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Advancing construction in existing contexts: Prospects and barriers of 3d printing with mobile robots for building maintenance and repair

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ABSTRACT

Mobile robots for 3D printing applications are ready to transition from factory floors to building sites. Their remarkable flexibility and adaptability support a variety of deposition-based 3D printing technologies that utilise materials ranging from concrete and earth for extrusion, spraying, or shotcreting to metals for processes like Wire Arc Additive Manufacturing. Not confined to new constructions alone, their mobility enables utilisation in corrective building maintenance, restoration, revitalisation, and repair. Their ability to cooperate with one another allows for deployment in multi-robot settings, offering scalability in speed by their number. Despite their promising potential, mobile 3D printing robots also encounter numerous technological challenges. These include ensuring the mechanical properties of printed structures meet required building codes, designing robust mechanical systems for large-scale construction projects, and integrating these systems seamlessly with existing architectural planning tools. Moreover, enhancing the precision and robustness of these robots through advanced sensing and control technologies is critical for their effective application in building manufacturing. With this paper, we detail selected current research trajectories and give insights into current challenges, open questions, and key prospects associated with mobile 3D printing robots for on-site construction within existing environments. To enrich the discussion, insights into potential architectural application scenarios for revitalising, repairing, and strengthening building structures are provided. The complex, interdisciplinary nature of these challenges underscores the need for a collaborative approach in advancing the field of mobile 3D printing technology.

1. Introduction

The practice of maintaining, renovating, retrofitting, repairing, and strengthening existing buildings, collectively referred to as "construction in existing contexts," gains increasing importance in our pursuit of sustainability and carbon neutrality [1]. These construction methods, which aim to preserve or enhance value, align closely with the objectives of the European Green Deal and the Renovation Wave Strategy. These strategies advocate for substantial reductions in energy consumption and resource waste [2]. Additionally, the Recovery and Resilience Facility plan encourages using circular economy principles in new and renovated buildings, while also promoting digitalisation and climate-proofing of the building stock [3,4]. Through accelerated renovation efforts across the EU, new energy performance standards for buildings should be met quickly [5]. The significance of long-term care, maintenance, and improvement for the built environment, working with existing building stock, is therefore also gaining importance in the contemporary discourse within the Architecture, Engineering, and Construction (AEC) domain [6]. Consequently, there is significant potential for expanding the use of Robotic Fabrication (RF) and Additive Manufacturing (AM), respectively, 3D Printing (3DP), in existing contexts, which currently lags behind their applications in new construction

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projects [7].

Automated processes related to building and infrastructure maintenance and repair involve direct engagement with the existing structures, essentially requiring robotic systems and equipment that is deployable and mobile. Mobile robots possess the capability to access and operate within enclosed spaces with great flexibility and near-unlimited workspace, making them valuable future tools for in situ building repair. Inspirations for building repair can be drawn from domains like shipbuilding and maintenance, which reflect the construction sector's need for custom solutions using robotic instruments that offer precision, efficacy, dependability, and performance equal to or surpassing human capabilities [8]. Existing examples from ship maintenance already demonstrate the potential of robots that are supervised and teleoperated by skilled human workers, capable of performing tasks both above and underwater from a safe, topside location [9]. Such approaches could be particularly crucial for maintaining building structures that are difficult to access by humans, such as offshore installations and underwater pipelines, due to their remote locations and harsh operating conditions [10].

Equipped with diverse tools such as cutters, millers, sand blasters, water jetters, cleaners, and drills, mobile robot platforms could execute complex repair tasks with high precision and efficiency. However, their potential could be further enhanced by integrating them with novel Additive Manufacturing (AM) and 3D Printing (3DP) technologies [11,12]. Mobile 3DP robots could additively manufacture replacement parts on-site, repair cracks, or create customised reinforcements. Such application scenarios motivate the development of novel platforms, methods, and tools that exhibit sufficient manoeuvrability, context-awareness, and manipulation capabilities, enabling the robotic manufacturing, corrective maintenance, and repair of structures tailored to specific sites and tasks.

However, achieving successful robot deployment for transforming existing structures necessitates overcoming significant technological challenges. It requires comprehensive spatial awareness—a geometrically precise and semantically rich internal representation of the robot's operational surroundings [13]. While robot mapping is well-explored for navigation, manipulating the physical space, particularly the precise deposition of material within encountered environments, demands expanding existing methods. Object recognition, capturing spatial relationships metrically (e.g., proximity, above, and below), qualitative and quantitative estimations of built structures, and identifying and reusing available materials are all areas of extensive ongoing research in this domain [6]. Moreover, carrying out automated manufacturing tasks within existing contexts also necessitates a thorough evaluation of the building's condition using expanded robot sensing capabilities. It further involves additional processes beyond 3D material deposition, such as removing degraded material, cleaning, and preparing surfaces, and applying new material and components. The ability of mobile robots to exchange data and cooperatively perform diverse tasks and the multi-functionality of systems are also crucial for establishing functionality and productivity in this domain [14]. Finally, the successful application also relies on employing structurally sound 3D printing techniques that can effectively handle respective repair and reinforcement tasks in building construction.

