kitchen utensils and workshop tools, with the aim to provide a departure point for initial scripting and tooling, including robot motion sequences and calibration. The toolholder is adapted for the robotic toolplate and secured with 4 screws, with a 3D printed base geometry, and a) variable additions that lock-in as quick adaptation with shared profile or diameters (spoon, ladle, knife, paintbrush, honey ladle); or b) larger dimension tools or bespoke profiles (stamping tool, measuring cup, sieve, skewer, glove); and c) end effectors that adapt typical workshop tools (saw, hammer, broom, palette knife, or carving tools). This toolholder design provides a customisable base that can be readily modified to hold further additions to the toolbox.

3.2 Robot Toolpath Library: Enabling Robot MOTIONS

Users with varying knowledge in computational design, scripting and robot programming (min 3D modelling -max introductory level robot programming) used Script Bites, with the objective to program and simulate an original motion sequence with a chosen tool of the robot toolbox, with a motion relative to their chosen dish. Scripts were simulated and then physically tested on a KUKA KR 10 or KR 6, relative to tool setup. Figure 5 shows an overview of available motions, tools and robot types.



	Motion	Tool	Robot
1	Signalling Motion	Glove	KR10
2.1	Scooping Motion	Measuring Cup	KR10
2.2	Scooping Motion	Watermelon Scoop	KR10
2.3	Scooping Motion	Wooden Spoon	KR10
3	Stamping Motion	Ravioli Stamp	KR6
4	Sweeping Motion	Pastry Brush	KR6
5.1	Slicing Motion	Palette Knife	KR6
5.2	Slicing Motion	Ravioli Cutter	KR6

FIGURE 5 A toolpath library that enables Script Bites (robot programming) for users without specialist knowledge, developed for action sets and tools, including signalling, scooping, stamping, sweeping and slicing motions.

Participants programmed two robot actions; first on a general level and then adopted as robot motion integrated into a human-robot interaction as part of a food production sequence. This means that participants were programming in a constraint knowledge space – effectively inhabiting a pre-set robot program) while exploring the potential solution space for their individual task set, with focus on constraints that are physically possible.

3.3 Human-Robot Action Sets: Allocating Therbligs

Each participant group was tasked with adopting the Therblig framework for their food production scenarios. The emphasis was placed on identifying actionable tasks suitable for robots (considering factors such as the absence of sensors, diverse toolsets, workplace definition, and reach) and/or humans (considering age, dexterity, and skillsets). Additionally, participants provided detailed descriptions of crossovers between both agents. The Therbligs served as pivotal reference points for discerning task divisions or sub-tasks that could be executed by either agent, determining which tasks could be shared, and specifying instances where interactions and handovers should be considered. Consequently, the allocation of Therbligs facilitated the planning of tasks, consecutive sequences, and interactions, considering the capabilities and restrictions of both agents (Figure 6 provides a concrete example of this process).

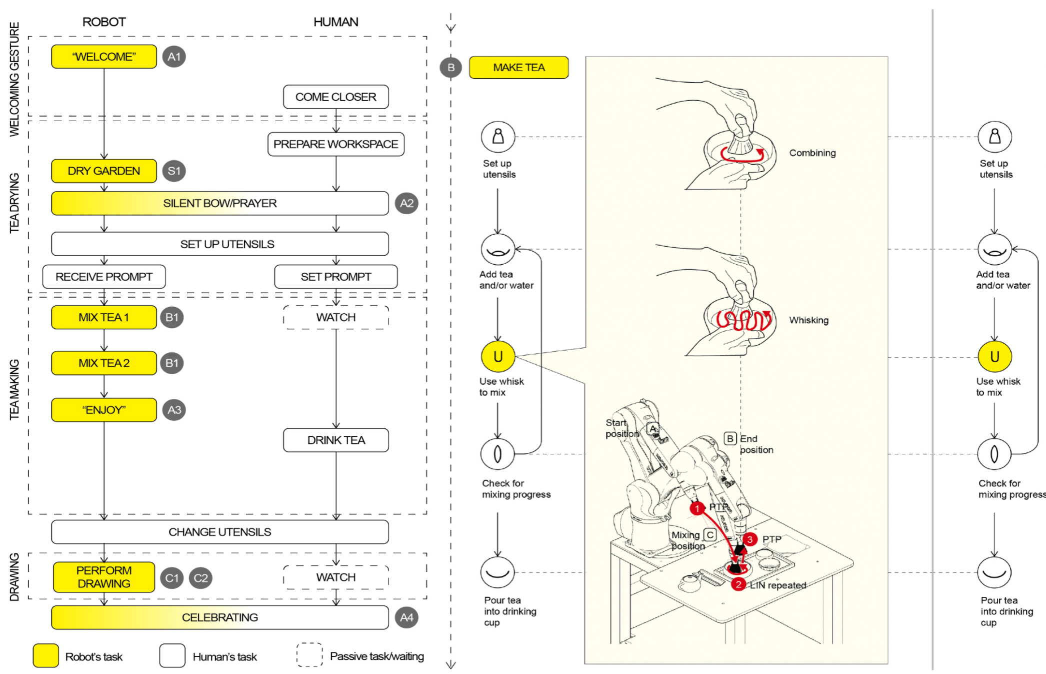


FIGURE 6 Diagrammatic analysis of shared action sets shared for human- robot team (left), and discrete sequences with Therbligs identified, here for tea making (right).

3.4 Demonstrators and Prototypes

Across a diverse range of food production scenarios that encompassed various cultural and social backgrounds, users demonstrated a remarkable capacity for adaptation and innovation. The incorporation of tools and ScriptBites was not merely limited to their intended purposes; rather, users expanded the boundaries of work processes by employing combinatorial logic to devise novel robot protocols, material applications, and tools. The spectrum of food concepts explored was extensive, spanning procedural tea-making, meat tenderization, pouring and mixing for jelly and no-bake cake preparation, as well as the construction of intricate desserts such as croquembouche and mille-feuille, as illustrated in Figure 7.

FIGURE 7 Overview of Case studies with six user groups, ranging from gestural and communication tasks for a robot (left, top) to precise and customised food gradients (right, bottom).

Significantly, the robot action protocols enable explorations with multiple materials and multiple tools. Similar to workshop, manufacturing or fabrication environments, this includes subtraction processes (cutting, slicing), production of finely tuned outcomes in ranges and gradients, additive processes such as mixing of various fluid materials (or granulates), changing textures and densities, handling temperature-based substances (hot/cold), and exerting directional force, pressure or repeated punching. While these actions take place in a kitchen environment here, there exists the potential to transfer these processes to more traditional fabrication and workshop domains. Tools and processes can be quickly and precisely adapted and adjusted to material constraints and variations.

The innovation extended beyond conceptualization, involving the development and 3D printing of new tools and tool adaptors. Users engaged in scripting iterative variations for robot motions, and an initial analysis of Therbligs played a pivotal role in human-robot task allocation. The results demonstrated the versatility and applicability of the framework across diverse knowledge sets of users. Moreover, it proved effective in task planning within a series of objectives (dishes), effectively accommodating new constraints introduced by the users and the specific task set. This multifaceted approach showcased the potential for creativity, intuitive handling and problem-solving within the context of human-robot collaboration in food production.

4 Discussion

Results are reported in the following. Participants quickly understood how to act within the given framework and system. The constrained solution space was useful for most participants in focusing on robot actions and workability in production of food segment. Executing the recipes on the robot shows a functioning open-ended system (as opposed to automated, end-to-end systems). While the set of motion primitives enable a variety of simple recipes to be executed with the industrial robot arms, several recipes could be successfully demonstrated. More significantly, the setup showed a high function of user acceptance, whereby participants were able to confidently use and riff off provided robot codes. A significant benefit is here the human capacity for innovation and intervention, with significant ability to assess, correct and control ongoing robot programs, constellation of material and utensil positions, and intervention in case of errors of the robot system. The Therbligs enabled participants to structure the workflows between human-robot teams; adjust according to agent capabilities; evaluate and control sub-tasks within the motion protocols, which enabled a much higher degree of precision planning.

