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.

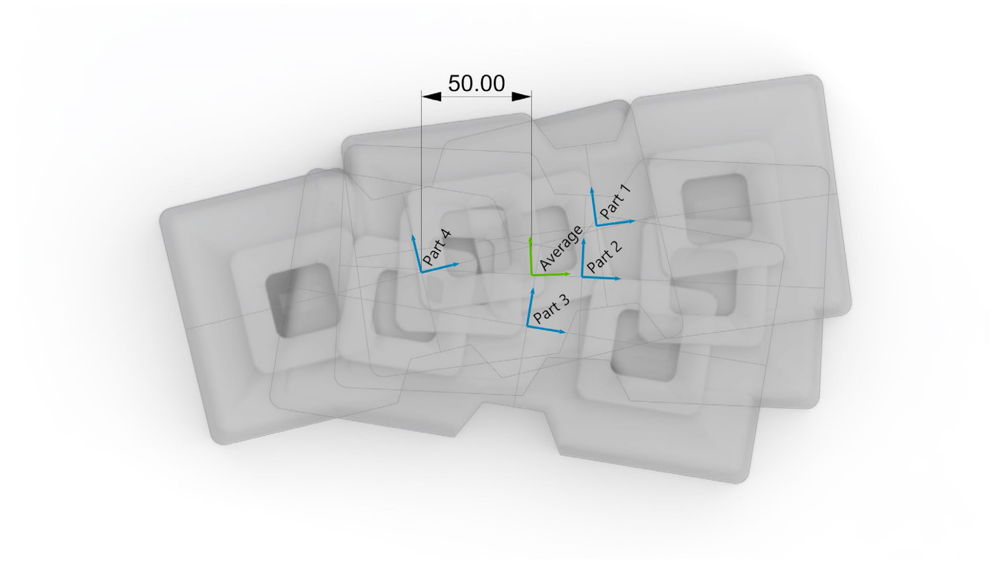

FIGURE 1 Diagram of the method for precision measuring. Authors, 2023.

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.

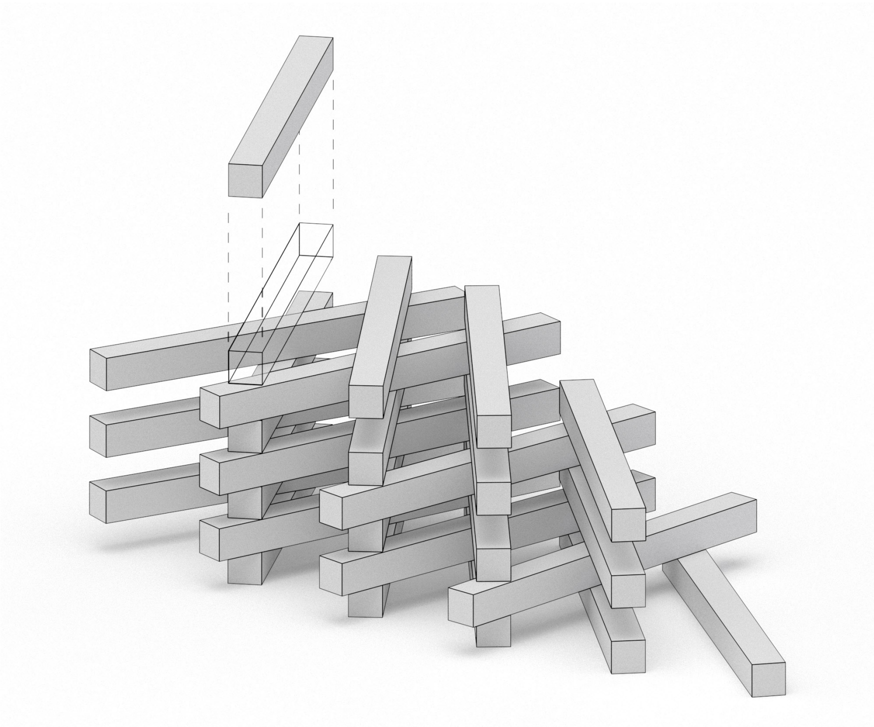

FIGURE 3 Logic of piling of the wooden slat structure. Authors, 2023.

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.

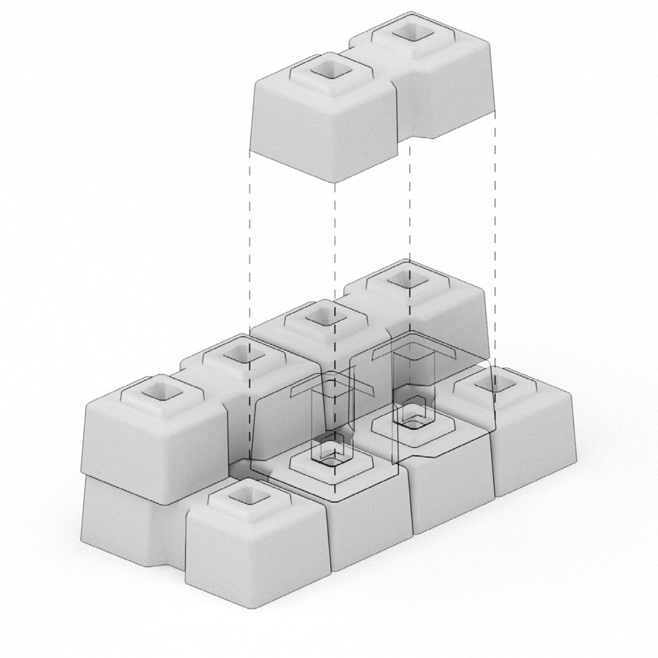

FIGURE 5 Custom-made interlocking brick. Authors, 2023.

