Chapter 8
Cooperative Robotic Fabrication for a Circular Economy

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Abstract In a cooperative robotic fabrication (CRF) framework, multiple industrial robots are specifically sequenced to work together, thus allowing them to execute coordinated processes with greater geometric and structural variation. In the context of the construction industry, agents in a cooperative setup can perform complementary functions such as placing or removing building components while simultaneously providing temporary support to a structure. This approach can reduce, or completely remove, the need for temporary external supports and scaffolding that would typically be required for stability during the construction of geometrically complex spanning spatial structures. For a circular economy, this means overall reductions to primary resource inputs and improvements to the disassembly, reuse, and reassembly potential of a structure at the end of its life. This chapter gives a summary of three projects that successfully demonstrate the use of cooperative robotic fabrication to promote several principles of a circular economy through different scaffold-free construction applications. The topics covered in this chapter will be of interest to researchers and professionals interested in the emergent intersection of digital fabrication, robotics, and sustainability applied to the building industry.

Keywords Robot · Cooperative · Collaborative · Construction · Assembly · Disassembly · Reuse

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8.1 Introduction

To reduce the environmental burden of the construction industry, new methods of practice must be adopted to help move away from a wasteful and resource-intensive design mentality. In this chapter, we introduce the emergent technology of cooperative robotic fabrication (CRF) and describe its potential to enable new applications that will facilitate a transition to more sustainable circular models of building design and construction. We focus on CRF as a technology strictly in the physical domain and demonstrate how such setups, when used to perform multiple tasks simultaneously in precisely choreographed sequences, can enable novel assembly, disassembly, and reuse processes.

8.1.1 What Is Cooperative Robotic Behaviour?

Robotic fabrication (RF) refers to any fabrication process that is completed with some degree of automation. CRF is a subset of RF and can be thought of as any process where the robotic agents are specifically coordinated to accomplish tasks that would not be possible if the robots were working alone. Cao et al. (1997, p. 8) state that "a multiple robot system displays cooperative behaviour if, due to [the mechanism of cooperation], there is an increase in the total utility of the system". Thus, cooperative robotic cells can fall under the category of either multi-arm individual robots, multiple single-arm robots, mechanical hands with independently controllable fingers, or a combination of these, working together in a synchronous fashion (Liu et al. 2004; Ranky 2003).

A single robotic agent, regardless of physical or digital complexity, is naturally limited in the type and number of actions it can simultaneously execute. Only in multi-robotic fabrication (MRF), where multiple agents are placed together in a work cell, does it become possible to unlock the potential of collective behaviour to achieve more complex outputs. All MRF setups exhibit some form of collective behaviour, but while cooperative behaviour is subset of collective behaviour (i.e. CRF $\subseteq$ MRF), the converse is not true (i.e. MRF CRF). A CRF process entails further utility beyond the collective behaviour that comes from a basic implementation of MRF. This hierarchy is illustrated in Fig. 8.1, where the output of an MRF setup is defined as scaling linearly with the number of agents to produce more of the same output (i.e. several robots working in parallel), as opposed to a CRF process where the output is uniquely contingent on all the agents working together.

Another important distinction is between the terms cooperative and collaborative, which are commonly used interchangeably to describe multi-agent robotic processes in the literature. To avoid ambiguity, collaborative is herein only used for a process where robot(s) work together with, or alongside, human operators. Collaborative processes exist across the entire RF hierarchy illustrated in Fig. 8.1. For example, collaborative processes are possible with a human working with a single robot

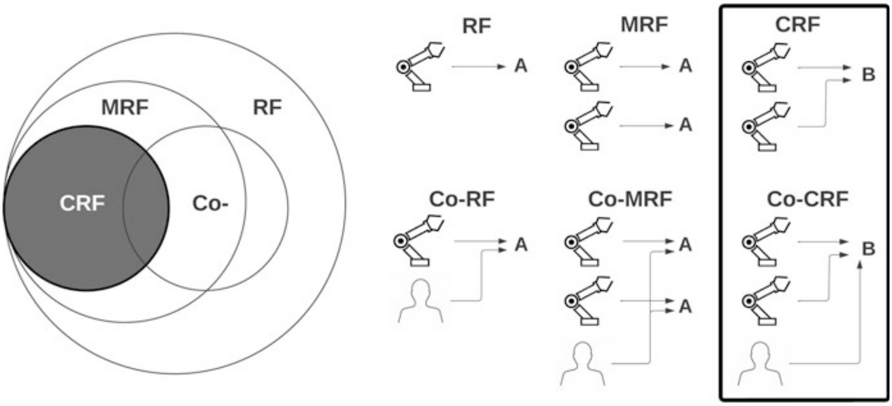

Fig. 8.1 Cooperative robotic fabrication as situated in the overall robotic setup hierarchy (*RF*-robotic fabrication, *MRF*-multi-robotic fabrication, *CRF*-cooperative robotic fabrication, *Co*-collaborative). A setup is cooperative, if by the process of cooperation, a novel output is made possible (i.e. B), as opposed to a basic MRF process which only allows more of the same output to be created in parallel (i.e. A)

