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Chapter 9
Circular Robotic Construction

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Abstract In situ robotic construction is a type of construction where mobile robotic systems build directly on the building site. To enable on-site navigation, industrial robots can be integrated with mobile bases, while mobile, high-payload construction machines can be adapted for autonomous operation. With parallel advances in sensor processing, these robotic construction processes can become robust and capable of handling non-standard, local, as-found materials.

The potential of using autonomous, mobile robotic systems for the development of innovative circular construction processes is presented in three exemplary case studies:(i) robotically jammed structures from bulk materials, (ii) robotic earthworks with local and upcycled materials, and (iii) robotic additive manufacturing with earth-based materials. These processes exemplify key strategies for a circular industry through the utilisation of materials with low embodied greenhouse gas emissions and the implementation of fully reversible construction processes.

For each case study, we describe the robotic building process, the enabling technologies and workflows, and the major sustainability and circularity benefits compared to conventional construction methods. Moreover, we discuss the difficulty of industry transfer, considering challenges such as detailing, integration, and engineering validation. We conclude with an outlook towards future research avenues and industry adoption strategies.

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9.1 What Is Robotic Construction?

Robotic construction is an emerging interdisciplinary field. Robots were first introduced to the construction sector in the 1970s in Japan, in part due to the lack of skilled labour. Early initiatives, such as single-task construction robotics (Bock and Linner 2016a) and fully integrated, on-site factories for buildings, failed to be widely adopted (Bock and Linner 2016b). However, there was a clear turning point when industrial robots were appropriated for architectural application and began to be digitally programmed in 2006, enabling the direct connection of computational design processes to physical fabrication processes and the development of novel material systems (Gramazio et al. 2014). In parallel, there have been advances in the automation of existing construction machinery, where common construction machines have been adapted for digital control and autonomous operation.

In this chapter, we consider the specific case of in situ robotic construction. In contrast to robotic prefabrication, where parts are prefabricated in a factory off-site, in situ robotic construction is a type of construction where robots move directly on the construction site and produce or assemble parts directly in their final position (Helm et al. 2012, 2014). This type of robotic construction has added benefits for a circular built environment because it enables material flows and production chains that minimise transportation overhead and material processing steps. However, the implementation of in situ robotic construction faces technical, logistical, and legal challenges, described below and then presented in more detail in the case studies.

From a technical perspective, robotic systems suited for on-site operation require robust systems for mobility, navigation, and localisation. Due to the unstructured nature of construction sites, such systems also require on-board sensing, such as LiDAR sensors and global navigation satellite systems. These same sensing technologies, when coupled with robust backend computational processes, can be leveraged to enable robotic systems to simultaneously handle unstructured and natural material systems with a high degree of variability and unpredictability.

Schematically, two of the most common types of robotic systems suitable for on-site construction tasks and deployed in the presented case studies include standard industrial robots integrated with mobile bases and mobile construction equipment, such as hydraulic excavators, modified for autonomous operation. At ETH Zurich, the In situ Fabricator (IF) is a prototypical mobile robotic system consisting of an ABB IRB 4600 robotic arm with 2.55 m reach and kg payload mounted on an automated excavator base that built off precedent iterations (Giftthaler et al. 2017; Sandy et al. 2016). This unit was first developed in 2016 and has so far been deployed in mobile robotic brick stacking (Dörfler et al. 2016), custom metal formwork for non-standard concrete (Dörfler et al. 2019; Hack and Lauer 2014), and in the robotic processes discussed in Sect. 9.4.1. In contrast, HEAP is a full-scale walking excavator developed by the Robotic Systems Lab at ETH Zurich (Jud et al.

2021b), with a vertical reach up to 9 m and a maximum payload of 3 tonnes. HEAP has been utilised primarily for automating existing construction processes such as autonomous trench digging, autonomous forestry work, semi-autonomous teleoperation, and the robotic earthworks and assembly processes presented in Sect. 9.4.2.

9.2 Robotic Construction for the Built Environment

To date, robots have not been widely used in the building industry for construction. This is in part due to low profit margins for various stakeholders, minimal research funding, and a lack of vertical and horizontal integration in the construction sector (Saidi et al. 2016). Because they operate near human workers, robots on the construction site also require necessary changes in safety protocols and legislation. Moreover, for on-site conditions, gantry-based systems currently have more widespread industry use, particularly for additive manufacturing and 3D printing (Wu et al. 2016). However, mobile robotic systems have clear benefits over such rigid, fixed installations, including higher geometric freedom, lower self-weight and volume, and the possibility for operation in unstructured and variable terrain. In contrast to gantry systems, mobile robotic systems also require less drastic site modifications and therefore can minimise the need for additional foundations that contribute to construction waste, greenhouse gas (GHG) emissions, and embodied energy. Existing diesel-powered construction machines allow for construction in remote, off-grid environments, while recent developments in electrification can greatly reduce the embodied energy of these machines where infrastructure allows.

A variety of material fabrication and building systems have been robotically automated for construction (Bock 2007; Melenbrink et al. 2020; Petersen et al. 2019). Some of the most common material applications with a high level of technological readiness are described in the following paragraphs. Predominantly, workflows based on prefabrication are more technologically ready than in situ–based approaches, while on-site fabrication exists as an alternative. In this case, critical equipment for subassembly or part fabrication is transported in a mobile container and set up as a small factory on site.