Within this context, this paper introduces mobile robotic 3DP systems designed for on-site construction, shedding light on the substantial challenges and promising future opportunities for in situ maintenance, repair, and strengthening using various material-process combinations. This paper particularly concentrates on assessing methods and approaches related to continuous material-deposition-based 3DP techniques defined for AM using mobile robots while largely excluding discrete procedures such as bricklaying, timber assembly processes, drilling, or fibre winding. The subsequent sections are thus structured as follows: Section 2 offers an overview of current methods and research trends regarding the application of mobile robotics for different material-deposition-based in situ 3DP processes and various material-process combinations. Section 3 outlines existing technological challenges and addresses open questions. Potential architectural application scenarios are presented in Section 4, concluding the paper with a forward-looking perspective and motivation for future research.

2. Mobile 3D printing: material and process combinations

Mobile extrusion 3D printing

As part of the broader advancement of digital fabrication technologies in AEC, large-scale extrusion-based or spray-based AM with cement-based mortars, commonly referred to as 3D Concrete Printing (3DCP), has emerged as a key response to the global demand for modernised manufacturing processes in construction [11]. Nevertheless, obstacles to implementing it on building sites arise from the fact that the machines are limited in their construction capabilities due to their size and transportability. While 3DCP in construction is typically deployed by stationary and monolithic systems such as gantries, crane or cable instalments [15], perhaps as early as 1997 it was already conceived that a "large structure could be built by an army of (robotic) ants, one grain of sand at a time" [16]. However, only recently, advances in mobile robotics allowed researchers to reconsider conventional machine-centric approaches and, instead, frame the structure being built not as an object to be manufactured but as an environment that robots may shape and inhabit simultaneously.

As such, Mobile 3D Concrete Printing (M3DCP) was developed in response to the shortcomings of static, tool-centric approaches [17–19]. M3DCP considers mobile-manipulator robots, capable of terrain navigation and equipped with dexterous manipulators, executing larger-than-self material extrusion tasks in place or in situ, and potentially in a continuous, i.e., in-motion, fashion. Compared to their static counterparts, ground-based M3DCP systems, as shown in [17–19] and depicted in Fig. 1, have drastically impactful advantages. Inherent mobility means M3DCP systems typically do not have significant installation or relocation costs, as is the case with gantries or cranes. In fact, M3DCP systems directly tackle build volume constraints by allowing printing over virtually infinite planes. Furthermore, their smaller scale and high degree-of-freedom on-board manipulators allow for greater local complexity in printed geometries compared to conventional three Degrees-of-Freedom (DoF) systems. However, it is important to note that relocating M3DCP systems to new locations may require time and resources for calibration to ensure precision, which should be considered when assessing overall deployment efficiency. Lastly, expanding M3DCP to multiple robots carrying out printing tasks in parallel shows capacity for great scalability in deposition throughput [20,21].

Lately, research has also demonstrated the feasibility of utilising aerial robots to perform 3D printing in mid-air with the objective of enabling unrestricted manufacturing for the construction and repair of building structures utilising novel AM technology (Fig. 2). In this research, referred to as Aerial Additive Building Manufacturing (AABM), drones carry a naturally limited amount of material to be deposited with virtually no restriction on positions [22].

Recently, a large consortium of UK-based researchers has demonstrated AABM using drones that construct small-scale cementitious structures as well as towers over two meters tall using expanding foam [22]. Such systems face multiple challenges; that is, the accuracy of the built structure is determined by both localisation accuracy, as well as control accuracy. The latter will, however, inadvertently be limited due to natural disturbances and limited control authority. Therefore, the system above was extended with a fast-reacting delta arm to compensate for deviations and keep the extrusion tip within less than 5 mm of the position reference – assuming de-facto perfect localisation, e.g., in the form of available motion tracking as was the case in those experiments using April tag fiducial markers. A second challenge that needed to be addressed was an accumulation of errors in the built structure,