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.

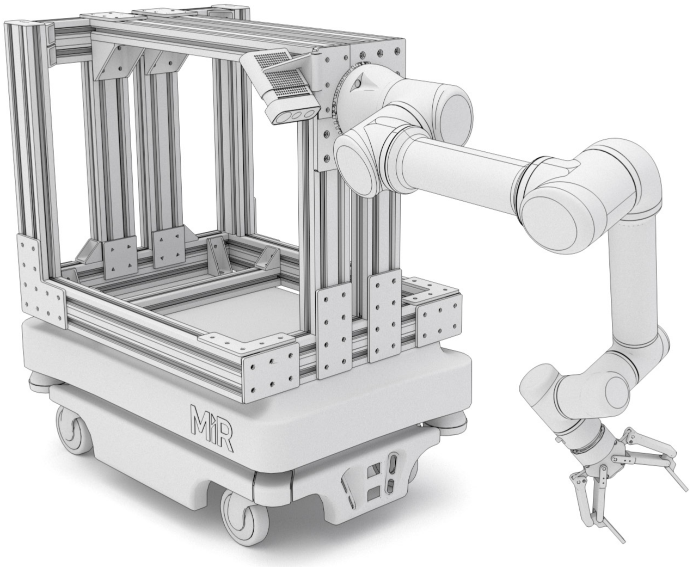

FIGURE 8 MiRo. MIR100 mobile platform with aluminum profiles and UR5 robot. An Azure Kinect camera assembled at 45 degrees close to the robot base. Authors, 2023.

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).

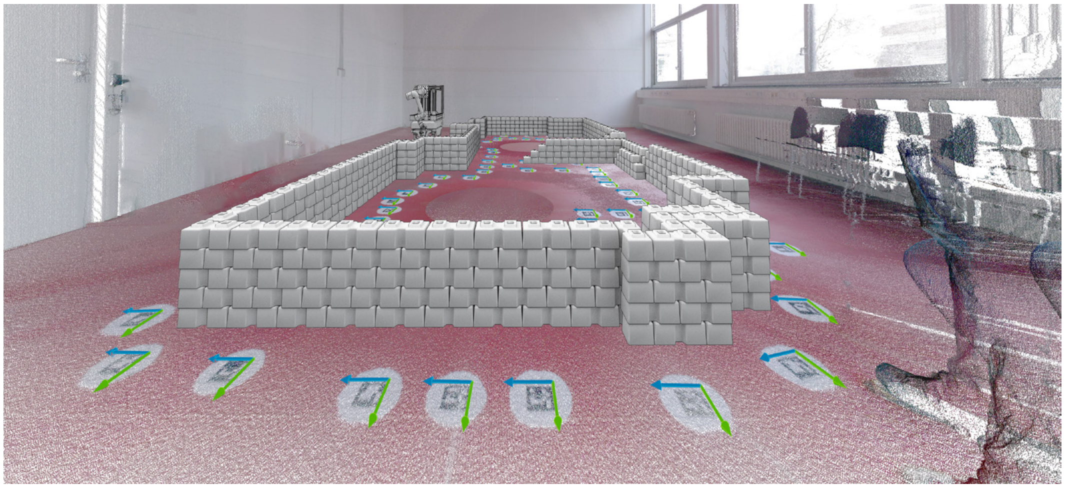

FIGURE 9 Wall with 450 possible positions for the bricks. In the background is the point cloud with the ArUco markers and the X and Y directions of each (blue and green). Authors, 2023.

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.

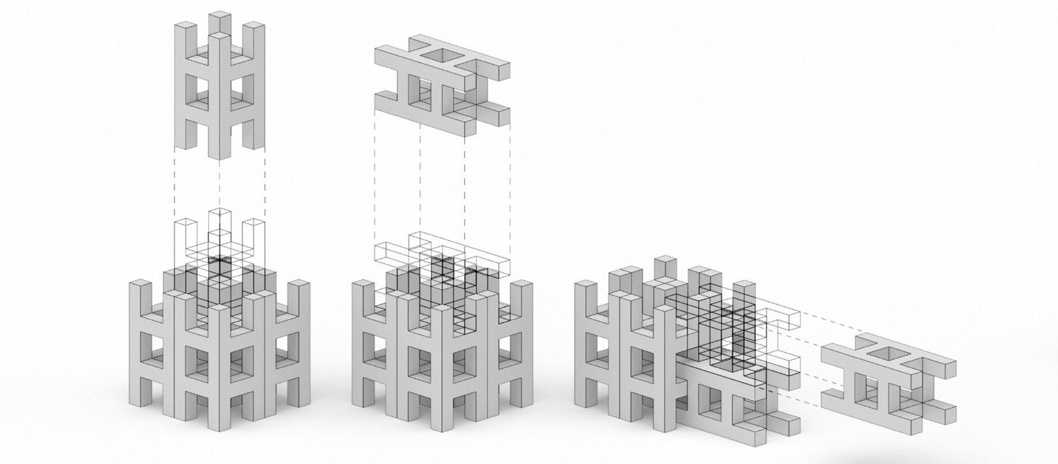

FIGURE 12 Drawing of possible H-Block assemble positions. Authors, 2023.