For concrete and other cementitious material types, common processes include layer-based extrusion, robotic slip forming, robotic shot-creting, and robotic spraying (Burger et al. 2020; Ercan Jenny et al. 2020; Hack et al. 2021; Hack and Kloft 2020; Wangler et al. 2019). Robotic fused-deposition modelling (FDM) printing has been used for custom concrete formwork, while robotically tended rebar construction (“mesh mould”) has been developed and transferred to industry through the start-up Mesh (Mirjan et al. 2022). Robotic wire cutting of foam formwork for concrete casting has been developed in academia and then also transferred to industry through the Danish company Odico (Feringa 2014; Søndergaard 2014; Søndergaard et al. 2016).

Robotic fibre composite manufacturing techniques, including coreless filament winding and tape laying, are processes that originated in the aerospace industries but have been modified for architecture applications (Prado et al. 2014; Vasey et al. 2015, 2020; Bodea et al. 2021, 2022). These fabrication methods have transferred into industry through the start-up Fibr (Dörstelmann n.d.).

A variety of approaches and building systems have been achieved in timber and wood construction, including multi-robotic assembly processes for timber framing systems (Willmann et al. 2016; Apolinarska 2018; Thoma et al. 2018; Leung et al. 2021), long-spanning robotically fabricated plate systems (Li and Knippers 2015; Schwinn and Menges 2015), and multi-layer cassette-based systems (Alvarez et al. 2019; Wagner et al. 2020a). A fully equipped multi-robot mobile factory for on-site prefabrication of timber modules has also been developed (Wagner et al. 2020b). Companies such as Intelligent City and Design-to-Production leverage robotic technologies for customised timber structures and housing (Scheurer et al. 2005; intelligent city 2023).

Robotic masonry construction has been explored extensively in both academic and industry contexts for facades and load-bearing walls (Bonswetch et al. 2006; Helm et al. 2012; Gramazio and Kohler 2014; Piškorec et al. 2019). Custom brickwork has been successfully transferred to the industry by companies such as ROB technologies and Keller Ziegeleien (Keller Systeme 2023; ROB Technologies 2023). Custom robotic systems such as the Hadrian X® mobile robotic block laying machine have achieved a high level of technical readiness for the on-site assembly of concrete masonry units (CMUs) (FBR 2023).

Several other efforts focus on automating existing manual tasks, such as dry wall installation, curtain wall installation, drilling, and welding, among others (Brosque et al. 2020, 2021; Iturralde et al. 2022).

9.3 Robotic Construction for a Circular Economy

In situ robotic construction can address the needs of a circular building industry primarily by slowing the consumption of resources through the following strategies:

- Enabling the use of natural and as-found materials with low embodied energy and GHG emissions.
- Minimising extra transportation steps of material, components, or assemblies to and from external processing or production sites.
- Minimising peripheral supporting elements such as formwork or falsework.
- Minimising material use through structural optimisation and realisation of complex geometries.
- Enabling reversible construction processes with minimal material downgrading.

In situ robotic construction can slow the consumption of resources using locally available, natural, and upcycled materials. Natural materials and local materials both exhibit high geometric and mechanical variability. Scanning, on-site robotic processing, and assembly can enable the use of completely natural materials with lower embodied energy and greenhouse gases. With design systems that adapt to these variable geometries of existing material or upcycled material stock, extra resource- and energy-intensive processing steps can be avoided. Energy and embodied GHG emissions due to transportation can also be minimised by utilising materials that are available near the construction site.

In situ robotic construction can also minimise peripheral equipment and extra site work. For example, formwork, which is a major component of construction and demolition waste (Shen et al. 2004), can be avoided, as demonstrated in the following case studies. Scaffolding, falsework, framing systems, and other stabilisation elements that enable the lifting of subassemblies or components are also made unnecessary. Furthermore, subassemblies do not have to be designed for the unique load cases incurred during lifting and transportation, leading to over-dimensioning. As mentioned in the previous section, mobile on-site robots potentially require less custom foundation work in contrast to more extensive on-site gantry-based systems.

Another important criterion is the reversibility of construction processes. On-site robotic assembly processes, such as robotic dry-stone masonry, which can achieve load-bearing behaviour without mortar or other adhesives, can also be largely reversible with minimal material downgrading and are therefore more circular. Robotic additive manufacturing with earth-based material mixtures, composed of materials like clay, gravel, sand, and silt, but without chemical stabilisers, can also be reversible with some additional, but minimal, processing steps.

The following exemplary case studies demonstrate the potential of in situ robotic construction towards enabling a circular building industry. These academic projects emerged out of a half-decade of interdisciplinary research at ETH Zurich. These projects are situated in their local economic context: sourcing materials from both local suppliers and the construction waste stream and engaging with industry partners offering material processing and construction services. Moreover, these full-scale and sometimes permanent demonstrators required collaboration with geotechnical engineers, structural engineers, and general contractors, thus engaging questions relating to implementation and long-term industry adoption.