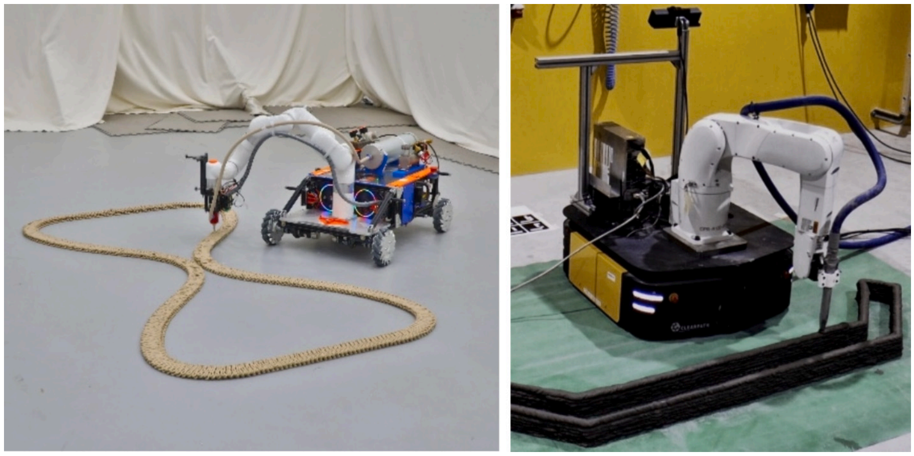

Fig. 1. Examples of mobile manipulators (left: Sustarevas et al. 2022 [19], right: Tiryaki et al. 2019 [17]) carrying out mobile extrusion 3DP tasks in full motion, that is, in printing-while-driving fashion.

Fig. 2. Aerial Additive Building Manufacturing, published by Zhang et al. in 2022 [22], has showcased the potential of using drones for M3DCP tasks for building construction and repair.

Fig. 3. Dielemans et al. 2024 [23] show the exemplary in situ 3DP of a replacement component within a brick assembly using surrogate material, employing a clay extrusion end-effector attached to the last link of a 6-degree-of-freedom (6DOF) robotic manipulator on a mobile robot platform.

particularly pronounced with expanding foam: to deposit at the right place just above the built structure and to keep the built structure from drifting away from its planned shape, in-the-loop mapping proved essential. In this case, this was carried out with a separate scan-drone that mapped the structure after every layer printed by a build-drone. While these developments are promising, the scalability of AABM systems presents further challenges, particularly concerning the weight limits of the drones and the materials used. The most commonly used material, concrete, is notably heavy, and there is a growing trend towards more advanced and consequently heavier print heads in two-component (2 K) systems, which further include sensors, reinforcement integration, and other components. This raises the question of whether there is a potential limit to scaling up these systems, as increasing the payload could impact the drones' manoeuvrability and energy efficiency. For real-world deployment, these issues must be addressed, along with the need for drones to localise in potentially unknown, dynamically evolving environments without any infrastructure and to autonomously navigate safely, avoiding other robots, drones, and people.

Still, within this context, mobile deposition-based 3DCP processes hold significant potential not only for new construction projects but also for the repair and strengthening of existing building structures. In the revAMp research, Dielemans et al. [23] investigated the potential of extrusion-based M3DCP processes for in-place 3D printing, aimed at utilising M3DCP for the first time for the on-site repair of building components (Fig. 3).

Dielemans' research proposed an integrated workflow combining 3D data capture, design generation, and in situ fabrication. The mobile robot was equipped with a stereo depth camera and a 2D laser profile sensor to achieve this. This combination allowed the robot to capture detailed 3D data of a damaged component, in this case, a damaged brick wall, enabling the robot to define the exact geometry and volume of printed material needed for repair. The entire workflow was validated through experimental trials, where clay extrusion was used as a surrogate material for concrete or earth mortar. As depicted in Fig. 4, this integrated workflow enabled in-place 3D printing for missing building components without prior knowledge of the existing geometry. A mobile robot was positioned close to the damaged area where it captured the area using a depth camera and a 2D laser profile sensor, generating detailed point clouds. These clouds were processed into a reconstructed surface, allowing the system to automatically detect the missing volume by splitting a user-made placeholder with the reconstructed surface, effectively isolating the region necessary for repair. Finally, the operator designed and generated a repair printing path that was compatible with the 3D printing system used.

The scope of the proposed approach is currently limited by several factors such as localisation and navigation capabilities, printing stability and mechanical properties of the surrogate material, or sensor field of view. However, the method holds promise for versatile, on-demand building repairs if combined with fully structural 3D printing materials and enhanced robotic planning and control capabilities.