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.

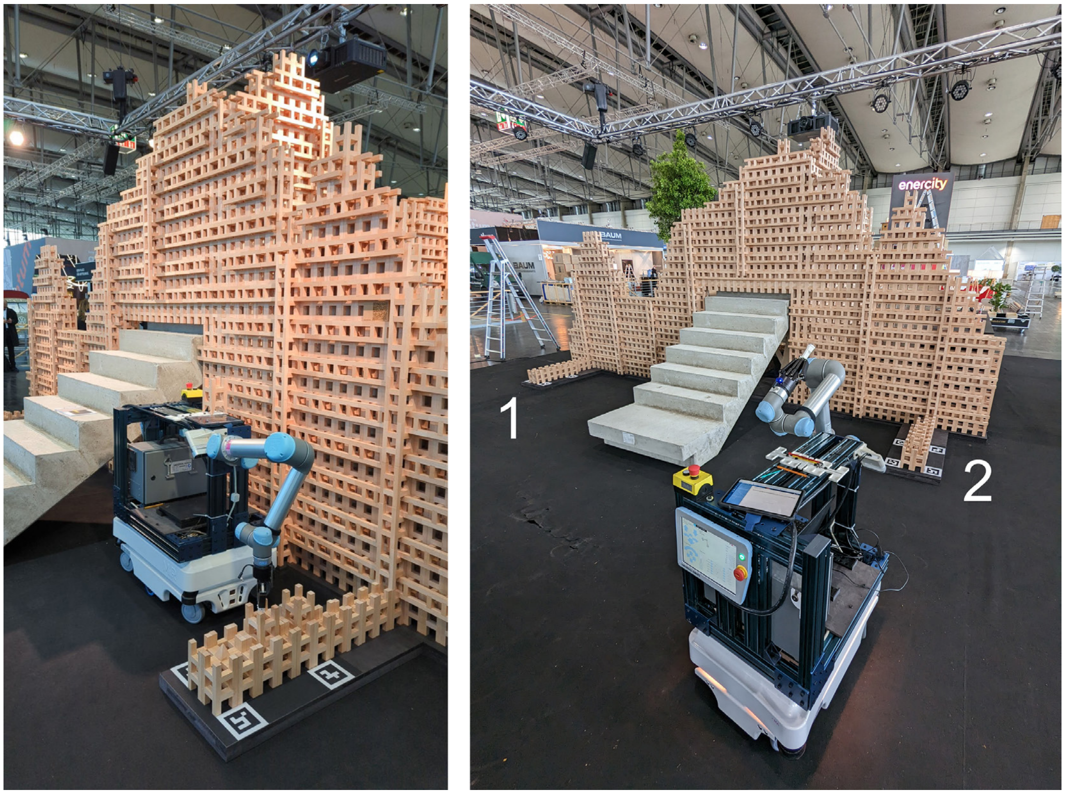

FIGURE 13 MiRo assembling the H-Blocks on-site. In the right image, both material stations are identified. Authors, 2023.

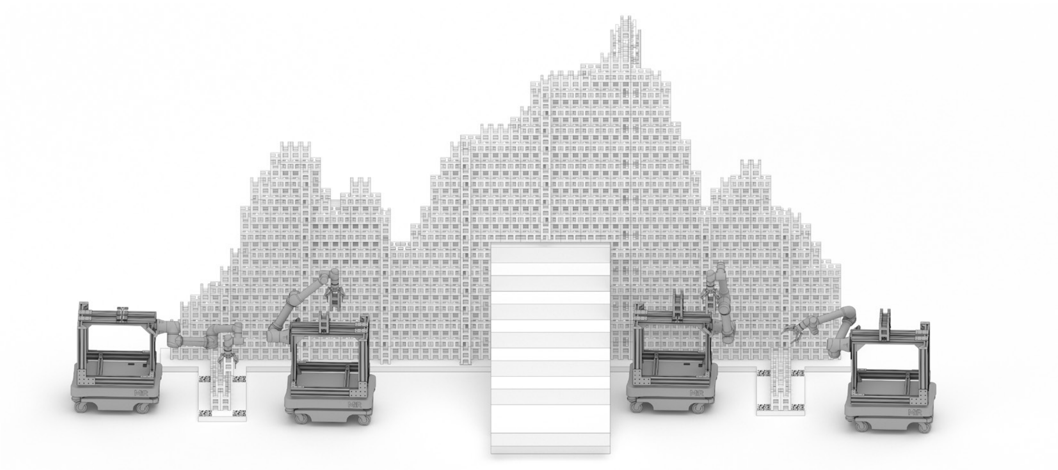

FIGURE 14 The four possible locations where MiRo loaded or unloaded H-Blocks. From left to right: Loading from platform 1 to its back; Unloading to platform 1; Loading from platform 2; Unloading to platform 2. Authors, 2023.