9.4 Examples of in Situ Circular Robotic Construction

9.4.1 Robotic Construction of Jammed Architectural Structures (JAS) from Bulk Material

The combination of robotic fabrication and structural health monitoring enables the construction of jammed architectural structures (JAS) composed of gravel, a common bulk material, and twine. Jamming is a physical phenomenon where loose granular materials are compacted into self-stable configurations through externally applied pressure, self-weight, and/or confinement. Jammed materials behave fundamentally differently than conventional construction materials as they can change back and forth between a jammed, solid state and a loose, malleable state. In robotic fabrication of JAS, crushed porphyry is held in place by robotically placed twine (Aejmelaeus-Lindström et al. 2016). In 2018, a full-scale architectural structure, Rock Print Pavilion, was built to demonstrate the potential of JAS (Aejmelaeus-Lindström et al. 2017, 2020). It was opened to the public in the historic city centre of Winterthur, Switzerland, and then fully deconstructed (Fig. 9.1).

Similar to dry masonry, JAS requires in situ fabrication and cannot be prefabricated, as the structural properties of the material change due to small changes of the confinement. Thus, the pavilion was built by the IF introduced in Sect. 9.1. The IF's tracked base enabled it to move on the construction site: an unpaved square covered with gravel at a slight (approximately 2-degree) angle and with significant surface irregularities. The robotic positioning system is based on a Hilti POS 150 robotic total station, a reflector prism mounted on the end-effector and custom software (Sandy et al. 2016). The robot arm was moved to a series of positions, which were automatically registered by the total station and used to calculate the transformation from the tool coordinate frame to the world coordinate frame. The IF is equipped with a custom, multi-purpose end-effector consisting of a gravel dispensing tool, a compacting tool, and a reinforcement-laying tool. First, it lays the twine in layers of aligned, interlocking circular loops, after which gravel is measured and placed inside the string loop and compacted. The compacting of the crushed rock and twine displaces the particles concentrically, which in turn tensions the reinforcement loops, providing the confinement necessary for jammed vertical structures.

The pavilion is designed as five tapered elements that are wall shaped at the base. Towards the top, they branch into 11 columns that carry an 8.7-tonne cantilevering steel roof. Each element is designed to fit within the work envelope of the robotic arm. The steel roof is temporarily mounted on pillars during the construction to protect the construction site from rain. The structure was fabricated from 36 tonnes of porphyry gravel and 85 km of string. After being exhibited for 6 weeks, the steel roof was dismantled and the string was pulled out, returning the raw material to its original state. A structural health monitoring approach was developed where the movement of the steel roof was monitored daily to ensure minimal movement, required by the supervising engineer. Additionally, deformation inside the structure was measured with a fibre optic strain measuring device (LUNA Sensor) to identify any internal changes to the structure. No major movement of the roof was recorded during the six-week lifespan. Custom detailing between the steel roof and top of the columns allowed for height adjustments and load redistribution in the case of asymmetric creep of the structure.

To conclude, JAS is a highly experimental robotic building process but with advantageous sustainability and circularity metrics, as it uses simple, widely available raw materials, and the resulting structures can be fully reversed without downgrading. For the demonstrator, the aggregates were sourced from a quarry located within 30 km of its construction site and returned after the life span of the pavilion. However, the material system is significantly different from conventional

Fig. 9.1 (i) The Rock Print Pavilion is a full-scale robotically jammed structure composed of gravel aggregates and twine. The enabling technologies facilitating the on-site adaptive construction process include a custom robotic end-effector (ii) for extruding twine, depositing aggregates, and compacting layers, a structural health monitoring approach for the movement of the structure and the roof over time (iii), and mobility and localisation of the IF enabling the production of a larger structure on uneven ground (iv). The structure can be easily deconstructed with no material downgrading by removing the twine (v). (© Georg Aerni)

and standardised construction material: it is significantly anisotropic and sensitive to surface erosion. Future work is required both to understand and monitor the structural behaviour and to increase the surface strength. In terms of possible applications, JAS might be suitable for infrastructure construction, with particular utility in increasing the stiffness and longevity of road substrates. This research area has been explored in collaboration with the Swiss Federal Laboratories for Materials Science and Technology (Empa 2017).

9.4.2 Robotic Earthworks with Local and Upcycled Materials

The application of roboticised heavy hydraulic machines has enabled recent advances in on-site excavation and assembly. Methods for robotic landscaping and the robotic assembly of dry-stone masonry walls have been integrated towards the construction of digitally designed earthworks and soil-retaining structures – executed in the form of a full-scale, publicly accessible Circularity Park that features a permanent stone retaining wall, terraced landscapes, and a public circulation trail (Fig. 9.2).

Robotic landscaping is a process for forming natural granular materials like sand, soil, and gravel utilising HEAP, the autonomous excavator. The process can realise geometrically complex landscape formations with high precision, with an estimated average error of 3–5 cm (Jud et al. 2021a). Digital terrain modelling tools based on signed distance functions enable the balancing of cut and fill volumes for material-neutral, on-site construction, while incremental LiDAR scanning enables digital reconstruction of the site and current ground condition (Hurkxkens et al. 2019; Jud et al. 2017).