(Co-RF, as in Asadi et al. (2018)), with multiple robots in series on an assembly line (Co-MRF, as in Weckenborg et al. (2020)), or to complement the cooperative function of multiple robots (Co-CRF, as in Bruun et al. (2020)).

8.1.2 *Broad Applications*

Alongside applications in the built environment, which are specifically discussed in Sect. 8.2, CRF is utilised in many industries when flexible manufacturing systems are necessary or where tasks occur in poorly structured environments (Caccavale and Uchiyama 2016). In generic manufacturing applications, CRF processes have a conceptual advantage over single robot processes with their ability to distribute the work among several potentially smaller robots and thus better control the internal forces, torques, and displacements associated with a payload (Montemayor and Wen 2005). In addition, CRF processes also allow for improved robustness against work interruptions through redundancy in the functions of the robots, improved flexibility through the ability to reconfigure a fabrication cell to fit different conditions, and improved task precision through the ability to dexterously grasp and then manipulate an object (Gudiño-Lau and Arteaga 2005; Montemayor and Wen 2005). Many generic tasks only become possible to automate when multiple robotic agents or manipulators are used cooperatively for carrying heavy loads, moving voluminous objects, avoiding obstacles through complex movements, handling flexible objects with extra degrees of freedom, and assembling multiple components without using dedicated supporting fixtures or jigs (Caccavale and Uchiyama 2016; Gan et al.

2012; Li and Zhang 2018). Different industries use CRF workflows for various industry-specific applications, for example:

- The agricultural industry has seen major adoption of automation technologies in recent years (Lytridis et al. 2021) and specifically in cooperative robotic setups for foraging and picking tasks for various fruits and vegetables (Ahlin et al. 2017; Ling et al. 2019; Sarabu et al. 2019; Sepulveda et al. 2020).
- The automotive industry has a long history of being at the forefront of automation and is a leader in developing and utilising both CRF and Co-CRF technologies (Michalos et al. 2010) for tasks such as welding (Papakostas et al. 2011; Pellegrinelli et al. 2017; Wu et al. 2000) and panel assembly (Connolly 2009).
- The fibre composite manufacturing industry has been using cooperating robots for laying and smoothing sheets of material (Malhan et al. 2018; Szcesny et al. 2017) and in filament winding (Sbanca and Mogan 2015) for fabricating high-strength, geometrically complex components.
- In heavy industry such as ship building and bridge construction, a dual-arm robot coupled with a hoist mechanism has been proposed to handle heavy workpieces (Shinohara et al. 2001).
- For generic industrial warehouse applications, cooperating mobile robots have long been used to move large and heavy objects (Hirata et al. 2000; Mataric et al. 1995).

8.2 Cooperative Robotic Fabrication in the Built Environment

The general use of robotics in the built environment is motivated by many of the same reasons as in the industries mentioned in Sect. 8.1, specifically high precision and task repeatability (Wang et al. 2021), improved productivity (Xu and Garcia de Soto 2020), improved site safety by reducing worker injuries (Chu et al. 2013), standardisation of product quality (Dritsas and Soh 2019), and the ability to conduct work remotely to facilitate any necessary social distancing (Wang et al. 2021). One of the first recorded uses of robots in the construction industry was the Motor Mason automated bricklaying machine from the 1960s (British Pathé 1967). But it was not until the 1970s, in Japan, that robots in the construction industry saw serious exploration and use, specifically for the prefabrication of modular housing components (Bock and Linner 2016). In the 1980s, more on-site robots appeared, followed by a proliferation of robots used for various specialised construction tasks over the next decades (Bock 2007). In the mid-2000s, the large-scale application of robotics in the context of architectural and building design began with the growth of the digital fabrication (DFab) movement (Bonwetsch et al. 2006; Gramazio and Kohler 2008). This movement emphasised the design and construction of geometrically complex, efficient, and bespoke structures that were often only made possible, or sufficiently productive (García de Soto et al. 2018), by combining novel digital technologies with more complex robotic setups.