However, several limitations should be noted. Limitation of the system stem from the lack of robustness, whereby failure in any of the robot's systems leads to a failure to successfully follow the recipe. Another limitation stems from the fact that materials are non-finite, ie consumables, with undetermined shrinkage, segmentation, change of gravity center, or changes from liquid to solid states. Real-time data feedback that continuously informs robot protocols; Machine-learning systems (ML) would enable increased response of the robot. Future potentials can offer another level of adjustment by expanding to Human-cobot collaboration, which is sensor based, offers continued data feedback, and allows integrating Graphical user interfaces, language processing, object recognition, task planning, and manipulation.

Significantly, the contributions of this research are in; a) a novel workflow based on a palette of work tools adopted for robot tooling to translate manual human tasks to human-robot tasks; b) an initial script series for work processes that represents modelling, planning, simulation, and implementation; c) a framework for task division through action sets based on Therbligs that supports users; and d) an empirical evaluation of the approach through a series of user studies. This can be of particular importance in a context of postcarbon, where architecture and construction industries need to respind to resource scarcity, circular materiality and careful considerations of embodied carbon. The robotic test studies serve here as departure point for embedding gradient conditions, working with non-finite and indeterminate substances and materials, and allow precise and versatile machining beyond automation.

5 Conclusion and Future Work

This research has introduced an innovative workflow cantered around a diverse set of work tools adapted for robot tooling, facilitating the translation of manual human tasks into human-robot tasks. It encompasses an initial script series that covers modelling, planning, simulation, and implementation of work processes, along with a task division framework based on Therbligs, supporting users in their interactions with robots. The empirical evaluation of this approach was conducted through a series of user studies. Future research directions may include three key dimensions: the reverse engineering of skill sets and process knowledge, facilitating the transfer and adaptation of the developed framework to other work processes and tasks, and extending its application to other cyberphysical systems for enhanced sustainability. The restructuring of human-robot interactions is envisaged, where robot/cobot systems can impart process knowledge and transfer skill sets for tasks related to food preparation and production.

Cooking, being a domain that necessitates physical, kinematic expertise in tool and utensil usage, heat source and hot material handling, temperature control, and understanding the chemistry of different ingredients, provides a context where a robot can be trained for actions and, reciprocally, teach and demonstrate process knowledge. While this research has primarily focused on kitchen scenarios as a distinctive robot work environment, the actions, tasks, analytical studies, framework, and workflows developed can be readily adapted for applications and contexts where collaboration and interaction between robots and humans are essential. This extends beyond traditional kitchens to include workshop and fabrication scenarios characterized by the complexity and variability of task applications. Additionally, in a robot-supported domestic environment, integration with big data can address issues related to reverse speed, homogeny, expediency, and globalization. This connection can align with initiatives such as the Slow Food and Farm-to-Fork movements, integrate with community gardens, embrace communal values associated with regional context and supply and assist individuals in adapting methods for sustainable resource utilization, waste and recycling strategies, and the promotion of circular economies in various domains, including food, architecture, design, fabrication, and manufacturing.

Acknowledgements

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INDEX/Definitions

- *Authoring pipeline:* refers to facilitating intuitive and effective translation of manual work into human-robot planning and programming of interactions and collaborations (Schoen et al, 2020).
- *Collaborative task execution (CTE):* an agent autonomously performing a task either collaboratively with or in the presence of other agents, while respecting any associated social roles and divisions of responsibility.
- *Learning from Demonstration (LfD):* refers to a robot control system that is capable of engaging in collaborative behaviors, including the capability for safe operations, physical manipulation, speech recognition, and even non-verbal communication, and intention detection.
- *Skill:* Refers here to either human or robot and is defined as a temporally extended action similarly to options in reinforcement learning, and is assumed to minimally include a set of known preconditions, expected post-conditions, and known goal states.
- *Trace observation:* a method of investigation in spatial planning and design for observing user movement in space, results of trace observation support design applications across all stages and are commonly used in the planning and evaluation of design solutions.
- *Task Allocation:* describes the division of tasks in Human-Robot Teams. Human-robot tasks can be derived from Hierarchical Task Analysis (HTA) and hierarchical learning. Interactions are then planned and managed by use of Therbligs, which support identifying action sets and task division.
- *Therbligs:* are basic actions required to complete a task and include effective, auxiliary and ineffective motifs (Chen). The analysis of kitchen behavior Therbligs focuses on the observation of actions in the kitchen of the elderly and the decomposition of continuous actions. The actions are categorised according to 18 kinematic factors and the process is optimised through ESRS (Eliminate, Combine, Rearrange, Simplify).

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Advancing Sustainable Approaches in Architecture by Means of Design-to-Robotic-Production

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Abstract

The construction sector accounts for about 40% of material-, energy- and process-related carbon dioxide (CO2) emissions [1], which can be reduced by introducing data-driven Circular Economy (CE) approaches [2]. For instance, Design-to-Robotic-Production (D2RP) methods developed in the Robotic building lab, at Technical University (TU) Delft are embedding data-driven systems into building processes. Their potential to contribute to sustainability through increased material-, process-, and energy-efficiency has been explored in several case studies that are presented in this paper. The assumption is that by using these methods and reclaimed wood to minimize demand for new resources and reduce deforestation along the way, CO2 emissions can be considerably reduced.

Keywords

Architecture, building construction, CO2, circular- and AI-supported robotic approaches

DOI

https://doi.org/10.47982/spool.2024.1.04Introduction

1 Link to IEA report:
https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019

2 Links to Springer volumes edited by Bier (2018) and Morel and Bier (2023):
https://link.springer.com/book/10.1007/978-3-319-70866-9 and
https://link.springer.com/book/9783031141591

1 Introduction

In the last decade, data-driven, and in particular, robotic applications in architecture and building construction have increasingly proven their potential for contributing to sustainability through increased material, process, and energy-efficiency (Ashby, 2024; Bier, 2018). When integrated with Circular Economy (CE) approaches additional carbon dioxide (CO_2) reduction is to be expected (Dokter et al., 2021).

Design-to-Robotic-Production (D2RP) methods presented in this paper as part of a larger Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) framework developed at Technical University (TU) Delft integrate data-driven design involving performance optimization techniques to maximize functional-, structural-, material-, and energy-efficiency with CE approaches that rely on the reuse of materials while taking life-cycles into account. Furthermore, they increasingly take advantage of Artificial Intelligence (AI) in various stages of the design to construction process (Bier et al., 2022).

2 Design-to-Robotic-Production

D2RP efficiently links computational design with robotic production. It involves subtractive and additive techniques such as cutting and milling into materials such as plastic, wood, etc. and robotic 3D-printing with materials such as clay, plastic, etc., respectively (Bier, 2018; Bier et al., 2020). When equipped with various end-effectors robotic arms are versatile and in combination with Machine Learning (ML) models that accurately simulate the process and predict how processes evolve over time, and optimal settings can be identified (Peters et al., 2011) to optimize energy consumption and thereby reduce material use and processing time.

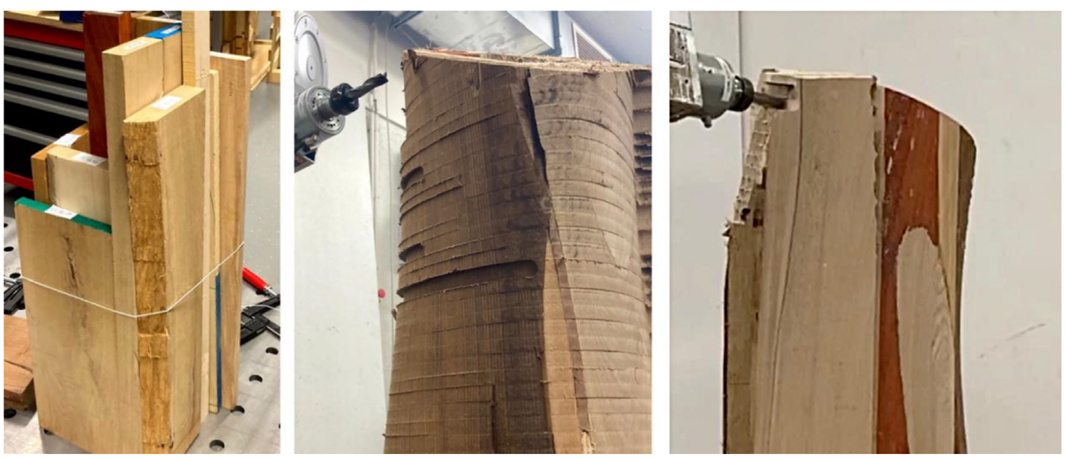

FIGURE 1 Packed, glued (left) and milled (middle and right) reclaimed wood boards serving as curvilinear beams for a larger structure.