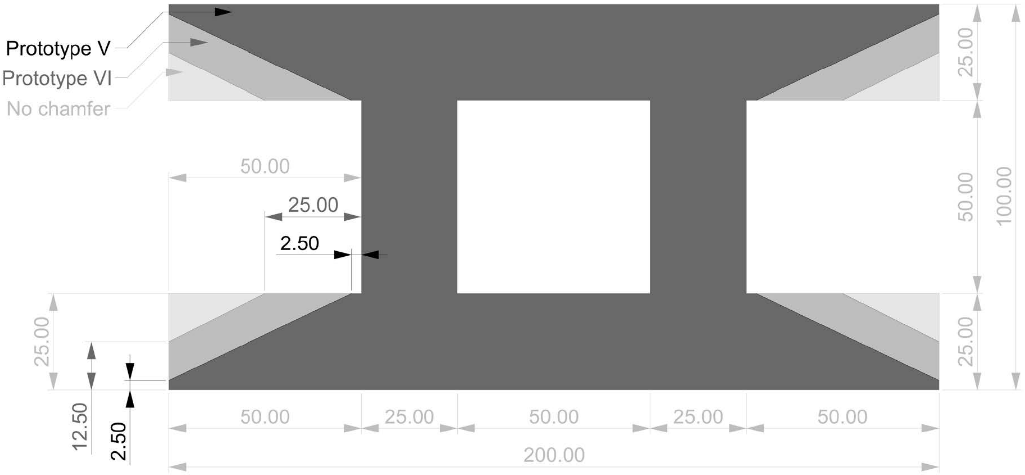

FIGURE 15 Dimensions in millimeters of the H-Blocks with varying hatches according to the tolerance of each prototype. Blocks are chamfered only on one side, both sides, or neither, according to their position in the prototype. Authors, 2023.

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.

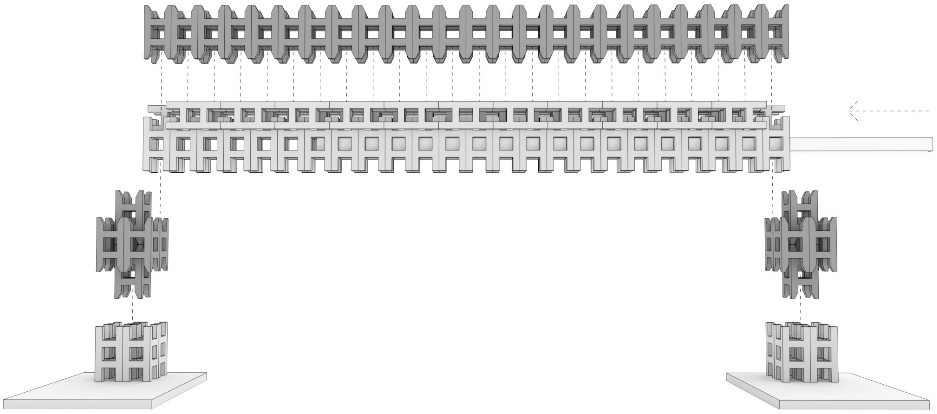

FIGURE 16 Diagram of beam assembly. In darker gray, parts were assembled by the UR5e, and in brighter gray, parts were assembled by people. Authors, 2023.

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.