A recent literature review on robots in the construction industry found that collaboration (used there to refer to both robot-robot and robot-human processes) is one of three major topics of recently published research (Xiao et al. 2022). CRF setups have been specifically demonstrated for automation, parallelisation, and scaling applied to rapid assembly and prefabrication, on-site additive manufacturing, and general task automation (Kayser et al. 2018; Petersen et al. 2019) and for future building applications in challenging environments such as space construction (Xue et al. 2021). In Sects. 8.2.1, 8.2.2, and 8.2.3, we summarise CRF applications in the construction industry organised according to the typical scale of their application (e.g. material, product, and building) and whether they originated specifically from the DFab research community or from the broader construction industry.

8.2.1 CRF at the Material Scale

CRF at the material scale is defined by small-scale processes that feature precise manipulation and subtractive/additive operations on single material units (e.g. a block of stone, a pipe, a structural member). General construction applications include the use of dual-armed table-top-sized robots, such as the IRB14000 (ABB 2015), for shaping materials and joining light building components such as small pipes (Afsari 2018). But in general such platforms suffer from limited payloads and are thus not capable of heavy lifting or manipulation of standard objects that are typical in most construction applications.

DFab applications include the use of CRF setups for cutting expanded polystyrene (EPS) foam blocks to create non-ruled and doubly curved surfaces. For example, custom concrete formwork was manufactured using a heated blade mounted on two robotic arms (Søndergaard et al. 2016). The relative displacement of the robot flanges was used to provide curvature to the blade, which shaped the cut through the workpiece as a third robot moved the foam block linearly through space. Another example used a heated wire instead, which two robots swept through a fixed foam block, using the resistance of the wire against the foam to create a non-standardised undulating surface profile for a series of wall panels (Rust et al. 2016). In the tying of knots in cables, which is a material-scale task, the creation of loops and crossings cannot be performed by a single robot (Augugliaro et al. 2015). In a project on the aerial construction of tensile rope structures, the spatial manoeuvrability of multiple flying unmanned aerial vehicles (UAVs) was utilised to tie a knot using coordinated multi-robot flight trajectories, thus establishing a structural node in three-dimensional space (Augugliaro et al. 2013; Mirjan et al. 2014).

8.2.2 CRF at the Product Scale

CRF at the product scale is common in modular construction applications, for building stand-alone components (i.e. walls, truss sections, shell panels) or transporting components as part of assembling a larger structure. In the context of prefabrication, CRF supports the goals of improving productivity, reducing labour, and maintaining a more predictable work environment (Vähä et al. 2013).

General construction applications include the assembly of a box girder structure, which was performed with a team of mobile robots that cooperated to move separate panels, align the parts, and fasten them together (Dogar et al. 2015). In another mobile robot example, NASA's Jet Propulsion Laboratory (JPL) Robot Construction Crew was used for picking and cooperatively transporting aluminium beams into an interlocking structure in the context of construction for space exploration applications (Huntsberger et al. 2005; Stroupe et al. 2005). In another space-related application, tetrahedral truss structure modules for an astronomical telescope were built on a rotating platform as a second robot placed struts into accessible regions of the structure (Doggett 2002).

DFab applications include the construction of modular components for both wood and composite fibre structures. In one project, timber modules with nonplanar geometries were constructed with two robotic arms used to place linear stud members while also supporting the corners of the structure in their unfinished state (Adel et al. 2018; Thoma et al. 2018). In another research project, prefabricated cassettes for a segmented timber shell pavilion were assembled on a rotating central turntable where one robot manipulated the unfinished module in space, while the other robot performed gluing, nailing, milling operations (Wagner et al. 2020). For composite fibre structures, a CRF process was used in the construction of a modular fibre shell pavilion consisting of 36 geometrically varying panels (Doerstelmann et al. 2015). Using the synchronised motion of two robots, a coreless filament was wound around an adaptable steel frame that defined the boundary polygon of each module (Parascho et al. 2015; Prado et al. 2014). In another filament winding project, two robots exchanged a spool of filament allowing it to reach and wind around support points in space to create varying modules for a spanning space frame structure (Duque Estrada et al. 2020).

8.2.3 CRF at the Building Scale

CRF at the building scale is common for the in situ construction of large structures or for performing work that requires complex task sequencing beyond what is possible by a single robot working alone. Processes at this scale emphasise the use of the robots to provide temporary support and guarantee stability for a structure as it is being built, and to expand the feasible work volume and reach beyond that of a standard RF setup.