Large-scale dry-stone masonry structures are constructed by the Mobile Robotic Aggregation of Found Objects, a robotic construction method that enables robotic construction from highly irregular local boulders and waste concrete. The process can realise mortar-free masonry walls as both free-standing and soil-retaining structures. One of the significant technical challenges of the process is that the geometry of the material stock is not known ahead of construction, and thus the walls cannot be designed ahead of time. A scanning routine was developed to locate and digitise individual stones utilising HEAPs cabin-mounted LiDAR: accumulating points that are meshed using Poisson reconstruction to provide a full 3D model of each stone with a resolution suitable for manipulation and construction. A custom geometric planner was developed within the scope of the project, and it algorithmically determines where stones can be placed within a designer-specified volume, given an inventory of available boulders and concrete debris (Johns et al. 2020). A robotic grasp-planning workflow uses 3D mapping and collision constraints to reliably grasp and reorient irregularly shaped stones, using the excavator’s 2-jaw gripper (Mascaro et al. 2021), allowing for solutions from the geometric planner to be placed on the wall. The locations of these stones are incrementally updated using the LiDAR

Fig. 9.2 (i) The Circularity Park is a full-scale and publicly accessible landscape park built with robotic landscaping and autonomous robotic dry-stone masonry, utilising HEAP. The material includes locally sourced boulders and waste concrete (ii). The main enabling technologies facilitating the on-site adaptive construction process included (iii) an adaptive planning computational design and tool and (iv) a scanning process for digitising the individual stones. Robotic landscaping enabled precise landscaping of the surrounding terraces (v). (© Gramazio Kohler Research. Drone Videography: Girts Apskalns. Photography: Mark Schneider)

scanner, ensuring that shifting and settling is accounted for in subsequent construction steps.

The developed construction method has several sustainability and circularity benefits when benchmarked against conventional methods of construction, particularly when compared to reinforced concrete retaining walls. For the case of retaining walls, previous research has suggested the sustainability advantages of masonry when benchmarked against concrete in terms of GHG consumption and energy footprint (Farcas et al. 2015). Significantly, dry-stone masonry surpasses these performances, considering that the construction process takes advantage of locally sourced materials, and the structures are produced without mortar, rendering them fully reversible with little downgrading. This robotic assembly process also includes no secondary processing, such as cutting the stones into shapes that more easily fit together. Additionally, the developed method of construction incorporates recycled concrete debris and thus could be used to upcycle a portion of the estimated 2.6 million tonnes of concrete recycled each year from demolished houses (Guerra and Kast 2015). In Zurich, for example, this has particular significance, as the approved landfill volume for recycled concrete will only be sufficient for the next 10 years (Guerra and Kast 2015). The design tool for the landscape design further enhances the sustainability of the developed methods, as the designer can balance cut and fill volumes, proactively avoiding transporting extra material to or from the site.

The two robotic construction processes were integrated into a workflow for the production of the full-scale demonstrator in collaboration with Eberhard AG, a Swiss construction and material processing company that operates the recycling facility where the park was built. To expedite construction, a rough cut of the landscape was first executed with a large, manually operated excavator within approximately 1 m of the target digital landscape. A minimal foundation for the wall was provided by compacting the local soil and further reinforcing it with a low-cement stabiliser. The robotic construction process was then staged accordingly to maintain the accessibility of HEAP to the area of construction. First, the upper terraces were autonomously and precisely excavated in accordance with the 3D digital blueprint. The construction of the retaining wall was then executed incrementally in stable layers. An inventory of approximately 25 stones was scanned and stored on-site and within reach of the excavator until it was replenished by truck-based material delivery. The wall was constructed from boulders from a local quarry, erratics unearthed during construction in nearby Eberhard building sites, and concrete debris from demolished structures around Zurich. Robotic landscaping final passes were then alternated with placing stones until the structure was complete. Finally, the whole site was scanned and additional details, such as stairs, railings, finishing layers, and benches, were put in place through conventional manual methods. Some details, such as the stair, had to be especially designed on site to fit with the stone wall dimensions. Here, the adjacent rocks were scanned, and an old concrete stair from the west side of the site was scanned, cut-to-size, reassembled, and fixed with mortar.

The Circularity Park occupied the private land of Eberhard but was intended to ultimately be permanently accessible to the public, so it was critical that safety measures were put in place. In addition to the academic research team, the project was supported by external contractors for permitting and a team of geotechnical engineers who oversaw and guided construction. Ultimately, because no existing building codes can certify robotically constructed walls, the construction elicited a high degree of risk. To mitigate risks, the structural engineer over-dimensioned the thickness of the wall, specifying an additional layer of backfilling stones that were collectively digitised such that the robotic process could also adapt. Additional manual-stability testing methods were ordered and executed at the end of construction to assess the stability of individual stones. One additional research trajectory investigated was to utilise HEAPs force-torque sensing to apply targeted point load cases on the wall. Currently, this method can realise similar conclusions as manual testing methods by identifying unstable and non-load-bearing stones that slip at low threshold forces. Loose stones discovered manually or robotically had to be mechanically fastened to neighbouring stones.

As the client, Eberhard assumed all liability for any issues with the function, serviceability, and safety of the retaining wall. Long-term industry adoption and implementation would necessitate new building codes and codified methods of validation and in situ testing. Being able to validate the structural ability to withstand typical retaining wall load cases would be a key hurdle to proving the technological soundness of the given construction process. Only then would the developed method be able to serve as a viable alternative for infrastructure such as concrete gravity retaining walls.