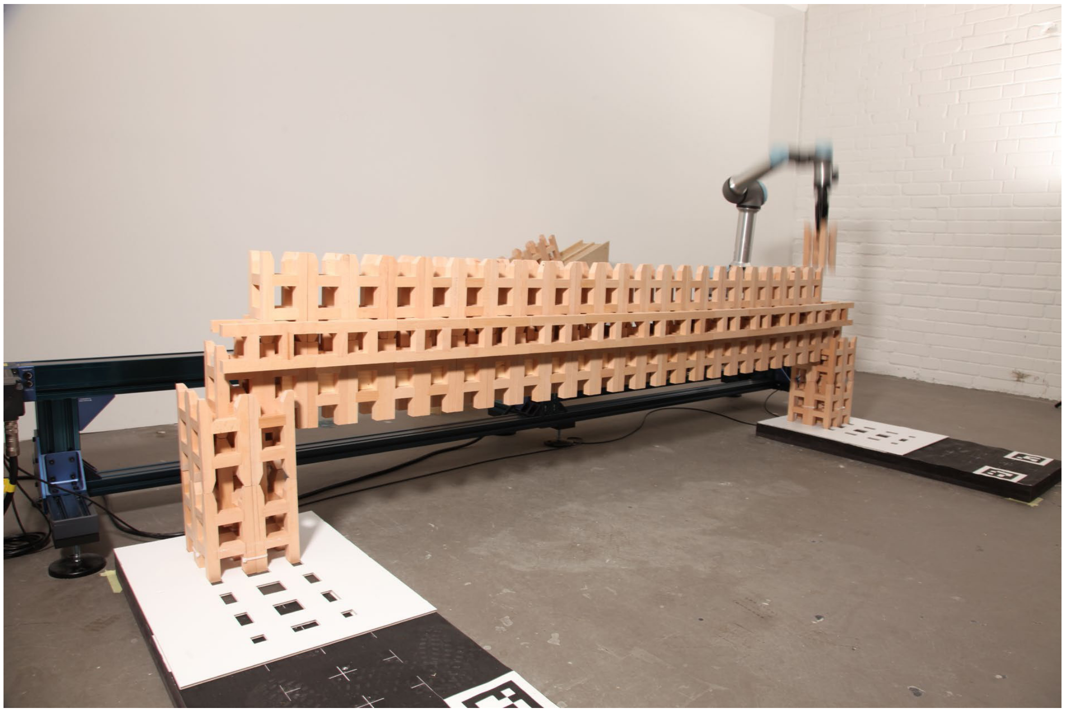

FIGURE 17 Beam comprised of H-Blocks assembled by a UR5e robot on top of an external linear axis. Authors, 2023.

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.

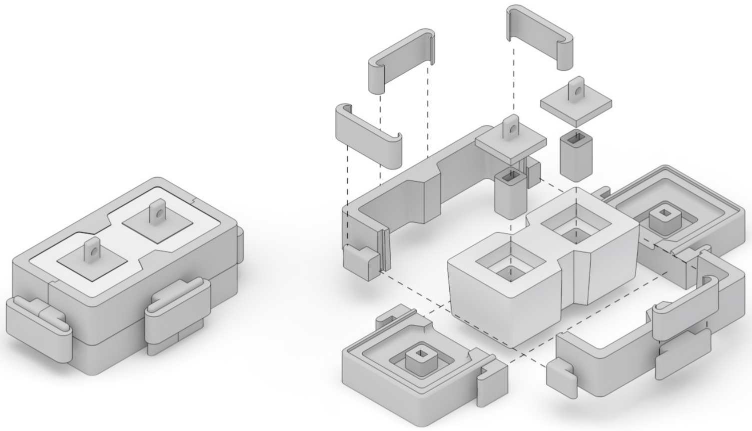

FIGURE 18 Custom brick and its mold with 12 parts.

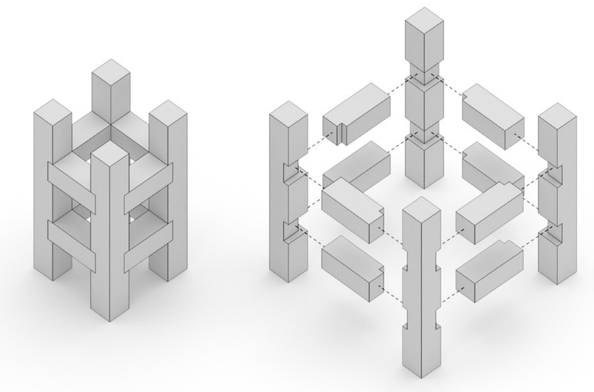

FIGURE 19 H-Block and its constituent parts.

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.