General construction applications of CRF include an integrated construction robot platform featuring multiple robotic trolley hoists and mobile welding robots that are used to reach all areas of a steel structure as it is being constructed (Saidi et al. 2016). In one research project, the challenge of small payloads in aerial construction was overcome by the cooperative effort of multiple UAVs used to grasp, manipulate, and transport large structural elements into a structure on site (Mellinger et al. 2013). Several examples exist for in situ construction for space-based structures and applications. The multi-limbed Hexbot robot was designed to assemble a telescope truss structure directly in space by carrying large components that required more than one arm to grasp. The robot used its multiple limbs to simultaneously walk on the structure, stay anchored, perform the gross movement of components, and connect them to the existing structure at the point of assembly (Lee et al. 2016). In another related space construction project, the two-armed RoboSimian robot was used in a similar role as the Hexbot, for the manoeuvring and in-place assembly of a telescope truss structure (Karumanchi et al. 2018).

DFab applications of CRF at the building scale have been demonstrated for various structural typologies and typically fall under two distinct categories of material systems: continuous (e.g. filaments or cables) or discrete (e.g. rods, studs, or bricks) elements. An example of a project where a continuous material system was combined with a CRF process was in the construction of a large monocoque shell structure, where a UAV was used to pass a fibre spool between two static robotic arms placed at either end of the work volume. The filament was wound between the two robotic arms, expanding the feasible build volume by making it possible to build a structure within the interstitial space outside the reach of the two stationary robotic arms (Felbrich et al. 2017; Vasey et al. 2020). In another aerial construction project, volumetric cable structures were built in situ using two flying UAVs in a cooperative process of tying knots in space (Mirjan et al. 2013, 2016). In a final example of a continuous material system CRF process, multiple wall-climbing robots were used to pass filament between themselves, winding it around fixed anchor points to construct an in situ tensile structure (Yablonina and Menges 2019).

CRF for discrete element assembly at the building scale was first developed for the assembly of geometrically differentiated metal space frame structures (Parascho et al. 2017, 2018). This research focused on developing sequences and path-planning methods that used two robotic arms to alternate either providing temporary support or adding elements to the structure. In another project where cooperating robots were used for temporary support, a branching arch structure was built out of foam blocks without requiring scaffolding by relying on two robots as simultaneous mobile temporary supports (Wu and Kilian 2018). In the final example of a discrete element CRF process, a cooperative building-scale sequence was also demonstrated in the construction of a timber pergola roof structure, where one robot was used to support the member in space while the other performed an in situ drilling and fastening operation (Thoma et al. 2019).

8.3 Cooperative Robotic Fabrication for a Circular Economy

CRF processes can be generally used to foster a transition towards a circular economy. This discussion is situated in the context of the narrow, slow, close, and regenerate framework developed by the editors of this book (Çetin et al. 2021). To date, CRF has been applied to address objectives that are part of the narrow (Sect. 8.3.1), slow (Sect. 8.3.2), and close (Sect. 8.3.3) principles, with potential future applications discussed in Sect. 8.3.4. The regenerate principle is not yet linked to CRF but may be in the future.

8.3.1 Narrow

With respect to the narrow principle, the following objectives are specifically applicable to CRF: (1) reducing primary resource inputs, (2) designing for structural performance, and (3) improving construction efficiency. First, primary resource inputs for constructing new structures can be reduced by leveraging the potential multi-functionality of a CRF setup. For example, while one robot places structural members during construction, other robots simultaneously provide temporary support to the structure in its unfinished state. All robots can then alternate their function throughout the fabrication process. Their function at each fabrication step, as either the active robotic agent (i.e. placing material) or the passive robotic agent (i.e. supporting the structure), is determined by the operator. A structure designed based on such an alternating "support-place" cooperative robotic sequence is considered fabrication informed as the fabrication process itself explicitly shapes its design. Using such an approach allows for the reduction, or complete removal, of temporary falsework, scaffolding, and supporting structure that would normally be required to build the structure using traditional construction methods, thereby reducing the primary resource inputs associated with constructing this temporary support structure. This cooperative approach is especially relevant for spanning discrete element structures (e.g. masonry vaults and space frame structures), which often require extensive temporary supporting structures as they are only self-stable at their completion or only at specific stages during the construction process. This type of cooperative sequencing is demonstrated in each of the three projects presented in Sects. 8.4.1, 8.4.2, and 8.4.3.