3 Subtractive D2RP

Subtractive D2RP methods were advanced at TU Delft amongst others in a case study involving reclaimed wood. The overall goal was to demonstrate the potential of robotically processed reclaimed materials in architecture (Fig. 1-3) to not only improve efficiency and reduce CO2 but also create aesthetically pleasing artefacts.

The use of circular wood has been explored in collaboration with the University of Applied Science (UAS) Amsterdam. It involved the processing of reclaimed wood by laminating reclaimed wood boards into a larger component, which was robotically milled into topologically optimized curvilinear beams as part of a larger structure[3]. The combination of various wood boards from various types of wood resulted in an aesthetically pleasing pattern of alternating darker and lighter wood (Fig. 1) due to the randomly packed wood boards.

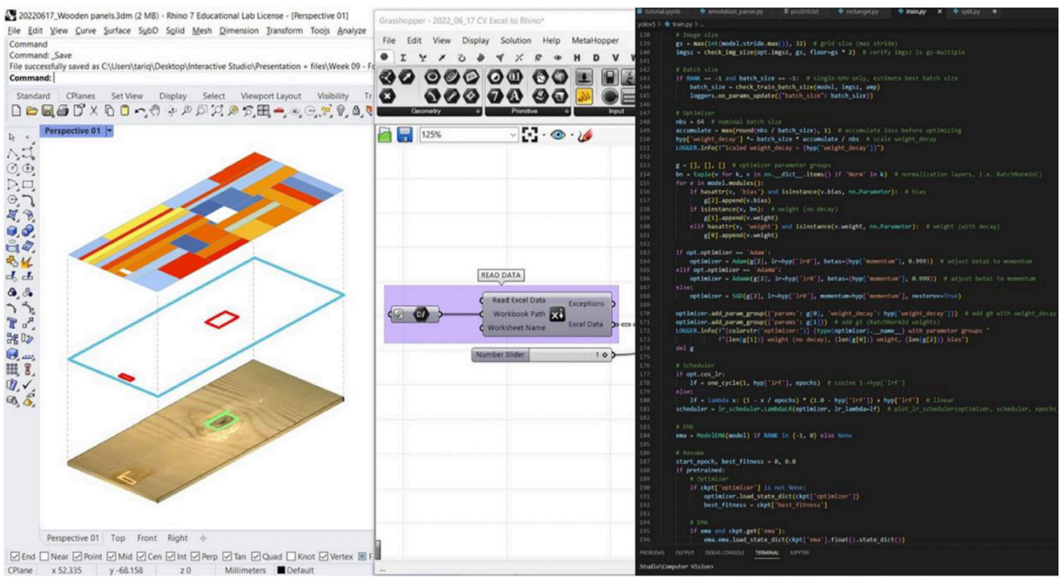

FIGURE 2 ML-supported processing of reclaimed wood panels.

The lamination of reclaimed wood boards in this initial study could have profited from the ML- supported approaches involving Computer Vision (CV) that was developed in a later study in collaboration with the AiDAPT lab at TU Delft. The CV was employed to identify defects in the wood with the goal to demarcate and remove them in order to ensure the structural integrity of the to-be-built structure. The defect recognition using images of wooden boards relied on a trained model that identified the size of the board and demarcated the defects (Fig. 2). These were used within Grasshopper Rhino [4], to generate cutting patterns to remove respective defects. The obtained dataset consisting of 4000 wood boards images with visible defects was pre-labelled as part of another dataset in Kaggle[5]. Upon training the Yolov5 model [6] with 200 epochs, the bounding boxes, object, and class loss in validation data, kept improving until the

3 Link to CW4N: http://www.roboticbuilding.eu/project/wood-reuse/

4 Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D application.

5 Online community platform that allows users to collaborate, publish datasets and use GPU-integrated notebooks.

6 Yolov5 is a compound-scaled object detection model.

200 epochs, which the dataset was trained on. While this ML-supported approach improved material- and process-efficiency, the CE approach remained incomplete. To complete the cycle, the sawdust generated during the milling and cutting phase was reused in another case study involving the robotic 3D printing of a small-scale urban intervention.

4 Additive D2RP

The wood-based polymer structure (Oskam et al., 2022) serving local biotopes was developed in collaboration with Landscape Architecture (LA) at TU Delft and industrial partners. As minimal intervention that stimulates both biodiversity and social accessibility of residual spaces, the intervention takes shape as a 0.8-meter diameter 'planetoid' prototyped using additive D2RP techniques [7]. Its cavernous design facilitates its appropriation by plants, insects, and small animals (Fig. 3).

While the overall form, porosity, and surface tectonics are informed by the use, structural requirements, and environmental conditions of the 'planetoid', the Voronoi mesh itself is optimised for support-free 3D-printing with a biopolymer consisting of cellulose, hemicelluloses, and lignin, which is processed from sawdust that is mixed with a binder, in this case, a thermoplastic elastomer (TPE) that is recyclable.

Support-free 3D printing is achieved by controlling the angles of the Voronoi cells to be within the printing constraints that take into consideration the maximum achievable printing angle, which depends on the viscosity of the material at extrusion temperature as well as cooling i.e., crystallization speed. The printing angles are limited to 45-55 degrees in relation to the printing bed. Since the Voronoi-based cellular structure is an inherently stable self-supporting type of geometry, the cells can be printed at more extreme angles, while continuous toolpaths ensure that the printing process is efficient. The prototype was subdivided into multiple components, allowing the 'planetoid' to be printed in smaller parts. Based on this strategy larger objects are assembled from multiple components (Fig. 3). The size of the assembled object is thus not limited to the size of the 3D printing system. Also, easy transportation and assembly are accounted for.

FIGURE 3 Wood-based polymer 3D-printed 'planetoid'.

7 Link to BcP Planetoid: http://www.roboticbuilding.eu/project/d2rp-for-product-from-landscape-microruin-lab/

5 Discussion

The reclaimed wood studies involved both, subtractive and additive D2RP processes that complement each other with the sawdust generated through milling being reused in 3D printing thus establishing a complete CE cycle. They are proof of concept for novel strategies and approaches that contribute to CO2 reduction since all materials used were recycled and recyclable. The studies involved optimization routines that ensured reduction of material use as well as production time. Hence, overall efficiency increased, which contributed towards achieving a more sustainable building construction approach.

While the processing of reclaimed materials into new, engineered products using advanced robotic and ML-supported techniques as presented in this paper is today achievable, robotization at large introduces challenges in architecture and building construction in terms of infrastructure and skill shift. However, the gain in terms of process, material, and energy- efficiency and implicit CO2 reduction is indisputable. By reusing materials that might otherwise be discarded and by sourcing them locally from deconstructed buildings the carbon footprint associated with the use of new resources and transportation is minimized.

The sustainable opportunities that involve AI-supported D2RP methods relying on CE considerations are various ranging from material to building scale. Hence, further exploration in and advancement of architectural applications is necessary in order to progress towards a society that meets its needs without compromising the ability of future generations to meet their own needs (United Nations General Assembly, 1987).

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In-Situ vs. Prefab 3D Printing Considerations for CO2-free Pop-up Architecture

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Abstract

This paper revisits existing pop-up typologies in architecture to identify opportunities for new shelter models to address current housing demands and future habitation requirements on Mars. It presents advancements in design to production methodologies based on computational and robotic techniques to meet current requirements and affordances while integrating sustainable and adaptive functionalities. The main goal is to advance pop-up architecture by developing methods and technologies for rapidly deployable on- and off-Earth habitats while addressing challenges of carbon-free architecture by means of 3D printing. By reviewing state-of-the-art in-situ vs. prefab 3D printing approaches with a particular focus on Human-Robot Interaction (HRI) supported Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) methods developed at TU Delft material, process, and energy efficiency using locally sourced materials is achieved.