In summary, the developed method of robotic construction updates a vernacular building process and enhances it through a digital toolset. The main circular attributes include the use of locally sourced natural stones and waste material and the reversible nature of the construction process. However, detailing and engineering validation remain significant challenges for long-term industry adoption.

9.4.3 Robotic Additive Manufacturing with Earth-Based Materials

Earth-based materials, such as soil, gravel, sand, silt, and clay have great relevance for circular and sustainable construction. Yet conventional earth-based construction methods such as rammed earth construction have high costs, low levels of digitalisation, and high dependency on manual labour. Rapid Clay Formations is an additive robotic fabrication process that reinterprets the traditional construction method for cob walls, where discrete parts of malleable earth blocks are manually aggregated to form a solid mass. The robotic process was developed to produce a full-scale and permanent demonstrator, the Clay Rotunda, a cylindrical structure constituting the outer soundproof shell of the electroacoustic auditorium SE MusicLab (Fig. 9.3).

For the robotic process, malleable cylindrical “soft bricks” were pre-produced off-site through an extrusion-based process within the standard brick production facilities of the industry partner, Brauchli Ziegelei, a local brick manufacturer. In the

Fig. 9.3 (i) The Clay Rotunda is a cylindrical structure constituting the outer, soundproof shell of the electroacoustic auditorium SE MusicLab. (ii) The soft bricks were produced externally with an industry partner. (iii) The robotic pressing process was realised with the IF, which could be relocated on a temporary scaffold to realise a two-story structure. (iv) Detail of structure showing the bonding and interlocking between adjacent elements. (© Gramazio Kohler Research)

additive robotic process, the soft bricks were grabbed by the robotic arm with a pneumatic end-effector from a picking station, precisely positioned and oriented, and sequentially pressed into their final position, thus bonding with the previous layers through material cohesion and geometric interlocking.

The hardware setup consists of the custom robotic platform – the IF – which allows relocation and navigation on a temporary scaffold after every built segment and therefore enables the construction of larger structures on site. The overall precision of the structure is achieved by monitoring the sequential buildup using both LiDAR scanning and point measurements, digitised with a robotic total station. Deformations due to shrinkage are partially compensated through a predictive computational workflow that estimates the expected deformations of a given subassembly of parts. A lean design-to-construction pipeline allows subsequent control code to be regenerated based on these tolerances and re-output to the robot control setup.

This first full-scale robotic clay pressing process addresses sustainability and circularity through several aspects. The material used for the soft bricks is a mix of 40% clay, 45% sand, 15% stones, and 16% water. The clay is sourced from a clay pit located in eastern Switzerland, right next to the brick production facility, which provided the sand for the mix. Stones were provided by Eberhard AG. The material thus has low embodied energy compared to concrete or bricks as it is locally sourced, minimally processed, and unfired.

The Clay Rotunda was designed for permanent long-term use. However, these structures can hypothetically be completely recycled, and the material can be completely reused. Once the structure is demolished, the material can be crushed, sieved to extract desired granulometry, rehydrated, and re-processed into soft bricks. In other additive manufacturing processes for cementitious materials such as concrete, chemical additives have been shown to be detrimental to both embodied GHG and recyclability (Flatt and Wangler 2022). A critical distinction to other earth-based additive manufacturing processes is that no chemical stabilisers such as lime or cement were used.

The digital design and additive manufacturing process enables the construction of highly efficient, thin, and complex structures without custom formwork, which allows the structures to be built with minimal waste produced. Reusable scaffolding and tension elements were used in some cases to stabilise the structure during construction. Besides the plastic sheets reused to maintain the malleability of the soft bricks during storage and transport, the presented project did not produce any significant waste.

The Clay Rotunda measures almost 11 m in diameter and reaches a height of 5 m with a (median) width of only 15 cm of earth. Rammed earth walls have a typical minimum thickness of 20 cm, so this is a material saving of approximately 25%. The single-layer, load-bearing, and free-standing wall is unique in its complex and structurally stiffened, undulating, and doubly curved geometry. This structure demonstrates how the soft-brick robotic pressing process can build highly efficient structures at the architectural scale that are fully recyclable. It shows that by combining digital design and fabrication methods with traditional earthen building methods, new and radically sustainable construction methods can be developed. In addition, it shows that highly efficient structures can be built from natural, nearly unprocessed, and circular materials systems.

Despite its success, several adaptations should be considered for future constructions of this type. Material shrinkage was a significant issue that resulted in high tolerances in addition to cracks that had to be filled in manually. This issue can for instance be improved by a further reduction of the water percentage or by introducing natural (mineral) additives or fibres to the mix. Further steps could be taken to source the material even more locally. In a different setup, excavation material, typically unused during construction processes, could be sieved, mixed, extruded, and used on site. By processing the material directly, the redundant transportation steps to and from processing facilities could also be minimised or excluded to lower the embodied energy and GHG emissions. For a viable integration of this additive manufacturing process in the building industry, the construction speed and level of automation should be dramatically increased; the Clay Rotunda had an average cycle time of 25 s per 1.5-kg brick, approximately 0.1 m^3 per hour, not accounting for initial material processing, other manual tasks causing machine downtime, or the robotic platform relocalisation time of 1 h.