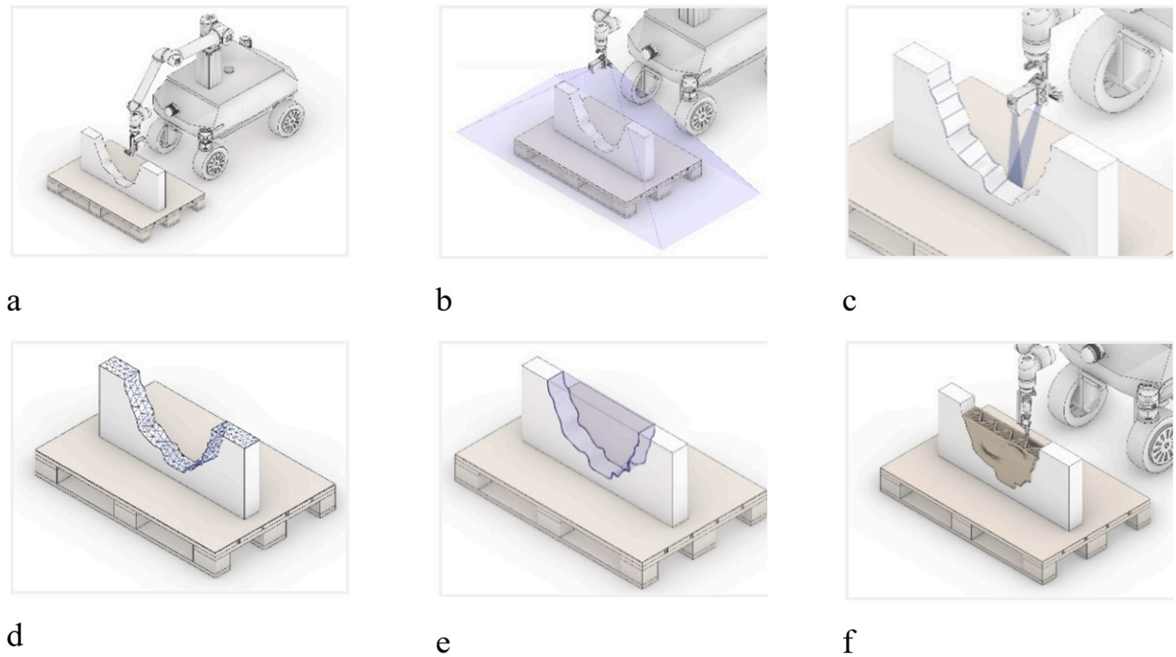

Fig. 4. Proposed workflow and stepwise method for in situ repair of an incomplete wall geometry: a) mobile robot positioning & object framing, b) initial 3D point cloud capture, c) refined 3D point cloud capture, d) reconstructed surface, e) repair design, and f) repair design & print path generation, by Dielemans et al. 2024 [23].

Mobile spray-based 3D printing

Like material extrusion, material spraying involves depositing material in thin layers. However, in material spraying, this process occurs at a greater distance, and it incorporates the use of air in the nozzle. The added distance between the nozzle and the substrate provides flexibility in the application, enabling the deposition of material in intricate patterns or hard-to-reach areas. Since the 1980s, studies sought to demonstrate the feasibility of robotically assisted plaster or concrete spraying as a time- and cost-efficient approach to the production of standardised, flat, and smooth surfaces, with the use of robotic units with multiple degrees of freedom (DoF), equipped with tools that enable plaster to be, i.e., sprayed, or levelled [24–26]. In the 1990s, initial experiments were carried out on a construction site for the autonomous plastering of walls and ceilings [27,28]. Similarly, current research on robotic plasterwork [29–31] aims to demonstrate the feasibility of a time and cost-efficient production method for standardised, flat surfaces, imitating the steps of a simplified wall plastering process. More recently, robotic spraying techniques have been employed in the area of additive manufacturing, where precise layering is used for creating complex three-dimensional structures in processes such as Shotcrete 3D Printing (SC3DP) [32,33] or robotic concrete [34] and robotic plaster spraying [35]. These methods are employed for shaping free-form designs on substrate surfaces or directly in free 3D space.

In Shotcrete 3D Printing (SC3DP) [33], the manufacturing of reinforced freeform concrete elements with high surface qualities is investigated, where strands of concrete are sprayed with pressure in successive layers from bottom to top to create a three-dimensional structure, with the option of embedding steel reinforcement sprayed around preinstalled rebar. Another robotic concrete spraying process referred to as Robotic AeroCrete [34] investigates a novel robotic spraying technology, where concrete is sprayed directly onto dense reinforcement meshes for the production of slender, bespoke concrete elements. A similar example can be found in SC3DP research by NTU [36], which investigates a spray-based 3D concrete printing process for functional coatings in the form of overhanging applications on facades and ceiling decorations. However, current examples mostly operate with static setups in limited work envelopes.