Keywords

Pop-up architecture, computational design, robotic production, assembly and operation, in-situ and prefab 3D printing, human-robot interaction

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1 Introduction

By studying current models developed for pop-up structures, in a range of specific contexts and by reexamining precedents, the potential and challenges for developing new design-to-production methodologies based on advanced computational and robotic techniques are identified with the aim to frame new models for pop-up structures.

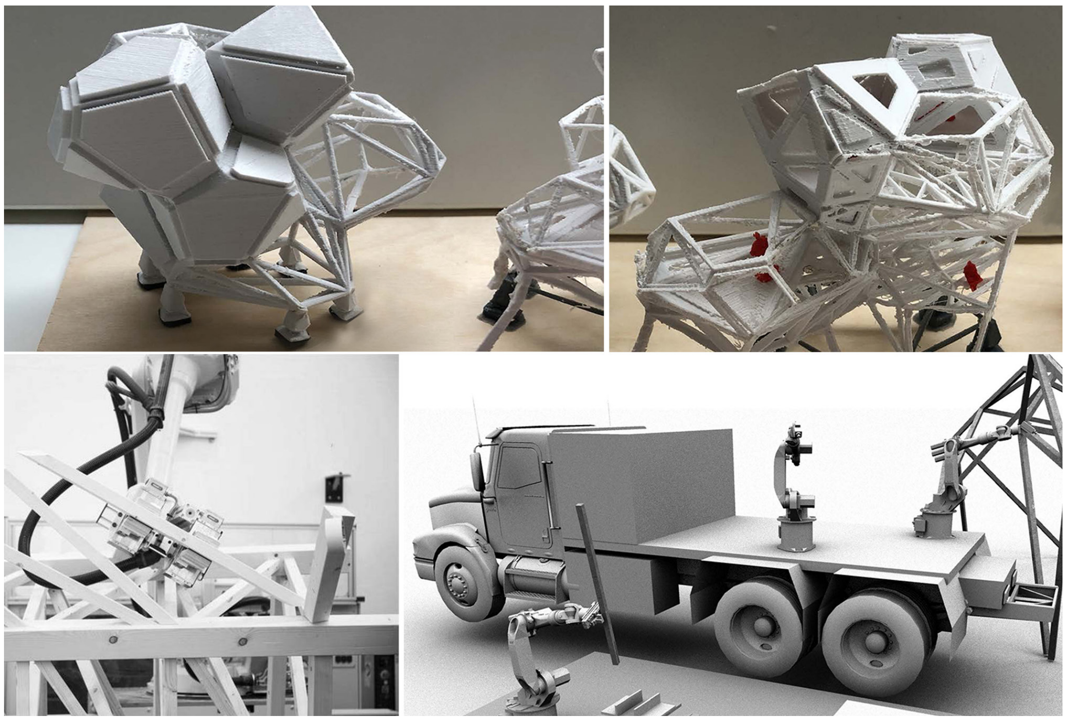

FIGURE 1 Design-to-Robotic-Production and -Assembly of wood-based hybrid structures (Bier, Hidding, et al., 2020)

Current models such as the pavilion developed at the Institute of Building Structures and Structural Design (aka ITKE) at the University of Stuttgart use a robotic fabrication process that is weaving fiber composite material to develop an enclosure (Doerstelmann et al., 2015) and the multi-material wood-based structures (Bier, Hidding, et al., 2020) developed at Delft University of Technology (TU Delft) that both rely on design to manufacturing and assembly methods using robots (Fig. 1), give insight into the potential of computational and robotic techniques. While the first one employs an in-situ weaving approach, the second engages in a prefab approach with in-situ robotic assembly to produce simple structures that can be upgraded to fully functioning housing units in due time. In the prefab approach, robots are not only involved in the fabrication but also in the aggregation of various housing units for the redevelopment of settlements in post-disaster situations.

The potential of such approaches lies in the fast deployment and construction of building envelopes on site, while the challenge remains the operation of robots on site considering their sensitivity to environmental factors. In terms of materials, the advantage of wood-based vs. fiber composite materials is that while wood may be resourced in-situ, fiber composites are not. Hence, the challenge is to identify methods that increase In-situ Resource Utilization (IsRU) and contribute to CO_2 reduction while ensuring that the material properties of the created material meet the requirements for structural performance, durability over time, etc.

2 Methods and Approaches

This paper focuses on computational design and robotic construction methods such as Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) developed in the Robotic Building (RB) lab at TU Delft (Bier, Latour, et al., 2020) that are employed to advance locally customizable approaches in order to address not only on-Earth post-disaster and emergency challenges but also off-Earth construction problems requiring pop-up architecture. This is because of their versatility in terms of materials, tools, and techniques that are employed. Furthermore, by connecting them with mobile energy systems such as the kite-power system developed at TU Delft production units become autarchic and can be deployed off-grid (Bier et al., 2017). Additionally, by integrating Artificial Intelligence (AI) in current D2RPA&O methods and by taking sustainable approaches into account, not only in terms of production but also the operation of shelters, a new model is proposed capable of improving in time and thus supporting habitation not only short but also mid and long term.

3 Precedents

21st-century pop-up architecture models rely on knowledge developed in experiments of the 20th century such as Prouvé's prefabricated house (Bell, 2018) designed for war victims (Prouvé, 2017), Webb's mobile inflatable structure, Cushicle and Suitaloon (Archigram.net, 1964), and Herron's Walking City (MoMA, 2013) that are proposing systems for customizable mobile habitats (Steiner, 2009).

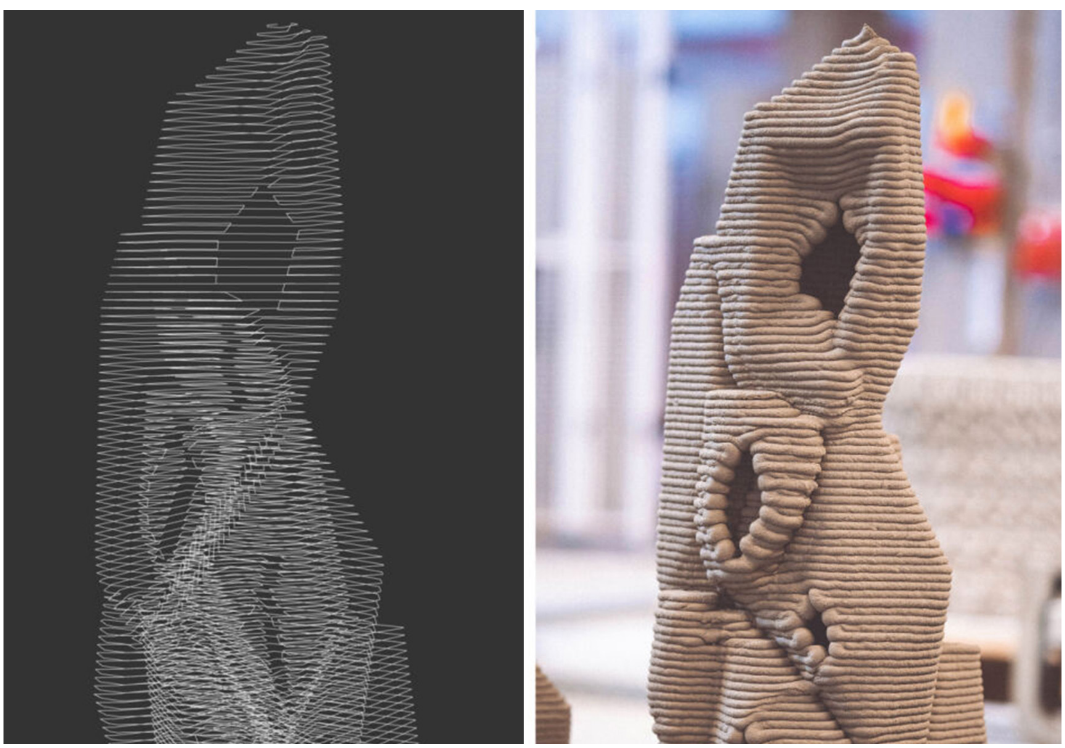

FIGURE 2 Computer-generated toolpath (left) and 3D printed prototype (right) by Vertico 3d printing specialists (©RB lab, TU Delft).