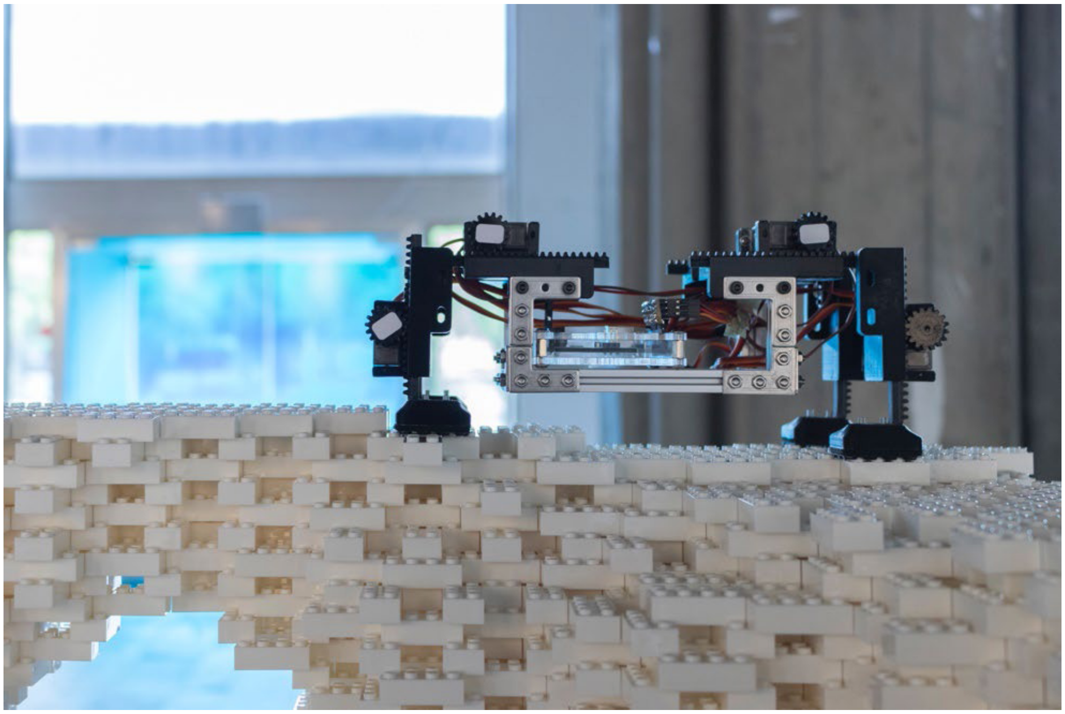

FIGURE 20 BrickrBot 0.1 climbing a wall made of LEGO® bricks. Authors, 2023.

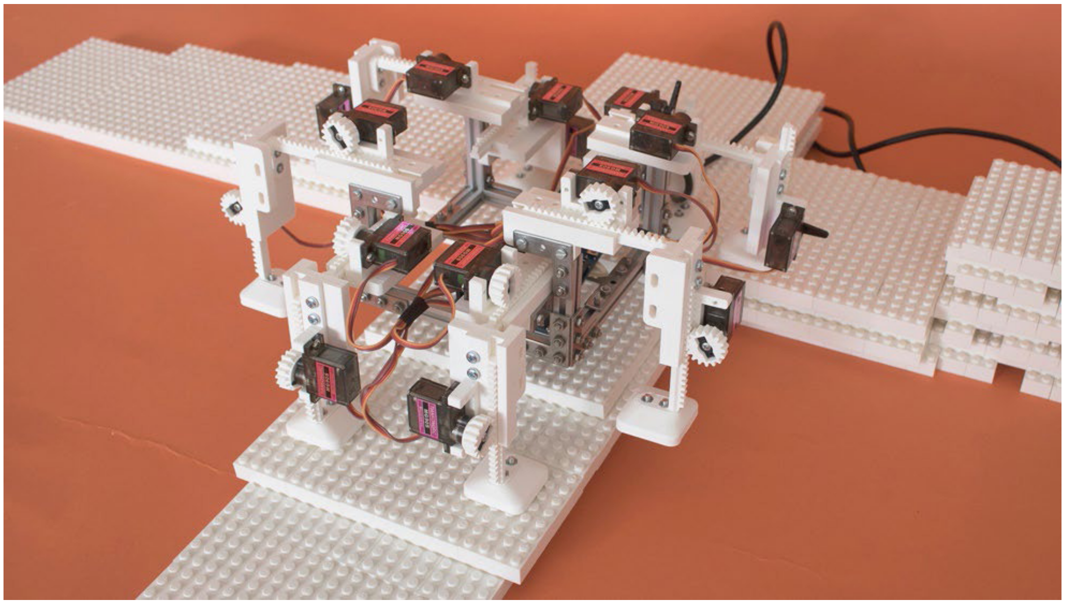

FIGURE 21 8-legged wall climbing BrickrBot 1.0. Authors, 2023.

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.

References

Abdel-Rahman, A., Cameron, C., Jenett, B., Smith, M., & Gershenfeld, N. (2022). Self-replicating hierarchical modular robotic swarms. *Communications Engineering*, *1*(1), Article 1. https://doi.org/10.1038/s44172-022-00034-3

Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., Bello, S. A., Jaiyeoba, B. E., & Kadiri, K. O. (2017). Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Management*, *60*, 3–13. https://doi.org/10.1016/j.wasman.2016.08.017

Anastasiades, K., Blom, J., Buyle, M., & Audenaert, A. (2020). Translating the circular economy to bridge construction: Lessons learnt from a critical literature review. *Renewable and Sustainable Energy Reviews*, *117*, 109522. https://doi.org/10.1016/j.rser.2019.109522

Arlet, J. L. (2021). Innovative Carpentry and Hybrid Joints in Contemporary Wooden Architecture. *Arts*, *10*(3), Article 3. https://doi.org/10.3390/arts10030064

Arquivo – simplificando o reuso de materiais. (n.d.). Retrieved July 27, 2023, from https://arquivoreuso.com.br/

Batalle Garcia, A., Cebeci, I. Y., Vargas Calvo, R., & Gordon, M. (2021). Material (data) Intelligence—Towards a Circular Building Environment. *A. Globa, J. van Ameijde, A. Fingrut, N. Kim, T.T.S. Lo (Eds.), PROJECTIONS - Proceedings of the 26th CAADRIA Conference - Volume 1, The Chinese University of Hong Kong and Online, Hong Kong, 29 March - 1 April 2021, Pp. 361-370*. https://papers.cumincad.org/cgi-bin/works/paper/caadria2021_088

Becker, M., Sardenberg, V., & Schacht, M. (2020). Extending the Robotic Workspace by Motion Tracking Large Workpieces. *International Conference on Human-Computer Interaction*, 156–162.

Berger, E. A., Markus. (2022). Community Repair in South Africa: An Interview with Kevin Kimwelle. In *Repair*. Routledge.