The second objective of the narrow principle applicable to CRF is based on how material usage in the structure itself can also be reduced by designing its form such that it maximises structural performance. For example, form-found or topologically optimised structures are materially efficient by virtue of their shapes or connectivity being optimised for various loading conditions but often result in geometrically complex structures that are challenging to construct with traditional methods. Applied to the prefabrication of structural modules, it is possible to realise complex geometries by relying on the spatial precision of a robot to place material accurately in 3D space. This capability is augmented in a CRF setup, which allows for the simultaneous cooperative manoeuvring and repositioning of structural modules that are under construction to facilitate accessibility.

The third objective recognises efficient but geometrically complex structures can be time-consuming and require several workers to construct (García de Soto et al. 2018). A CRF process can improve construction efficiency by taking on certain material handling and movement tasks to reduce the overall time and labour resources required.

8.3.2 Slow

With respect to the slow principle, the following objectives are specifically applicable to CRF: (1) design for reversibility and (2) lifetime extension. Regarding the first objective, design for reversibility, CRF setups can be used for the disassembly of geometrically complex or spanning structures, which can thus be designed with explicit potential for reversibility from the outset. For example, the structure can be designed as an assembly of modules that can be more easily isolated and removed from the overall structure. To assist in this process, a CRF setup can be used with similar robotic task allocations as in assembly: the robots work cooperatively acting as temporary supports while simultaneously separating and removing self-rigid modules from the structure. The robots perform the physically demanding, and potentially dangerous, tasks of removing material while also indefinitely supporting and stabilising the structure in its temporary state of disassembly. The project described in Sect. 8.4.2 features a structure that is specifically designed so that it can be taken apart in a stability-preserving way when using a cooperative robotic sequence.

Regarding the second objective of the slow principle, CRF setups assisting in the task of disassembling a structure create an opportunity to start considering the use of automation for building lifetime extension. If a structure is designed with modularity in mind, damaged components can be more quickly isolated, removed, and eventually replaced without requiring large interruptions to the function of the structure (e.g. construction of temporary support or scaffolding).

8.3.3 Close

Regarding the close principle, the following activities are made possible through CRF: (1) tracking, documenting, and tracing building components and (2) reuse and reassembly. First, accurate 3D models of a structure can be created and used to build a digital twin to document geometric location and placement accuracy of structural and nonstructural components or to perform visual grading and inspection. CRF setups facilitate this process as the positional information that is inherent in a robotic platform can be used to accurately stitch together multiple 3D image captures from different cameras and perspectives. This can create a complete digital model of an existing structure, which would not always be possible with a single robot due to obstructed perspectives. In terms of the second objective, when CRF is applied to disassembly, it also facilitates the reuse and reassembly of structural components while modifying a building or recuperating material that would normally be treated as construction waste. This approach is demonstrated in the project described in Sect. 8.4.3.

8.3.4 Future Applications

CRF is typically used within laboratory environments. However, if research expands from static industrial robots towards mobile machines and large-scale construction machines, the technology could be directly applied on construction sites to enable more material-efficient construction and engender faster and more precise disassembly and reassembly processes. These developments would contribute to the slow and close principles.

In addition, integrated force-torque sensors mounted on the robot tool flange can be leveraged in a cooperative manner to carry out in situ non-destructive testing on structures to further collect data on their performance in their final state or as they are being assembled or disassembled. This wealth of data can be used to design more materially efficient structures, better evaluate overall structural performance during fabrication, and measure parameters like the stiffness or degree of damage to a member. Effectively, each robot could act as a 6-degree-of-freedom actuator capable of applying forces and moments to a structure at any location and orientation in space. If the robots are sequenced cooperatively, it would be possible to apply non-standard loading conditions, which for geometrically complex structures would be difficult to evaluate in situ using conventional load testing methods.

8.4 Examples of Cooperative Robotic Fabrication for a Circular Economy

The following section describes three recent research-based examples of how CRF is used for discrete element assembly (Sects. 8.4.1 and 8.4.2), disassembly (Sects. 8.4.2 and 8.4.3), and reassembly (Sect. 8.4.3) to target objectives related to the narrow, slow, close circular economy principles described in the previous section.