This wide design spectrum of typologies, approaches, and scales is further enlarged by extreme climate design for arctic exploration modules and off-Earth habitats, as well as emergency response and temporary specialist structures. In this context, pop-up structures to support the underserved in economically underdeveloped communities (Bertino et al., 2019), as well as habitats for extreme environments need further investigation. In particular, their design and construction by means of advanced computational design and robotic production and operation technologies have the potential to create customizable structures that can be optimized for various performances. For instance, structural optimization reduces material usage while ensuring the creation of structures that use less material and need less production time. Hence, the parametric design is customized based on the functional and structural requirements of spaces, as well as environmental factors. In the design process, the parametric model is also informed by the limitations of the computer numerically controlled production equipment (Fig.2).

4 Application and Development

Technology influences the architecture of pop-up structures in various ways. The 3D printing approach developed so far for the Rhizome 1.0 project developed at TU Delft involves a Voronoi-based material and architectural design (Fig. 2).

The habitat is to be constructed in empty lava tubes on Mars. By building below ground level not only natural protection from radiation is achieved but also thermal insulation because the temperature below ground is more stable due to insulating qualities derived from the rock's thermal properties at depth. The idea is that a swarm of autonomous mobile robots developed at TU Delft, Zebro, scans the caves, mines for in-situ resources, and with the excavated regolith that is mixed with cement, 3D prints the habitat by means of D2RP&O. The 3D printed rhizomatic habitat is a structurally optimized structure with increased thermal insulation properties due to its porosity. Similar to previous projects (Bier et al., 2017; Bier, Hidding, et al., 2020), the production and operation/ use of the habitat are powered by renewable energy systems, which in this case combine an automated kite-power system with solar panels. The ultimate goal is to develop an autarkic D2RP&O system for building off-Earth subsurface autarkic habitats from locally obtained materials (Bier et al., 2022).

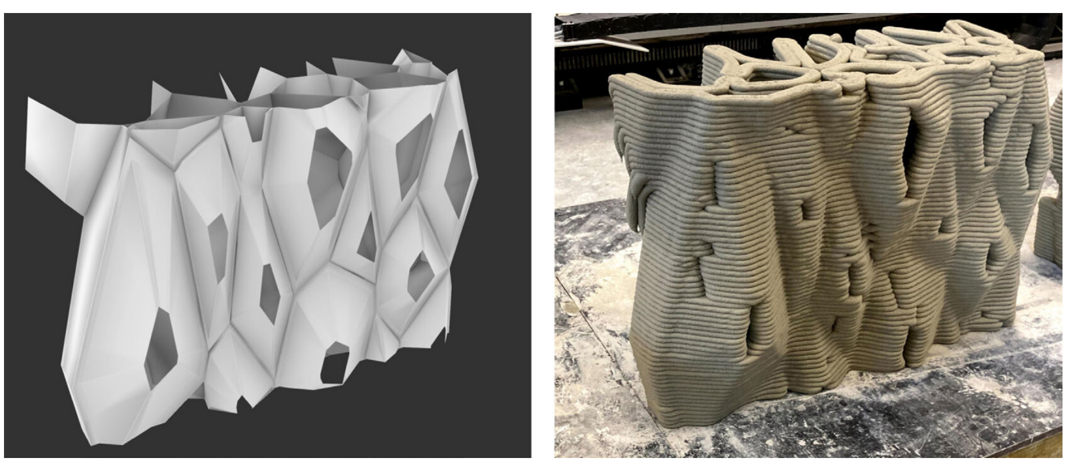

FIGURE 3 At Vertico 3D printed prototype of a fragment of the rhizomatic habitat on Mars developed at TU Delft ©RB lab, TU Delft.

In the first two prototyping sessions of Rhizome 1.0 presenting considerable differences between the digital model and the 3D printed fragment (Fig. 3) has been identified how the cell sizes, the robotic setup, and the material influence each other.

Rhizome 1.0, which indicates the potential of D2RP&A for developing innovative designs for pop-up architecture is now followed up by Rhizome 2.0. The innovation lies not only in the material design but also in the autarchic D2RP&A approach using IsRU. The knowledge developed in Rhizome 1.0 project (Bier, Latour, et al., 2020) will allow to scale up from 3D printed componential approach to building scale in Rhizome 2.0 project (Bier et al., 2023) while employing cementless concrete with the mid- and long-term goal to implement technology transfer from off-Earth to on-Earth applications.

5 In-Situ vs. Prefab 3D Printing

In the context of CO2-free pop-up architecture, in situ and prefab 3D printing have pros and cons. In situ 3D printing involves constructing structures on-site using eco-friendly materials and reducing transportation emissions while allowing for site-specific customization. This method is, however, considerably influenced by weather conditions. In contrast, prefab 3D printing involves manufacturing building components off-site, which enables increased quality control. Material durability and adaptability remain key concerns for in-situ 3D printing of pop-up structures. Material extrusion is a frequently employed method of 3D printing, especially with concrete as a prime material.

CONPrint3D, for instance, is an extrusion-based printing method for on-site, monolithic 3D concrete printing that provides high mechanical strength and consistent printability to the concrete up to 90 minutes after water addition, which is a promising approach for rapid response and large-scale construction (Nerella & Mechtcherine, 2019).

Profile 3D printing is a mold-less additive/subtractive manufacturing approach that combines the deposition of concrete for a rough layup with precision tooling for surface finishing of architectural building components (Bard et al., 2018). This method offers a framework for robotic concrete finishing and the production of mold-less custom designs. This approach is favorable for the pop-up structures' interior and exterior surfaces that require a fair finishing quality.

In the context of in-situ 3D printing for pop-up structures, another important aspect to consider is the impact of local materials on sustainability. Using locally sourced materials for 3D printing further reduces CO2 emissions associated with transportation and contributes to a more environmentally friendly construction process. Local materials also add unique character and cultural relevance to the structures, enhancing their connection to the surrounding environment. Moreover, due to the elimination of formwork, and manual labor, and the reduction of material wastage, some savings in material, process and energy are expected.

In this context, the parametric design is customized to accommodate specific needs or unforeseen challenges that may arise during the construction process. This adaptability is particularly valuable for pop-up architecture, where time and efficiency are critical factors in both disaster and extreme environments scenarios. On the other hand, prefab 3D printing offers solutions to increase efficiency and reduce the cost of construction processes while delivering higher quality control and safer working environments (Anton et al., 2021). However, weight and size constraints of the to-be-assembled components need to be considered.

Also, while casting concrete on site reduces transport issues, it increases sensitivity to temperature variations in different environmental conditions (Burger et al., 2023). In summary, both in-situ and prefab 3D printing methods present unique strengths and challenges for CO2-free pop-up architecture. In-situ printing and assembly offers benefits like adaptability to local materials and site conditions, while prefab printing excels in quality control and efficiency.

Furthermore, cementless concrete formulations present an opportunity to significantly diminish the environmental impact of pop-up structures. They are often based on geopolymers or other ecologically sound alternatives that substantially curtail the carbon emissions linked to conventional cement production. Moreover, the digital workflow not only heightens the precision of the end product but also mitigates material wastage, while the human-robot collaborative nature of the process facilitates efficient construction.

6 Artificial Intelligence and Human-Robot Interaction (HRI)

Simulation, algorithmic and parametric methods involving feedback analysis make it possible to rapidly prototype, test, and refine a wide range of designs from which the optimal design is selected to meet specific needs (Dunn, 2012). In particular, Artificial Intelligence (AI) helps design by, amongst others, analyzing environmental and human needs in order to actively propose designs customized for specific environments and users (Tamke et al., 2018), while through cloud-computing technologies, designs are increasingly transferred and fabricated across various locations.

When it comes to construction, AI assists the Human-robot Interaction (HRI) assembly process (Peternel et al., 2018) as well as the operation of environmentally controlled housing units. The interaction between the environment and the human and non-human agencies requires definition in terms of identifying tasks that are automated and tasks that rely on HRI versus tasks that remain in human control. These aspects have been in the Rhizome 1.0 and continue to be explored in 2.0. Both projects are co-funded by the European Space Agency (ESA) and the 3D printing firm Vertico.