In situ Robotic Plaster Spraying (RPS) using a mobile ground-based robot, as introduced by Ercan Jenny et al. [35,37], introduces mobile thin-layer spray-based printing on building elements, merging constant material-feed with whole-body motion planning and control in a workflow that synchronises the robotic platform, the construction environment, and the spraying process. The setup combines a mobile robotic arm with a sprayable material like cementitious plaster unlocking new crafting techniques to produce building elements with three-dimensional bespoke as well as flat standard surfaces. This combination is used to explore both bespoke and standard plasterwork as volumetric formations on a building structure through an innovative additive manufacturing process. Using sprayable materials such as cementitious, lime, gypsum, or clay plaster in such a combination opens new architectural potentials, such as improving the visual or acoustic qualities of building structures with geometric complexity. Rather than considering plasterwork as a standardised application, RPS introduces new degrees of design freedom for the craft of plastering through its digitalisation. Instead of spraying centimetre-thick layers, RPS introduces a thin layer with a high-resolution, spray-based, vertical printing technique that resists gravity. The applicability and scalability of this spray-based printing technique have been explored through empirical research with architectural prototypes. These architectural prototypes have been produced by spraying multiple millimetre-thin layers of plaster onto a building structure, enabling the incremental build-up of 3D formations without the use of additional smoothing or profiling tools, formwork, or support structures (Fig. 5).

RPS uses the parameters of the fabrication process—such as distance, angle, and velocity of spraying—to control the material formation. The malleability of the wet material is combined with the digitally controlled, pneumatic spraying, which acts as a dynamic formwork for the resulting surface geometry or pattern. The mobile robotic process thus can be extended to explore different techniques used in manual plastering, such as rubbing, combing, or stamping and their effect on the surface geometry and texture, leading to various functions. Thus, the

Fig. 5. Ercan Jenny et al. 2023 [37] introduced Robotic Plaster Spraying (RPS), a mobile, spray-based plaster printing technique.

commonly known roles of plaster can be revisited, which provide i.e. durability, insulation and weather protection to the building structure while seeking the correlation to additional qualities of the material that involve providing visual, acoustic, or light diffusing effects through geometric complexity. For this purpose, a catalogue of different surface geometries and resolutions is currently being developed, and their functional application is investigated. The target is to address the combination of the functional layers of a building structure with their ornamental qualities through the dynamic forming of the wet material directly on the building structure.

Going from ground-based robots to aerial ones, MuDD, an architecture firm, has demonstrated the utilisation of tethered aerial robots for the precise application of a clay-based mixture onto a fabric formwork [38]. The composition of this mixture includes clay, sand, and rice husks, presenting an environmentally conscious approach to lightweight construction development (Fig. 6).

Next to deposition-based 3DP, mobile spray-based 3DP processes can also be readily employed for building repair and strengthening. In the context of mobile spray-based plaster printing, application areas could involve non-structural renovation of exterior surfaces. Mobile shotcreting applications also have the capability to address crucial structural aspects, including strengthening reinforced concrete columns, walls, or bridges within on-site concrete infrastructure constructions. The promising potentials of such applications have previously been shown in [39] using stationary robotic setups in a prefabrication setting. As shown in

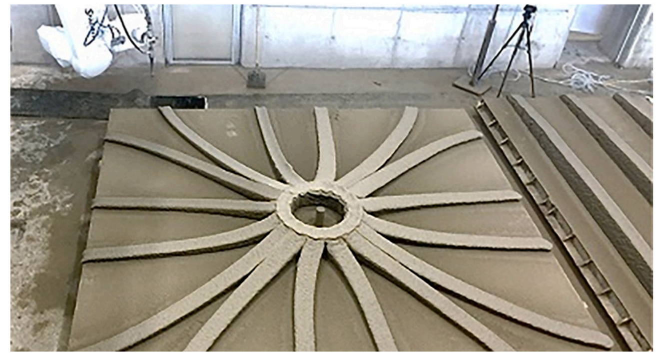

Fig. 7. Kloft et al. 2020 [39] imprinted 12 cm wide SC3DP concrete ribs for structurally enhancing a thin-plated floor slab for a point-supported column consisting of an 8 cm thick concrete slab with dimensions of 4 m × 4 m.

Fig. 7, a hybrid version of SC3DP was applied to imprint concrete ribs as a structural enhancement for floor slabs sprayed around mechanically connected steel reinforcement. In the future, these applications can offer bespoke solutions by facilitating custom connections between pre-existing building elements, thereby serving the purpose of fully structural on-site strengthening.