Currently in development as a next research step is an alternative additive manufacturing process based on high-velocity discrete deposition, or “impact printing,” which was first explored on a prototypical scale (Ming et al. 2022). The process is being developed for implementation on HEAP to realise full-scale earth-based structures in situ. The project explores the added values of integrated material processing and rheological control, and it has the goal to streamline the integration of scan data for automatic adjustment to the as-built conditions.

9.5 Discussion

The presented projects demonstrate that in situ robotic processes have reached technological maturity and that they can offer significant benefits for a circular building industry, but several hurdles must still be solved before these building methods are embraced in the construction sector. Regarding engineering validation: materials that are as-found or natural are highly heterogeneous and thus pose problems to verification or calculation methods that rely on standardised or isotropic properties. Moreover, adaptive design workflows based on available materials result in structures that cannot fully be pre-designed and pre-calculated. These construction techniques require new methods of analysis and design workflows which compensate for uncertainty and tolerances and consider a high number of unknowns. Here, data-driven analysis methods and in situ non-destructive testing suggest high potential and relevance for verifying the structural performance of both components and structures. Non-standard materials with emergent geometric boundary conditions from adaptive robotic processes also pose challenges for detailing and interfacing with other standardised building systems. Downstream and subsequent construction tasks would need to be adjusted to the resulting geometry only emerging at the end of construction. Thus, truly adaptive robotic building methods are not compatible with fragmented and compartmentalised production chains where there is a lack of transfer of digital information between multiple actors and stakeholders. All three example projects exhibited long-term issues with durability, requiring both monitoring overtime for quality assurance and structural performance, while yearly maintenance was also required. Thus, industry adoption is inextricably tied to other developments such as structural health monitoring.

In summary, on-site robotic construction can be deployed towards novel methods of circular construction. The key circular strategies employed include the utilisation of highly natural and local material; minimisation of site work, peripheral equipment, and formwork; and robotic assembly for reversibility. These strategies primarily align with slowing the consumption of resources. In addition to mobile robotic platforms, the main enabling technologies include sensor-based methods for geometry acquisition of material stock and as-built global conditions, suggesting that there could be strong overlaps with other technological developments, including scan-to-BIM workflows and material passports. Lean and adaptive computational design-to-fabrication workflows are also essential to enable just-in-time adjustments and adaptive planning due to material, construction, and on-site variability.

9.6 Key Takeaways

- In situ robotic construction is a type of construction where robots move directly on the construction site and build structures in their final position.
- The key circular strategies implemented in the presented robotic construction methods include (i) utilising locally sourced or natural material; (ii) minimising site work, peripheral equipment, and formwork; and (iii) implementing reversible processes.
- LiDAR scanning and other sensor-based methods can be used for geometry acquisition of material stock and as-built global conditions.
- Lean and adaptive design-to-fabrication workflows can also enable just-in-time adjustments and adaptive planning due to material, construction, and on-site variability.
- Several barriers prevent robotic methods from being embraced in the building sector, including engineering validation, integration, detailing, and safety.

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References

Aejmelaeus-Lindström P, Willmann J, Tibbits S et al (2016) Jammed architectural structures: towards large-scale reversible construction. Granul Matter 18:1–12

Aejmelaeus-Lindström P, Mirjan A, Gramazio F et al (2017) Granular jamming of loadbearing and reversible structures: rock print and rock wall. Archit Des 87:82–87

Aejmelaeus-Lindström P, Rusenova G, Mirjan A et al (2020) Rock print pavilion: robotically fabricating architecture from rock and string. Construction Robotics 4:97–113

Alvarez M, Wagner H, Groenewolt A, et al (2019) The BUGA Wood Pavilion: integrative interdisciplinary advancements of digital timber architecture. In: 2019 39th ACADIA conference, ubiquity and autonomy. Austin, Texas, pp 1–14

Apolinarska AA (2018) Complex timber structures from simple elements: computational design of novel bar structures for robotic fabrication and assembly. PhD Thesis, ETH Zurich

Bock T (2007) Construction robotics. Auton Robot 22:201–209

Bock T, Linner T (2016a) Site automation. Cambridge University Press

Bock T, Linner T (2016b) Construction robots: elementary technologies and single-task construction robots, 1st edn. Cambridge University Press

Bodea S, Zechmeister C, Dambrosio N et al (2021) Robotic coreless filament winding for hyperboloid tubular composite components in construction. Autom Constr 126:103649

Bodea S, Mindermann P, Gresser GT, Menges A (2022) Additive manufacturing of large coreless filament wound composite elements for building construction. 3D Print Addit Manuf 9:145–160

Bonswetch T, Kobel D, Gramazio F, Kohler M (2006) The informed wall: applying additive digital fabrication techniques on architecture. In: Synthetic landscapes proceedings of the 25th annual conference of the association for computer-aided design in architecture, pp 489–495

Brosque C, Skeie G, Orn J, et al (2020) Comparison of construction robots and traditional methods for drilling, drywall, and layout tasks. In: 2020 international congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA). IEEE, Ankara, Turkey, pp 1–14