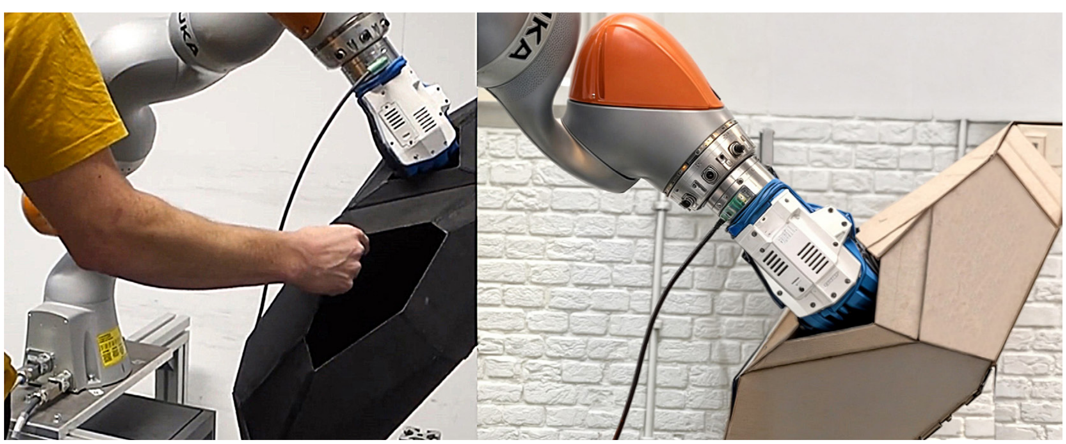

FIGURE 4 Collaborative construction using HRI method developed at CoR, TU Delft..

In this context, the team at Cognitive Robotics (CoR) at TU Delft developed HRI methods for the assembly of prefab 3D printed components. These Voronoi-based building components, which have variable shapes, are picked up from the printing location and moved to the place where the envelope of the habitat is being built. The carried component is then placed to the specific location. To implement this task, intelligent collaborative robots are employed to safely assist humans by handling the heavy loads, while the human takes over the cognitively complex aspects of the task (Fig. 4).

The challenges of scaling up Rhizome 1.0 from component to building are extensive. In Rhizome 1.0 one component was picked and placed using HRI. When this process is scaled up to the assembly of a whole habitat multiple challenges arise. The first challenge is to stack multiple components horizontally and vertically while maintaining component stability and keeping the robotic arm within the range of possible positions for picking and placing.

Developing the HRI process in combination with Computer Vision (CV) will ensure the correct recognition and placement of the components, while picking and placing relies on sharing the responsibility of tasks between humans and robots (Peternel et al., 2021).

Since the structure is much larger than the workspace of the robotic arm another challenge of scaling up is providing access to the structure at increasingly growing heights. Both on-site printing and assembly of prefab components will rely on ramps that will have to be integrated in the structure (Fig. 5 and 6). The challenge extends to encompass the intricate interplay between the robotic system and human operators, where effective communication and coordination become essential to harmonize the movements of the robotic arm and the activities of the human workforce.

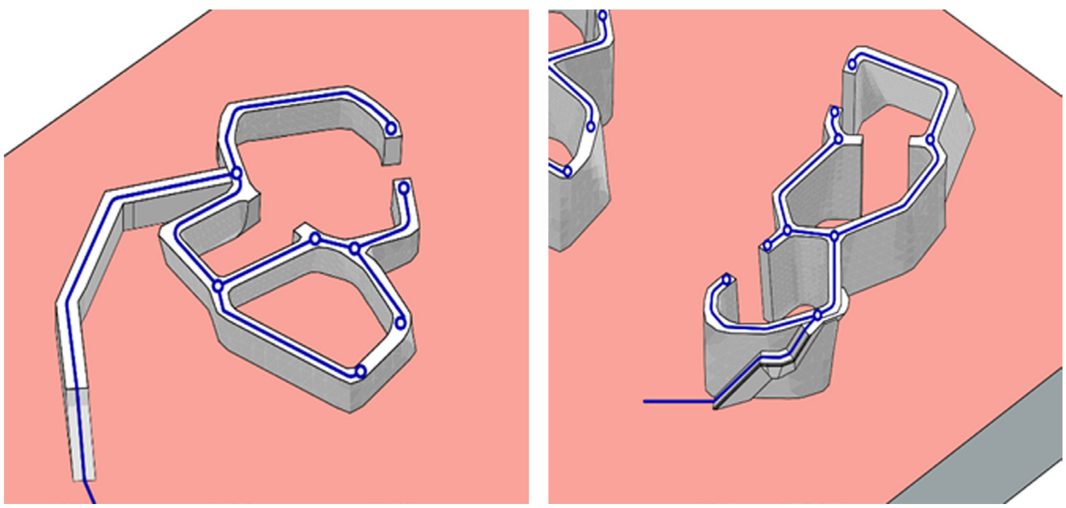

FIGURE 5 Diagram showing approach for printing or assembling in-situ using an integrated ramp

Maneuvering the components into their designated location, cementing them together and coating them for achieving airtightness requires path-planning algorithms informed by real-time sensor feedback and computational modeling.

Furthermore, the electromechanical systems to sustain the Life-support System (LSS) have to be integrated into the structure and will have to be accessible for maintenance.

7 D2RPA&O for Carbon-free Pop-up Architecture

D2RPA&O represents a significant advancement in the field of CO2-free pop-up architecture. With increasing awareness of environmental issues and the need for sustainable solutions, TU Delft collaborates with partners, such as ESA, Vertico, University of Antwerp, International Research School of Planetary Sciences Pescara to address these challenges by optimizing material and energy usage through structural optimization and use of cementless concrete. A review of the literature has unveiled the potential viability of adopting a lime-centered methodology as a prospective resolution for Rhizome 2.0 (Bier et al., 2023). On the other hand, geopolymers present alluring material traits with a concurrent reduction in energy demands (Davidovits, 2013). It is crucial to underscore that the distinct material attributes of both lime-infused and geopolymer amalgamations will significantly hinge upon the distinctive attributes of the regolith simulant applied. Sustainability and waste reduction are key considerations in the development of pop-up habitats, ensuring their adaptability in spatial, environmental, social, and economic aspects of design.

This cutting-edge approach integrates computational design methodologies and robotic production technologies, providing flexibility and customization for pop-up architecture applications. By optimizing shape complexity and employing cementless concrete in Rhizome 2.0, D2RPA&O enhances material efficiency, resulting in better overall environmental performance due to reduced CO2 emissions.

While there are challenges to overcome in in-situ production, such as robot sensitivity to environmental changes and autonomous operation in unstructured environments, the incorporation of AI within D2RPA&O offers promising solutions by enabling learning and improvement over time (Bier et al., 2023). This approach leads to the development of customizable models for carbon-free pop-up habitats, addressing social, environmental, technological, and economic needs with local material utilization and CO2 low approaches as core principles.

While growing awareness of the impacts of global warming, environmental threats, and the need to build sustainably have initiated efforts undertaken by local and international organizations and governments, TU Delft in collaboration with various partners aims to contribute to reducing material and energy use by implementing structural optimization and therefore utilizing material only where it is structurally or functionally needed.

Also, environmental consequences of 3D printing using concrete are currently reconsidered in Rhizome 2.0 by printing with cementless concrete. In comparison to the conventionally manufactured concrete structures, 3D printed cementless structures will promote better overall environmental performance for the pop-up structures throughout their lifespan which results in CO2 emission reduction.

8 Discussion

Various computational design methodologies and robotic production technologies are advanced in the design and building processes of Rhizome 1.0 and 2.0 developed in the RB lab in collaboration with various intergovernmental, academic, and industrial partners (Bier et al., 2023; Bier, Latour, et al., 2020). In particular, for pop-up architecture applications, the D2RP&O approach is valuable because of its versatility and ability to link the design to customized production and operation processes. Challenges of production in-situ remain to be addressed with respect to the sensitivity of robots towards environmental changes as well as their semi- and autonomous operation in unstructured environments.