8.4.1 LightVault

The LightVault was a 3.6 × 6.5 × 2.2 m doubly curved masonry vault built with two stationary robotic arms as a demonstration of CRF applied to an assembly process (Parascho et al. 2021). In the first phase of the project, a central arch was constructed utilising the alternating cooperative robotic placement and support approach inspired by previous research on the assembly of metal space frame structures (Parascho et al. 2017, 2018). One robot continuously acted as a support to the partially completed arch, while the other was used to place additional bricks into the structure (Fig. 8.2). Thus, the arch was built from one end to the other without requiring any additional temporary supporting structure. The structural performance of the arch during construction was assessed using a discrete element modelling approach (Paris et al. 2021), and the cooperative sequencing was later theorised to setups with more than two robots to further improve the structural performance during assembly (Bruun et al. 2021). In the second phase of the project, the rest of the vault was built

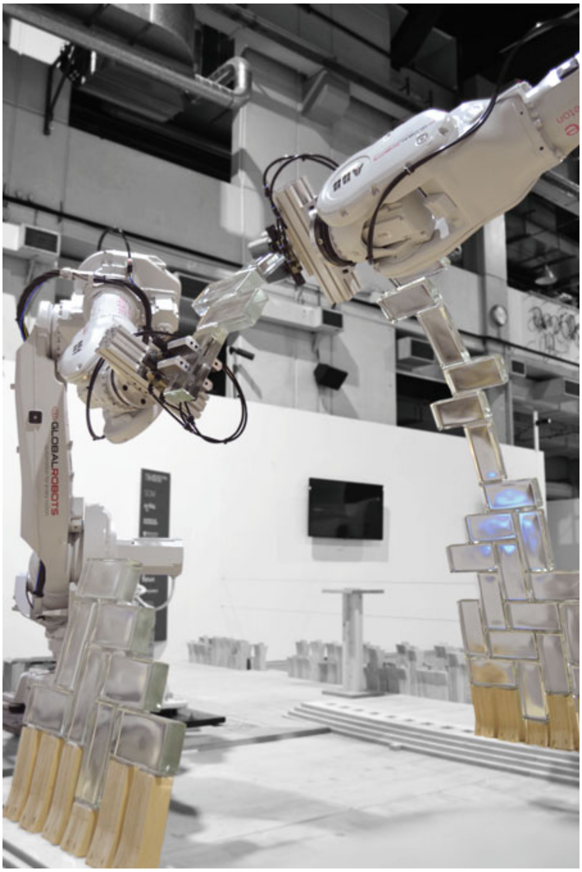

Fig. 8.2 Building the central arch as the first phase in the scaffold-free cooperative robotic assembly of a masonry vault

layer by layer using the central arch as a backbone structure (Han et al. 2020; Parascho et al. 2020).

Overall, the LightVault demonstrated the potential application of CRF for scaffold-free construction of spanning structures made from heavy material. With respect to circular economy principles, the use of primary resources was reduced by eliminating temporary supporting structures and minimising the material in the structure itself by enabling the construction of a structurally efficient but geometrically complex compression-only form.

8.4.2 Remote Robotic Assemblies Workshop

In the Remote Robotic Assemblies workshop held at the 2021 Association for Computer Aided Design in Architecture (ACADIA) conference, a timber space frame arch structure was constructed using two cooperating robotic arms on linear tracks. This project was a demonstration of CRF applied to not just the assembly of the structure but extending its use for the first time to disassembly as well. Using a method based on rigidity theory, the space frame was designed explicitly to leverage cooperative robotic support sequencing to replace temporary supporting structure during both the construction and deconstruction phases (Bruun et al. 2022b). The structure was first assembled element by element, where one passive robotic agent was always required to provide support to the partially assembled structure. Following this, the structure was disassembled cell by cell, taking advantage of the fact that it was designed explicitly as an assembly of locally rigid tetrahedral cells. These cells were sequentially supported, isolated, and then removed with one robot, while the other robot supported the partially disassembled structure (Fig. 8.3). The disassembly process is an example of a collaborative-CRF (Co-CRF) process as the removal of individual elements to disconnect the rigid tetrahedral cells from the remaining structure was done in collaboration with a human.

Overall, the Remote Robotic Assemblies workshop demonstrated that CRF is a viable technology to reduce primary resource inputs in the form of scaffolding during both the assembly and disassembly of spanning space frame structures. In addition, extending the application of CRF to disassembly tasks highlighted the potential of including considerations for disassembly at the outset of a design to better facilitate the reuse and recycling of building components at the end of a structure's life.