Brosque C, Skeie G, Fischer M (2021) Comparative analysis of manual and robotic concrete drilling for installation hangers. Constr Eng Manag 147:05021001

Burger J, Lloret-Fritschi E, Scotto F et al (2020) Eggshell: ultra-thin three-dimensional printed formwork for concrete structures. 3D Printing and Additive Manufacturing 7:48–59. https://doi.org/10.1089/3dp.2019.0197

Dörfler K, Sandy T, Giftthaler M et al (2016) Mobile robotic brickwork. In Reinhardt D, Saunders R, Burry J (eds) Robotic fabrication in architecture, art and design 2016. Springer International Publishing, Cham, pp 204–217

Dörfler K, Hack N, Sandy T et al (2019) Mobile robotic fabrication beyond factory conditions: case study Mesh Mould wall of the DFAB HOUSE. Constr Robot 3:53–67

Dörstelmann M (n.d.) Unique Filament Structures | Germany | FibR GmbH. In: fibr-current. https://www.fibr.tech. Accessed 20 Apr 2023

Empa (2017) Empa – Concrete & Asphalt – Completed Project: ASTRA 2017/005 Robotic reinforcement concrete. https://www.empa.ch/web/s308/astra-2017/005-robotic-reinforcement-concrete. Accessed 3 Feb 2023

Ercan Jenny S, Lloret-Fritschi E, Gramazio F, Kohler M (2020) Crafting plaster through continuous mobile robotic fabrication onsite. Constr Robot 4:261–271. https://doi.org/10.1007/s41693-020-00043-8

Farcas V, Ilies N, Cot R (2015) Co2 and energy footprint of different retaining walls solutions. Masonry Retaining Wall VS. cantilever Retaining Wall. Environmental Engineering & Management Journal (EEMJ) 14

FBR. Hadrian X® (2023). https://www.fbr.com.au/view/hadrian-x. Accessed 21 Apr 2023

Feringa J (2014) Entrepreneurship in architectural robotics: the simultaneity of craft, economics and design. Arch Des 84:60–65

FibR (n.d.). https://www.fibr.tech. Accessed 20 Apr 2023

Flatt RJ, Wangler T (2022) On sustainability and digital fabrication with concrete. Cem Concr Res 158:106837

Giftthaler M, Sandy T, Dörfler K et al (2017) Mobile robotic fabrication at 1: 1 scale: the in situ fabricator: system, experiences and current developments. Construction Robotics 1:3–14

Gramazio F, Kohler M (2014) Made by robots: challenging architecture at a larger scale. Wiley

Gramazio F, Kohler M, Willmann J (2014) The robotic touch: how robots change architecture: Gramazio & Kohler Research ETH Zurich 2005–2013. Park Books

Guerra F, Kast B (2015) Bauabfälle in der Schweiz-Hochbau Studie 2015. Bundesam t für Umwelt BAFU, Zürich

Hack N, Lauer WV (2014) Mesh-mould: robotically fabricated spatial meshes as reinforced concrete formwork. Archit Design 84:44–53. https://doi.org/10.1002/ad.1753

Hack N, Kloft H (2020) Shotcrete 3D printing technology for the fabrication of slender fully reinforced freeform concrete elements with high surface quality: a real-scale demonstrator. In: Second RILEM international conference on concrete and digital fabrication: digital concrete 2020. Springer, pp 1128–1137

Hack N, Bahar M, Hühne C et al (2021) Development of a robot-based multi-directional dynamic fiber winding process for additive manufacturing using shotcrete 3D printing. Fibers 9:39

Helm V, Ercan S, Gramazio F, Kohler M (2012) Mobile robotic fabrication on construction sites: DimRob. In: 2012 IEEE/RSJ international conference on intelligent robots and systems. IEEE, pp 4335–4341

Helm V, Willmann J, Gramazio F, Kohler M (2014) In-situ robotic fabrication: advanced digital manufacturing beyond the laboratory. In: Röhrbein F, Veiga G, Natale C (eds) Gearing up and accelerating cross-fertilization between academic and industrial robotics research in Europe. Springer International Publishing, Cham, pp 63–83

Hurkxkens I, Mirjan A, Gramazio F et al (2019) Robotic landscapes: designing formation processes for large scale autonomous earth moving. In: Design Modelling Symposium. Springer, Berlin, pp 69–81

Intelligent City (2023). https://intelligent-city.com/. Accessed 20 Apr 2023

Iturralde K, Feucht M, Illner D et al (2022) Cable-driven parallel robot for curtain wall module installation. Autom Constr 138:104235. https://doi.org/10.1016/j.autcon.2022.104235

Johns RL, Wermelinger M, Mascaro R et al (2020) Autonomous dry stone: on-site planning and assembly of stone walls with a robotic excavator. Constr Robot 4:127–140. https://doi.org/10.1007/s41693-020-00037-6

Jud D, Hottiger G, Leemann P, Hutter M (2017) Planning and control for autonomous excavation. IEEE Robot Autom Lett 2:2151–2158. https://doi.org/10.1109/LRA.2017.2721551

Jud D, Hurkxkens I, Girot C, Hutter M (2021a) Robotic embankment. Construction. Robotics 5: 101–113