Mobile wire-and-arc additive manufacturing

Next to 3DP using extrusion and spray-based methods for concrete structures, the use of Wire-and-Arc Additive Manufacturing (WAAM) for the 3DP of steel structures has gained major relevance in construction research. An important characteristic of the WAAM manufacturing process is that the substrate is monolithically connected to the existing steel structure. Hence, in recent years, the use of WAAM for joining and strengthening standardised steel elements has also gained significant interest within the research community, exploring its potential for on-site repair, and strengthening of existing structures.

For example, Kloft et al. [40] have explored the potential of deploying load-bearing stiffeners to standard steel profiles using WAAM (Fig. 8). The study focused on examining the welding of ribs in regions where local loads are introduced, exploring ways to reinforce flexural beams in areas experiencing heightened moment loading. Various approaches for the sequence of applying individual layers were experimented with to achieve these objectives.

Ariza et al. [41] demonstrated the potential of highly customised connection details that are 3D printed directly onto off-the-shelf

Fig. 6. Chaltiel et al. 2020 [38] demonstrated how a 2 m-wide drone with 50 cm legs and 20 min of flight autonomy tethered with a 20 m-long hose enabled the spraying of earthen mortar onto a fabric formwork.

Fig. 8. WAAM stiffeners on IPE200 profiles, introduced by Kloft et al. 2023 [40]

building members during their assembly process (Fig. 9). The use of the robotic WAAM process, combined with object localisation and path-planning strategies, provided precise control over the design of the geometry of the details. This approach facilitated the production of customised welded joints capable of addressing material and construction tolerances. Recently, she also demonstrated a highly adaptive WAAM connection strategy for reusing reclaimed steel elements [42].

However, traditional robotic systems to carry out WAAM processes are characterised by significant dimensions and static positioning, necessitating workpiece transportation to the robot cell. This approach presents inherent limitations for scenarios of on-site repair, where large-scale structures dictate robotic mobility to access the weldment directly. Recent developments in the design and functionality of portable welding robots show potential applicability in large-scale fabrication contexts, such as preliminarily demonstrated by Dharmawan et al. [43] and Chen et al. [88] (Fig. 10). They developed an agile robotic system for general in situ construction work of large-scale structures. The robotic system comprises of a lightweight industrial robot mounted on a specially designed robot platform capable of being quickly integrated into available scaffold structures. The mobile robotic welding system was validated on behalf of a case study with a surrogate welding setup using a drawing pen, related to the automation of the in situ welding of jack-up oil rig structural components.

In the future, a combination of in-place WAAM strategies with mobile robotic systems could allow for novel approaches in the domain of steel infrastructure repair, and corrective and enhancing maintenance of steel constructions.

3. Current challenges

Print path design and planning strategies

To employ 3DP robots safely and efficiently in construction sites, it is necessary to incorporate high-level task planning and detailed simulation of construction robots into the overall construction planning process. Following the execution of high-level task planning, a comprehensive task simulation must be conducted, in which precise robot motions are generated. These simulations must also consider the unique characteristics of the working scene, that is, a continually evolving construction site environment. Mobile robot behaviours in built environments must leverage contextual information sourced both through real-time sensor-based perception and embedded knowledge sourced from the architectural planning environment, i.e., the building model. For example, a robot's navigation proficiency can be activated by providing the coordinates of the printing location as an input argument. With the destination coordinates and a map of the environment, the navigation skill generates a path and guides the robot to the intended location to carry out a printing task. Along the way, the navigation path is continuously updated based on observed obstacles, ensuring adaptability to the dynamic conditions of the environment.

In the case of segmented printing using mobile ground robots—where a mobile robot prints in situ but in a stationary mode on a construction site—this can be carried out by performing navigation and manipulation actions sequentially, as depicted in Fig. 11.

High-level robot task planning for such a task involves identifying all the required actions, including but not limited to navigating to the printing location, taking a detailed scan of the work environment, depositing material, and determining the sequence between the actions, for example, shown in [23]. This limits the planning problem of the actual material extrusion to the 6DoF of the manipulator. While this

Fig. 9. Ariza et al. 2018 [41] developed adaptive in-place detailing methods through WAAM for joining steel members.