The proposed D2RP&O methods offer multidimensional advantages responding to social, environmental, technological, and economic needs such as potential for community engagement in production, assembly and operation processes, use of easy-to-operate tools and locally obtained materials, increased material, and energy efficiency, etc. Their advancement through integration of AI will offer solutions to some challenges by providing the system with the ability to learn and improve in time. Machine Learning (ML) algorithms and Computer Vision (CV) systems can analyze the generated data during robotic 3D printing and provide real-time feedback for quality control in the production process. Additionally, robotic path planning tools optimize this process by reducing material waste and printing time. The ultimate goal is to advance autarchic D2RP&O methods and develop customizable models for pop-up habitats.

For diverse construction applications, in-situ and prefab 3D printing provide significant advantages and challenges. Customization, quick building, and design flexibility are all strengths of in-situ 3D printing. It reduces the need for huge components to be transported, resulting in lower costs and on-demand production. This technology is ideal for disaster relief and remote research, where construction time and flexibility are important. In-situ 3D printing, on the other hand, presents obstacles in terms of equipment transportation, labor intensity, weather limits, and restricted scalability for major projects.

Prefabricated 3D printing, on the other hand, features controlled manufacturing and rapid assembly, ensuring uniformly consistent quality and replicability of designs across projects. The independence from on-site weather conditions, as well as the reduction in on-site labor, improve safety and minimize disturbance. Prefabricated components can be inspected and delivered off-site, maximizing resource utilization and scalability. Material adaptability allows for a wide range of applications, including utility integration and automation. However, when compared to in-situ technologies, prefabricated 3D printing may have limits in terms of customization and design adaptability. Transportation expenses, storage requirements, and coordination issues can complicate logistics, reducing cost-effectiveness.

In the context of off-Earth applications, combination of both in-situ and prefab 3D printing approaches may be a more practical solution, reinforcing the advantages of each method to optimize the efficiency and effectiveness of construction on Mars.

The presented D2RPA&O approach in CO2-free pop-up architecture represents a substantial advancement, meeting the critical requirement for long-term solutions in the face of environmental issues. The research at RB Lab optimizes material and energy usage in collaboration with partners through structural optimization and innovative technologies. The prospective use of lime-centered approach and geopolymers improves pop-up habitats' environmental impact. The integration of computational design and robotic production empowers designers by optimizing shape complexity and reducing CO2 emissions using cementless concrete.

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Dialogues on Architecture #6

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[3] *Leibniz University Hannover (Germany)*

Abstract

Dialogues on Architecture, published in various issues of Spool CpA, is a series of dialogues between researchers and practitioners, who are embracing the intellectual model of high technology and are involved in its advancement and application in architecture. Dialog #6 presents discussions risen during an online symposium on challenges of the Architecture, Engineering and Construction (AEC) industry, which is facing a threefold challenge involving the (i) digital transformation of all design and planning processes, (ii) automation of construction processes, and (iii) reconsideration of energy, process, and material use.

These challenges involve issues with respect to productivity, scalability, safety, labour skill shift, and environmental impact. Acknowledging that there is a particular urgency in transferring effective solutions from research to building practice to meet significant carbon reduction goals by 2040, the one-day symposium organized as an online event in 2022 [1], Human-Robot Interaction for Post-Carbon Architecture (HRI4PCA), was an opportunity to make an inventory of current tendencies in autonomous construction and human-robotic interaction in architecture. It aims at affirming and/or challenging research agendas in the domain of architectural robots.

Keywords

Human-robot interaction, post-carbon architecture, autonomous construction, AI

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1 Link to HRI4PCA announcement: http://www.roboticbuilding.eu/2022/03/09/symposium_hri4pca/

Dialogue

Mirco Becker (MB): When we started drafting the call for the Human-Robot Interaction for Post-Carbon Architecture symposium in 2021 we had a few questions in mind to frame the topic. Let's look back at these questions and reflect on how they were addressed during the symposium as well as by publications and projects implemented shortly thereafter. We start with the question addressing climate change, which by now seems to be woven into almost any project and call. Very simply, we asked: What are the fundamental research questions for framing post-carbon autonomous construction?

Henriette Bier (HB): Some of the considerations concern material, energy, and process efficiency focusing on (i) how to develop sustainable and low-carbon construction materials that minimize embodied carbon emissions and environmental impact while maintaining structural integrity and performance, (ii) how to optimize energy efficiency in construction processes by autonomous manufacturing, assembly, and operation of buildings, (iii) how to automate construction tasks, optimize resource utilization, and reduce energy consumption while ensuring safety, quality, and precision in construction. These questions were explored in the symposium from synthesizing big data to semi-/ autonomous AI-driven fabrication with robots (Fig. 1) envisioned as 'heterogeneous robot fleets on construction sites' providing a blueprint for the next-generation building in which robotic hardware development is part of the overall design process and its output.

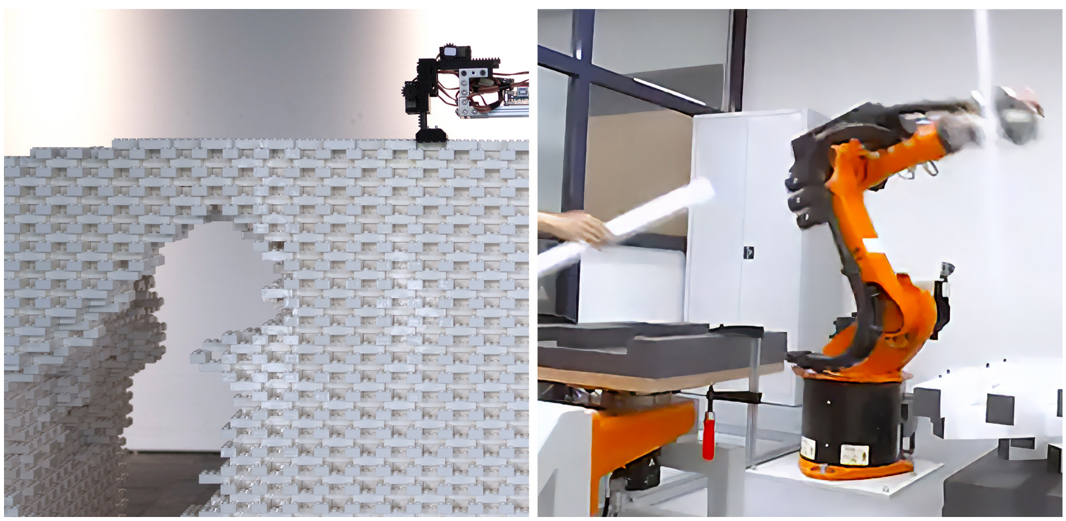

FIGURE 1 Computer-generated toolpath (left) and 3D printed prototype (right) by Vertico 3d printing specialists (©RB lab, TU Delft).

MB: Digital technologies in architecture have accumulated an extensive body of research and methods over the past 20 years. Various topics accompanied the development of the digital in architecture including geometry, material and fabrication, and robotics. For the symposium, we wanted to shed light on a particular triplet by posing the question: What are the interdependencies between machines, humans, and materials? Are we at a point where we can identify promising research and projects emerging from this question?

HB: Various speakers [1] from the EU, Australia, Canada, and the US presented research developed at TU Delft, Leibniz University Hannover, TU Darmstadt, ETH Zürich, University of Stuttgart, the Bartlett (UCL),

1 Link to HRI4PCA speakers: http://www.roboticbuilding.eu/hri4pca-speakers/

RMIT, McNeel, University of Toronto and Boston Dynamics. The themes ranged from synthesis of big data to human-robot collaboration, mobile and miniaturized robotic approaches, and robotic spaces, structures and building systems. All speakers acknowledged that robots, humans, and space are increasingly intertwined with robot systems evolving into 'robotic spaces, structures and building systems' that rely on AI-supported semi-/ automated processes.

MB: Let's look again at the question of material. Our attitude towards material is fundamentally challenged. We need different materials ideally carbon-positive ones, we need to reuse and recycle materials that are already in the cycle, and we need to invent strategies to disassemble and reassemble buildings constructed today so the material stays in the cycle far longer than the lifespan of a single building.