Bock, T. (2007). Construction robotics. *Autonomous Robots*, *22*(3), 201–209. https://doi.org/10.1007/s10514-006-9008-5

Ca gaze ? (n.d.). Saga | Collectif d'architecture | Nantes | Port Elizabeth. Retrieved July 27, 2023, from http://www.collectifsaga.com/fr/ca-gaze/

Carney, M., & Jenett, B. (2016, September 27). *Relative Robots: Scaling Automated Assembly of Discrete Cellular Lattices*. ASME 2016 11th International Manufacturing Science and Engineering Conference. https://doi.org/10.1115/MSEC2016-8837

Certain Measures. (n.d.). Retrieved July 27, 2023, from https://certainmeasures.com

Claypool, M. (2018). *Disrupting the Digital: An Architecture of Parts*. https://www.acsa-arch.org/chapter/disrupting-the-digital-an-architecture-of-parts/

de Paula, A. (2023). *Discrete Automation: Robotic Construction Workflow for Reconfigurable Timber Housing*. https://repository.tudelft.nl/islandora/object/uuid%3Ac3436d86-c7d7-48c2-833a-d2fad07fabe5

Dounas, T., Jabi, W., & Lombardi, D. (2021). Non-Fungible Building Components: Using Smart Contracts for a Circular Economy in the Built Environment. *Gomez, P and Braida, F (Eds.), Designing Possibilities - Proceedings of the XXV International Conference of the Ibero-American Society of Digital Graphics (SIGraDi 2021), Online, 8 - 12 November 2021, Pp. 1189–1198*. https://papers.cumincad.org/cgi-bin/works/paper/sigradi2021_20

Drude, J. P., Rossi, A., & Becker, M. (2020). Project DisCo: Choreographing Discrete Building Blocks in Virtual Reality. In C. Gengnagel, O. Baverel, J. Burry, M. Ramsgaard Thomsen, & S. Weinzierl (Eds.), *Impact: Design With All Senses* (pp. 288–299). Springer International Publishing. https://doi.org/10.1007/978-3-030-29829-6_23

Dunker, P. A., Lewinger, W. A., Hunt, A. J., & Quinn, R. D. (2009). A biologically inspired robot for lunar In-Situ Resource Utilization. *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 5039–5044. https://doi.org/10.1109/IROS.2009.5354202

Fingrut, A., & Leung, C. K. S. (2022). Rapid Assembly of Masonry Structures with Ad-Hoc Material Attributes, Computer Vision and SCARA Robots. *Jeroen van Ameijde, Nicole Gardner, Kyung Hoon Hyun, Dan Luo, Urvi Sheth (Eds.), POST-CARBON - Proceedings of the 27th CAADRIA Conference, Sydney, 9-15 April 2022, Pp. 11-20*. https://papers.cumincad.org/cgi-bin/works/paper/caadria2022_72

Giftthaler, M., Sandy, T., Dörfler, K., Brooks, I., Buckingham, M., Rey, G., Kohler, M., Gramazio, F., & Buchli, J. (2017). Mobile robotic fabrication at 1:1 scale: The In situ Fabricator. *Construction Robotics*, *1*(1), 3–14. https://doi.org/10.1007/s41693-017-0003-5

Huang, C. (2021). Reinforcement Learning for Architectural Design-Build—Opportunity of Machine Learning in a Material-informed Circular Design Strategy. *A. Globa, J. van Ameijde, A. Fingrut, N. Kim, T.T.S. Lo (Eds.), PROJECTIONS - Proceedings of the 26th CAADRIA Conference - Volume 1, The Chinese University of Hong Kong and Online, Hong Kong, 29 March - 1 April 2021, Pp. 171-180*. https://papers.cumincad.org/cgi-bin/works/paper/caadria2021_118

Jahn, G. F. (2022). *Mixed reality fabrication—RMIT University* [PhD Thesis, RMIT University]. https://researchrepository.rmit.edu.au/esploro/outputs/doctoral/Mixed-reality-fabrication/9922199313401341?institution=61RMIT_INST

Kaltenbrunner, M., & Bencina, R. (2007). reacTIVision: A computer-vision framework for table-based tangible interaction. *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*, 69–74. https://doi.org/10.1145/1226969.1226983

Kunic, A., Kramberger, A., & Naboni, R. (2021). Cyber-Physical Robotic Process for Re-Configurable Wood Architecture—Closing the circular loop in wood architecture. *Stojakovic, V and Tepavcevic, B (Eds.), Towards a New, Configurable Architecture - Proceedings of the 39th eCAADe Conference - Volume 2, University of Novi Sad, Novi Sad, Serbia, 8-10 September 2021, Pp. 181-188*. https://papers.cumincad.org/cgi-bin/works/paper/ecaade2021_205

Lachmayer, L., Recker, T., Dielemans, G., Dörfler, K., & Raatz, A. (2022). Autonomous Sensing and Localization of a Mobile Robot for Multi-Step Additive Manufacturing in Construction. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIII-B1-2022*, 453–458. https://doi.org/10.5194/isprs-archives-XLIII-B1-2022-453-2022

Leder, S., Weber, R., Wood, D., Bucklin, O., & Menges, A. (2019). *Distributed Robotic Timber Construction: Designing of in-situ timber construction system with robot-material collaboration*. https://doi.org/10.52842/conf.acadia.2019.510

Mangliár, L., & Hudert, M. (2022). Enabling circularity in building construction: Experiments with robotically assembled interlocking structures. In *Structures and Architecture. A Viable Urban Perspective?* CRC Press.