8.4.3 ZeroWaste

ZeroWaste was a research project exploring the idea of treating existing buildings as stores of valuable reusable material in the context of a circular economy (Bruun et al. 2022a). Rather than demolishing and disposing of a building at the end of its life, the

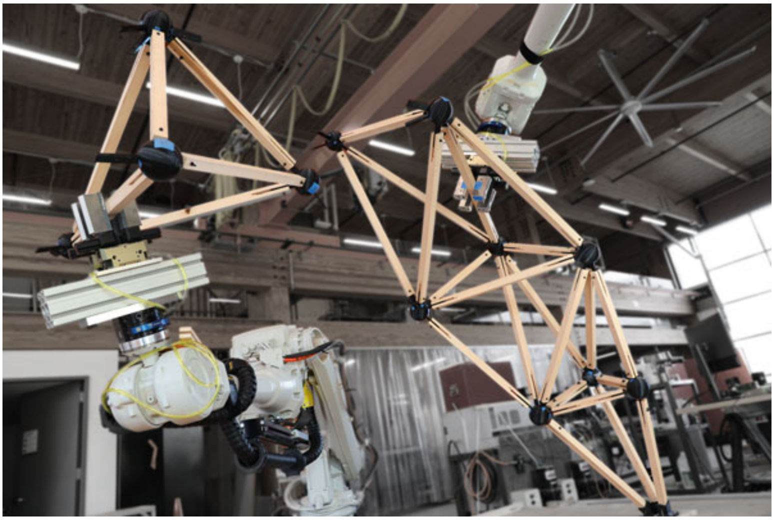

Fig. 8.3 Isolating locally rigid cells in the scaffold-free cooperative robotic disassembly of a spanning timber space frame arch structure

goal was to leverage the use of a CRF setup to first gather data about an unknown existing structure and then use this information together with the robotic setup to disassemble and then reassemble the structure into new feasible configurations.

As the starting point, a pavilion-scale timber structure was built manually to act as a stand-in representing a generic unknown existing structure built according to standard stick framing construction practices. Next, 3D cameras were mounted on two robotic arms, which were then used to take several point cloud captures of the structure from various locations and angles. Using the accurate positional information queried from the robotic controller, the individual point cloud captures were transformed and then stitched together to create a complete spatial model of the existing structure. Creating this complete model was only possible when using multiple robots, as a single robot would not have the required reach and manoeuvrability to fully capture the structure. For an existing building, the exact geometry and spatial location of the structure is not known; thus, the as-built geometric information gathered in this imaging process was necessary when later planning the RF sequences.

Next, scaffold-free robotic cooperative disassembly and reassembly sequences were calculated algorithmically using a support hierarchy graph representation of the structure – this method is described further in Bruun et al. (2022a). These sequences were specifically planned for execution with the three robotic arms available in the fabrication cell, two on linear tracks and one stationary, without requiring external temporary formwork. The physical RF process was split into four distinct phases, targeting different objectives with respect to the cooperative robotic sequencing and the degree of disassembly and reassembly (Fig. 8.4).