HB: Recycling is a big concern that we have been addressing in the Robotic Building (RB) lab at TU Delft by reprocessing reclaimed wood. Identifying which strategies are more efficient, ranging from reassembling to reprocessing, is one of the challenges that one of my PhD students is now investigating. There is also the aspect of design for circularity as Oliver Tessmann presented: a novel construction system made up of interlocking dry joint SL blocks. Such construction systems fully assembled and reassembled by AI-guided robots would stay in the built environment over a very long period of time multiple times the life span of a single building.

MB: The work presented by Daniela Mitterberger is especially forward-looking. She presented novel human-augmentation strategies and tools needed for human-machine collaboration to perform non-standard fabrication tasks at full architectural scale (Fig. 2) This might also lead to a very different understanding and use of material. Such machine-augmented construction processes have the potential to not only execute the defined task or target but also to give individual insight into material construction logic and its environmental performance.

FIGURE 2 Co-Corporeality – eye tracking device to control machines (© Zita Oberwalder).

Against the backdrop of climate change the responsibility of the building sector is undisputed. Still, it is not clear at all how and when we can make a significant contribution to mitigating CO2 expenditure. *How do different implementation timeframes define strategies for transferring research, as for instance, continuous transformation vs. leapfrogging?* With this third question we wanted to get insight into different research strategies and how they compete or complement each other.

HB: Continuous transformation focuses on making incremental improvements within the existing framework, while leapfrogging involves making disruptive innovations to achieve rapid advancement. Both strategies have their advantages and challenges, and often instead of adopting one or the other, a combination of both approaches proves to be effective.

MB: Interestingly there is a remarkable variety of novel robotic concepts beyond the industrial robot. At the symposium, we saw established legged robots like SPOT presented by Brian Rigley from Boston Dynamics. Enabling mobile robots with infinite workspace to perform building tasks has great potential in construction as confirmed by Brian Ringley, who presented new mobile modalities for more effective site management, for instance, wheeled/tracked mobile robots. By employing building autonomous navigation systems and agile mobile robots an unprecedented amount of data is captured in dynamic, human-purposed environments. The integration of geospatial hardware, 5G telecommunications, cloud computing, and emerging AI for unstructured reality capture data provides new approaches of feeding digital twins in construction. Twins are the key to establishing reality feedback loops accurately coupling the virtual and the real using heterogeneous robot fleets on construction sites.

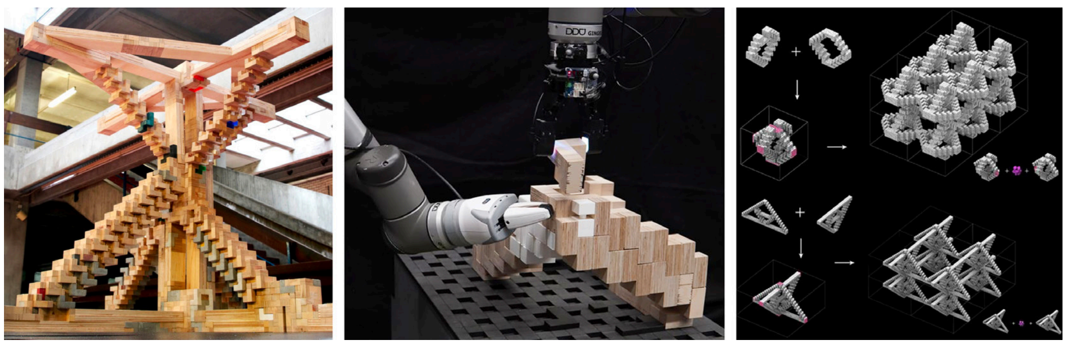

FIGURE 3 Autonomous assembly of modular systems employing AI-driven robots equipped with visio-tactile sensors implemented at TU Darmstadt.

Maria Yablonina is considering robotic hardware development as part of the overall design process and its output, as I do too. In this context, design moves beyond the design of objects towards the design of technologies and processes that enable new ways of both creating and interacting with architectural spaces. I presented the miniaturization of autonomous construction robots and material formats, which involves the design not only of buildings but building systems. Similarly, Oliver Tessmann presented autonomous assembly of modular systems employing AI-driven robots equipped with visio-tactile sensors (Fig. 3). Dry-jointed and reversible elements allow for their assembly, disassembly, and reassembly in a circular fashion. In contrast to HRI, the project shifts away from immediate collaboration. Valentina Soana develops lightweight structures with shape-changing behavior. She designs adaptive material and structural systems that can achieve multiple states of equilibrium. Robotic systems are not tools anymore but become robotic spaces, structures and building systems, opening up new interaction scenarios between humans, materials, and machine systems.

HB: In addition, Serban Bodea's research into advancing robotic coreless filament winding as enabler of mass customization of large-scale lightweight structures [2] requires acknowledgement. Lukas Lachmayer however, re-evaluates large-scale production, whether additive, subtractive or through forming, which is often realized by upscaled machinery. He highlights that while this appears the easiest way to achieve required tolerances, such production systems lack flexibility.

2 Link to AddFiberFab: https://serbanbodea.com/addfiberfab/

MB: While the programming of industrial and collaborative robots becomes ever easier and thus more accessible for designers, we also see the fundamental limits of these types of robots in terms of their use in construction. There is certainly a need for novel types of robots, but inventing robots is neither trivial nor fast. Are we at a point where we might need a new attitude towards breeding new robots? Analogous to the didactic question of the 2000s inquiring if *'every architect needs to be capable of scripting' the question now is if 'every architect needs to be a robotic inventor'*.

HB: I am a strong promoter of collaboration with computer scientists and roboticists. The architect remains the generalist, having an understanding to some degree of all aspects and relying on specialists for the implementation. I presented Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) methods developed in the Robotic Building (RB) lab at TU Delft. These link efficiently computational design with robotic production, assembly, and operation and employ a customizable multi-robot and multi-effector approach relying on Human-Robot Interaction (HRI) to facilitate effective and safe physical interaction between robots and humans implementing complex tasks.

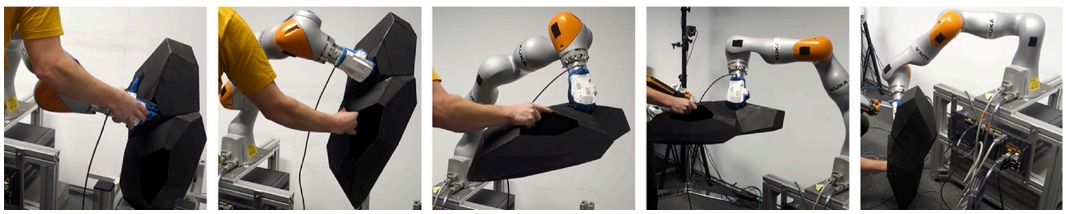

FIGURE 4 HRI-supported pick-and-place study implemented at CoR lab.

Aspects of HRI are implemented in collaboration with Luka Peternel from Cognitive Robotics (CoR) lab at TU Delft (Fig.4), who considers robots as very good at handling high physical workload and performing precise and fast movements, while humans have superior cognitive capabilities and manual dexterity. He combines these attributes in physical human-robot collaboration for construction and employs methods based on impedance control to enable compliant and safe operation. Higher-level reasoning and communication between the human and the robot are handled by an AI system based on machine learning (ML) methods and various sensory interfaces. The ultimate goal is to advance robotics in architecture while taking into consideration that more than 50% of tasks can and will be fully automated, while 45% rely on HRI, and only 5% remain in human hands.

MB: After carefully framing the call for the symposium and having invited an inspiring selection of contributors, the question is if there was any perspective or topic during the symposium which shifted the focus beyond what we anticipated.

HB: One of the research questions that we did not formulate explicitly, but was addressed by one of the speakers, Alisa Andrasek, reflected on the current synthesis of big data from a multitude of sources enabling context-sensitive and integrated systems within information-rich simulations and applications as for instance typologies synthesized with local data and computational physics, context-sensitive models for buildings and green energy infrastructure, or artificial intelligence (AI) combinatorics for increasing variability of prefabrication . Perhaps, the next symposium will focus on questions such as (i) how can machine learning algorithms be applied to big data for predictive modelling, classification, and clustering, and (ii) what are the challenges and opportunities of deploying machine learning models in architecture.

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