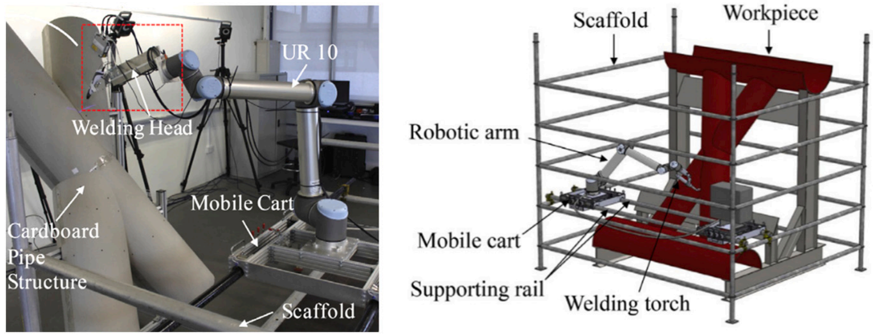

Fig. 10. The robotic system and the lab experimental setup introduced by Dharmawan et al. [43] and Chen et al. [88] consists of a representative dummy weld head equipped with a 2D laser scanner and a 1:1 scale mock-up jackup rig pipe structure.

Fig. 11. In Dielemans et al. 2020 [18], segments (here: segments 19, 20, and 21) of a larger structure are manufactured within the static reach of the mobile robot, allowing for sequential navigation and manipulation. Optimal task segmentation considers the workspace limitations of the respective robot in use.

simplifies the problem, task clustering [44,45] ought to be used for finding optimal base placements to allow for general task definitions.

With the use of multiple cooperative robots, as shown with the Ambots robots in [46], the challenge in task clustering is in scheduling multiple robots to print multiple jobs and to find optimal job assignments and path planning for multiple jobs carried out concurrently, as depicted in Fig. 12.

In the case of continuous printing via mobile ground robots, increased planning and control challenges arise, as navigation and manipulation actions must be carried out simultaneously. As depicted in Fig. 13, Sustarevas et al. [47] show an autonomous path planning approach for mobile material deposition by using a modified version of the Rapidly-exploring Random Tree Star (RRT*) algorithm.

In both cases, segmented and continuous printing, an underexplored problem lies in the interplay between task decomposition, sequencing, and robot navigation. While existing methodologies, shown in [47,48], tackle navigation challenges for prescribed printing tasks, the task construction itself—specifically, delineating the printing trajectories for constructing the desired geometry—remains largely unexplored. Existing literature in robotic 3DP suggests methods such as constraint-based print path design for industrial robots [49,50], or chunk-based slicing for mobile robots [18,51,52]. Challenges remain for continuous mobile printing considering the mobile ground robot's unhindered planar workspace potential contingent upon both traversability and robot reach. The printing trajectories must not only adhere to the structural requirements of the target geometry but also be crafted to ensure that all intermediate states of partially completed geometry maintain navigable pathways with sufficient reach for subsequent printing. Although some preliminary research explored the sequencing aspect of this problem [53], none thus far have bridged the gap entirely between the navigational capacity of robots and the derivation of printing trajectories. Particular challenges in the corrective maintenance and repair of building structures will thus also revolve around the topic of the recording of existing conditions and the ad-hoc 3DP task generation for structural component completion, as shown in rudiments for in-place printing for building component repair [23], or enhancements, as shown in [40].

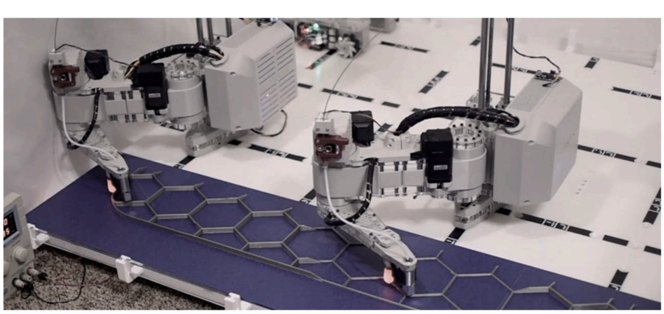

Fig. 12. With the Ambots project, generating viable print schedules with collision-free path planning allows multiple robots to cooperate on a single 3DP job. AMBots Inc. 2020, Video frame from [89]

What mobile 3DP robots need to see

Robots need advanced perception and estimation skills upon which to base their actions for safe navigation and printing operation within often-times chaotic and dynamic construction sites. First, mobile robots need to be able to localise sufficiently accurately within an infrastructure-free environment, i.e., without the availability of GPS or other external localisation systems. Moreover, this localisation must be absolute in the sense that it must align with the coordinates in which the building was planned and is being constructed; and it must stay consistent throughout successive robot deployments over time, as well as across parallel, simultaneous robot deployment. These aspects are quintessential for the overall accuracy of the built structure, as well as for the orchestration of individual robot tasks in a safe manner. Current industrial onboard localisation methods used in commercial platforms often fall short, typically offering positioning accuracies within a margin of approximately +/− 5 cm [54]. In contrast, external tracking systems currently offer superior accuracy, providing highly precise data for