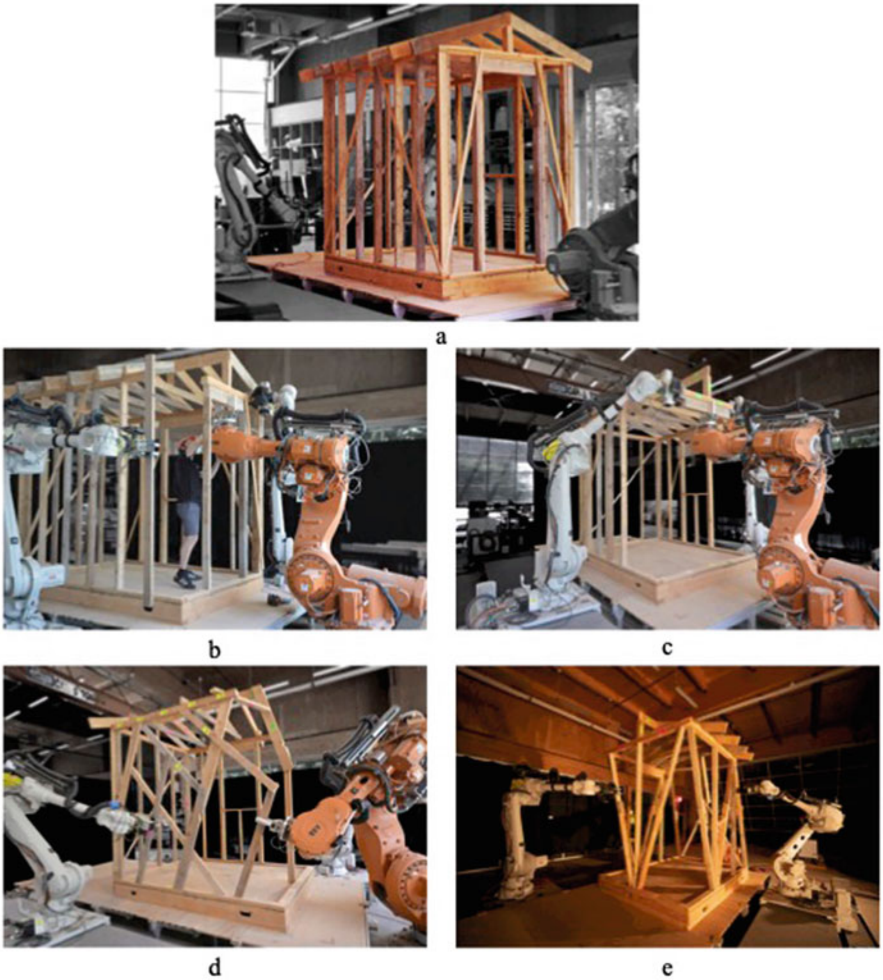

Fig. 8.4 Snapshots of the four cooperative robotic fabrication phases for the ZeroWaste project. (**a**) Starting timber structure built according to traditional American stick framing construction practices; (**b**) phase 1: disassembly of a corner using a two-robot CRF process, no reassembly; (**c**) phase 2: disassembly of the front wall using a three-robot CRF process followed by reassembly of four members as a new supporting structure for the roof girder at the front of the structure; (**d**) phase 3: disassembly of a side wall using a two-robot CRF process with simultaneous parallel 1-to-1 reassembly (i.e. each member removed is reused) to create a stiff lattice configuration for the same wall; (**e**) phase 4: disassembly of all remaining walls using a three-robot MRF process with simultaneous parallel reassembly into an inclined system vertical member system

As in the project described in Sect. 8.4.2, ZeroWaste demonstrated the use of a CRF setup in providing temporary support to a structure during disassembly but further extended its use to perform scaffold-free reassembly and reuse of removed material. Improvements in construction efficiency were also demonstrated as the full fabrication process only required a single person working alongside the robots, whereas using non-robotic methods would typically require several workers to accomplish the same tasks. Overall, the successful use of CRF in the ZeroWaste project to assist in structural disassembly and reassembly tasks highlighted the potential of this technology to facilitate a more circular treatment of existing timber building stock through its reuse.

8.5 Discussion

As demonstrated in this chapter, cooperative robotic fabrication (CRF) has the potential to enable novel assembly, disassembly, and reuse processes that promote several essential principles of a circular economy. Primary resource utilisation can be reduced by minimising, or completely removing, the need for temporary scaffolding during the (de)construction of geometrically complex spanning structures. In addition, general construction efficiency can be improved by shifting certain challenging and dangerous tasks related to material handling and transport from human workers to the robotic setup. If modularity is considered and originally designed into a building, CRF can facilitate selective disassembly and removal of structural components to replace damaged elements and extend the life of a building. In the eventual decommissioning of existing buildings, CRF setups can also be used to catalogue, disassemble, and then reuse components to divert building materials away from waste streams and return them back to productive use.

Challenges with broadening the adoption of CRF technology in the construction industry relate to the complexity of implementing these setups in an on-site unstructured environment. While stationary robots, or robots with limited mobility on linear tracks, are well suited for off-site prefabrication tasks, CRF with mobile robotic setups will be required in the future to broaden the ranges of applications that are possible in larger volumes, as would be expected on a job site. Other chapters in this book describe technologies that are adjacent and relevant to CRF: scanning technologies and scan-to-BIM (Chap. 3), building information modelling (BIM) and digital twins (Chap. 1), computational design (Chap. 6), and on-site robotic fabrication (Chap. 9).

8.6 Key Takeaways

- In a cooperative robotic fabrication setup, the robotic agents are specifically coordinated to accomplish tasks that would not be possible if the robots were working alone.
- Multiple robots can be sequenced to place or remove structural components while alternating temporarily supporting the structure, performing material handling, or data acquisition operations.

- Primary resource inputs in the form of scaffolding and temporary support can be removed during construction when using a cooperative robotic fabrication setup.
- Disassembly and reuse of existing buildings is made possible when using a cooperative robotic fabrication setup.

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