Menges, A., & Knippers, J. (2020). *Architecture Research Building: ICD/ITKE 2010-2020* (1st edition). Birkhäuser.

Minibuilders—Institute for Advanced Architecture of Cataloni. (n.d.). *IAAC*. Retrieved July 27, 2023, from https://iaac.net/project/minibuilders/

Mobile robot from Mobile Industrial Robots—MiR100. (n.d.). Retrieved September 20, 2023, from https://www.mobile-industrial-robots.com/solutions/robots/mir100/

Norell, D., Rodhe, E., & Hedlund, K. (2020). Completions. *ACADIA 2020: Distributed Proximities / Volume I: Technical Papers [Proceedings of the 40th Annual Conference of the Association of Computer Aided Design in Architecture (ACADIA) ISBN 978-0-578-95213-0]. Online and Global. 24-30 October 2020. Edited by B. Slocum, V. Ago, S. Doyle, A. Marcus, M. Yablonina, and M. Del Campo. 446-455.* https://papers.cumincad.org/cgi-bin/works/paper/acadia20_446

Pan, M., Linner, T., Cheng, H., Pan, W., & Bock, T. (2018). *A Framework for Utilizing Automated and Robotic Construction for Sustainable Building* (p. 88). https://doi.org/10.1007/978-981-10-6190-5_8

Petersen, K. H., Nagpal, R., & Werfel, J. K. (2011). TERMES: An Autonomous Robotic System for Three-Dimensional Collective Construction. *Robotics: Science and Systems VII*. https://doi.org/10.15607/RSS.2011.VII.035

Petersen, K. H., Napp, N., Stuart-Smith, R., Rus, D., & Kovac, M. (2019). A review of collective robotic construction. *Science Robotics*, *4*(28), eaau8479.

Popescu, G. (2008). *Digital materials for digital fabrication*. MIT.

Retsin, G. (2016). Discrete and Digital. *TxA EMERGING DESIGN + TECHNOLOGY*.

Rossi, A. (2023). *Wasp—Discrete Design for Grasshopper* [Python]. https://github.com/ar0551/Wasp (Original work published 2017)

Rotor Deconstruction – Reuse of building materials made easy. (n.d.). Rotor Deconstruction Scrl. Retrieved July 27, 2023, from https://rotordc.com/home

Sardenberg, V., & Becker, M. (2022, October 20). Aesthetic Measure of Architectural Photography utilizing Computer Vision: Parts-from-Wholes. *Design Computation Input/Output 2022*. Design Computation Input/Output 2022. https://doi.org/10.47330/DCIO.2022.GGNL1577

Schumacher, P. (2012). *The Autopoiesis of Architecture, Volume II: A New Agenda for Architecture* (1. edition). Wiley.

Skibniewski, M. J., & Garcia de Soto, B. (2020). Future of robotics and automation in construction. In *Construction 4.0*. Routledge.

Tedbury, I. (2018). *Relative Bricklaying Robot*. Ivo Tedbury. https://www.tedbury.co.uk/relative-bricklaying-robot

Tedbury, I., & Vaughan, F. (2019). *Walking Construction Robot Simulations*. Ivo Tedbury. https://www.tedbury.co.uk/walking-construction-robot-simulations

Tessmann, O. (2012). Topological Interlocking Assemblies. *Achten, Henri; Pavlicek, Jiri; Hulin, Jaroslav; Matejovska, Dana (Eds.), Digital Physicality - Proceedings of the 30th eCAADe Conference - Volume 2 / ISBN 978-9-4912070-3-7, Czech Technical University in Prague, Faculty of Architecture (Czech Republic) 12-14 September 2012, Pp. 211-219*. https://papers.cumincad.org/cgi-bin/works/paper/ecaade2012_176

visose. (2023). *Robots* [C#]. https://github.com/visose/Robots (Original work published 2015)

Yablonina, M., & Menges, A. (2019). Distributed Fabrication: Cooperative Making with Larger Groups of Smaller Machines. *Architectural Design*, *89*(2), 62–69. https://doi.org/10.1002/ad.2413

Yoshida, T. (2006). A Short History of Construction Robots Research & Development in a Japanese Company. *ISARC Proceedings*, 188–193.

Zhang, K., Chermprayong, P., Xiao, F., Tzoumanikas, D., Dams, B., Kay, S., Kocer, B. B., Burns, A., Orr, L., Choi, C., Darekar, D. D., Li, W., Hirschmann, S., Soana, V., Ngah, S. A., Sareh, S., Choubey, A., Margheri, L., Pawar, V. M., … Kovac, M. (2022). Aerial additive manufacturing with multiple autonomous robots. *Nature*, *609*(7928), Article 7928. https://doi.org/10.1038/s41586-022-04988-4