Jud D, Kerscher S, Wermelinger M et al (2021b) HEAP - the autonomous walking excavator. Autom Constr 129:103783. https://doi.org/10.1016/j.autcon.2021.103783

Keller Unternehmungen (2023). https://robmade.com. Accessed 20 Apr 2023

Leung PY, Apolinarska AA, Tanadini D, et al (2021) Automatic assembly of jointed timber structure using distributed robotic clamps. In: 'PROJECTIONS'–Proceedings of the 26th international conference of the association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2021), pp 583–592

Li J-M, Knippers J (2015) Segmental timber plate shell for the Landesgartenschau exhibition hall in Schwäbisch Gmünd – the application of finger joints in plate structures. Int J Space Struct 30: 123–139

Mascaro R, Wermelinger M, Hutter M, Chli M (2021) Towards automating construction tasks: large-scale object mapping, segmentation, and manipulation. Journal of Field Robotics 38: 684–699

Melenbrink N, Werfel J, Menges A (2020) On-site autonomous construction robots: towards unsupervised building. Autom Constr 119:103312. https://doi.org/10.1016/j.autcon.2020.103312

Ming C, Mirjan A, Medina Ibanez J et al (2022) Impact printing. 3D Printing and Additive Manufacturing 9:203–211

Mirjan A, Mata-Falcón J, Rieger C et al (2022) Mesh mould prefabrication. In: Third RILEM international conference on concrete and digital fabrication: digital concrete 2022. Springer, pp 31–36

Petersen KH, Napp N, Stuart-Smith R et al (2019) A review of collective robotic construction. Sci Robot 4:eaau8479. https://doi.org/10.1126/scirobotics.aau8479

Piškorec L, Jenny D, Parascho S et al (2019) The brick labyrinth. In: Willman J, Block P, Hutter M et al (eds) Robotic fabrication in architecture, art and design. Springer, Cham, pp 489–500. https://doi.org/10.1007/978-3-319-92294-2_37

Prado M, Dörstelmann M, Schwinn T, et al (2014) Core-less filament winding: robotically fabricated fiber composite building components. In: McGee W, Ponce de Leon M (eds) Robotic fabrication in architecture, art and design, pp 275–289. https://doi.org/10.1007/978-3-319-04663-1_19

ROB Technologies (2023). https://rob-technologies.com. Accessed 20 Apr 2023

Sandy T, Giftthaler M, Dörfler K et al (2016) Autonomous repositioning and localization of an in situ fabricator. In: 2016 IEEE international conference on robotics and automation (ICRA). IEEE, pp 2852–2858

Scheurer F, Schindler C, Braach M (2005) From design to production: three complex structures materialised in wood

Schwinn T, Menges A (2015) Fabrication agency: Landesgartenschau exhibition hall. Arch Des 85: 92–99. https://doi.org/10.1002/ad.1960

Shen LY, Tam VWY, Tam CM, Drew D (2004) Mapping approach for examining waste management on construction sites. J Constr Eng Manag 130:472–481. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:4(472)

Søndergaard A (2014) Odico formwork robotics. Arch Des 84(3):66–67. https://doi.org/10.1002/ad.1756

Søndergaard A, Feringa J, Nørbjerg T et al (2016) Robotic hot-blade cutting: an industrial approach to cost-effective production of double curved concrete structures. In: Reinhardt D, Saunders R, Burry J (eds) Robotic fabrication in architecture, art and design. Springer, Cham, pp 150–164. https://doi.org/10.1007/978-3-319-26378-6

Thoma A, Adel A, Helmreich M et al (2018) Robotic fabrication of bespoke timber frame modules. In: Willmann J, Block P, Hutter M et al (eds) Robotic fabrication in architecture, art and design: foreword by Sigrid Brell-Çokcan and Johannes Braumann, Association for Robots in architecture. Springer, Cham, pp 447–458

Vasey L, Baharlou E, Dörstelmann M et al (2015) Behavioral design and adaptive robotic fabrication of a fiber composite compression shell with pneumatic formwork. In: Computational ecologies: design in the anthropocene, Proceedings of the 35th annual conference of the Association for Computer Aided Design in Architecture (ACADIA), University of Cincinnati, Cincinnati, pp 297–309

Vasey L, Felbrich B, Prado M et al (2020) Physically distributed multi-robot coordination and collaboration in construction: a case study in long span coreless filament winding for fiber composites. Constr Robot 4:3–18

Wangler T, Roussel N, Bos FP et al (2019) Digital concrete: a review. Cem Concr Res 123:105780. https://doi.org/10.1016/j.cemconres.2019.105780

Wagner HJ, Alvarez M, Groenewolt A, Menges A (2020a) Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA wood pavilion. Constr Robot 4:187–204

Wagner HJ, Alvarez M, Kyjanek O et al (2020b) Flexible and transportable robotic timber construction platform: TIM. Autom Constr 120:103400. https://doi.org/10.1016/j.autcon.2020.103400

Willmann J, Knauss M, Bonwetsch T et al (2016) Robotic timber construction: expanding additive fabrication to new dimensions. Autom Constr 61:16–23

Wu P, Wang J, Wang X (2016) A critical review of the use of 3-D printing in the construction industry. Autom Constr 68:21–31. https://doi.org/10.1016/j.autcon.2016.04.005

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