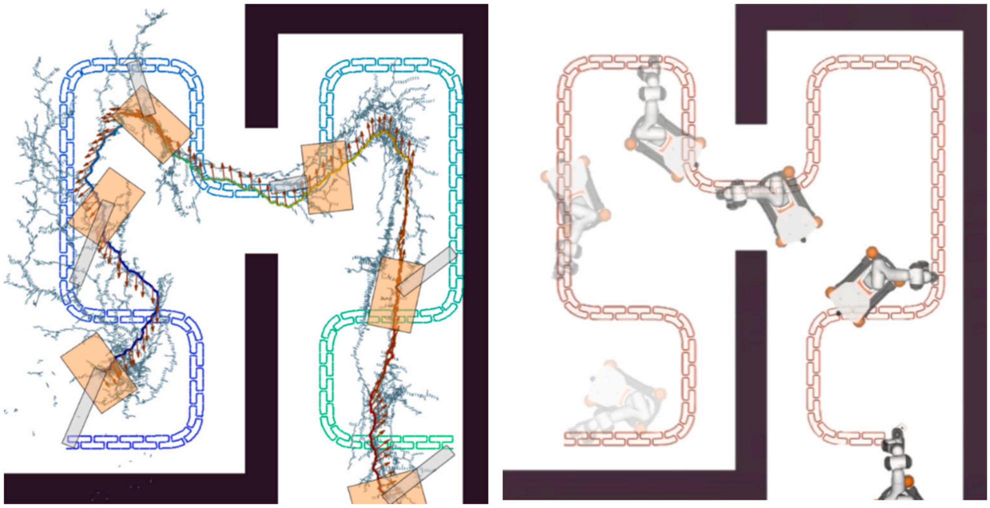

Fig. 13. A path planning illustration. Static Obstacles (Black), Print Task (Blue to Green), b(s) found (Blue to Red), RRT* tree exploration, visible in blue, shown only in 2D, for 3DP in motion, as shown in Sustarevas et al. 2021 [47].

localisation. These challenges highlight the need for advanced localisation techniques to enable enhanced control strategies for mobile 3DP in construction settings [19].

While external localisation will restrict the workspace of mobile platforms, current research partially focuses on relative robot referencing with respect to a surface or object of interest using onboard sensing. As such, localisation approaches often involve some form of multi-sensor fusion, e.g., between exteroceptive sensors such as (depth) cameras, LiDARs, as well as proprioceptive sensing, e.g., IMUs and wheel odometry. Regarding Visual-Inertial state estimation, respective Simultaneous Localisation and Mapping (SLAM) systems have been developed, e.g., ORB-SLAM3 [55] or OKVIS2 [56], where the former includes a multi-session extension, and the latter is also under development to support multi-session and multi-agent localisation. To carry out tasks of structure-building, however, the notion of relative localisation is equally important, i.e. the relative relation between the end effector and the current printing area. This local accuracy is needed to carry out the printing task safely, as well as to take corrective action to reconciliate deviations from the planned structure considering absolute accuracy. Approaches here include dense mapping, such as [57] as used by [22], or, alternatively, estimation of poses of building blocks and elements, possibly including their shapes [58].

Finally, it is absolutely crucial for safe robot deployment to include a level of 3D scene understanding to allow for safe action planning, navigation, as well as collision avoidance and reactive control in general. For planning, a static but dense map that is maintained might be sufficient, but for collision avoidance and possibly co-deployment or even cooperation with human actors, their motions and activities need to be understood. Melenbrink et al. proposed a tailored system classifying the Levels of Autonomy (LoA) from 0 to 5 for construction equipment [59]. A system achieving a LoA of 3 can autonomously transition to a safe state in the event of a fault, a critical feature for 3D printing using mobile systems to prevent unintended material discharge during disruptions. Properly handling such an unexpected disturbance, relatively common due to e.g. people on construction sites, is associated with LoA 4. Therefore, LoA 4 can likely be considered a future minimum requirement for the development of platforms for mobile 3DP. As part of their research, Yeong et al. [60] have compiled a comprehensive review of the sensor systems, currently available to approach higher autonomy levels, and the challenges that apply to the autonomy of mobile platforms on construction sites.

For the purpose of co-deployment with humans, GloPro [61] and BodySLAM++ [62] (Fig. 14) are examples of recognising people and accurately estimating their poses and postures over time from the perspective of a mobile robot in motion.

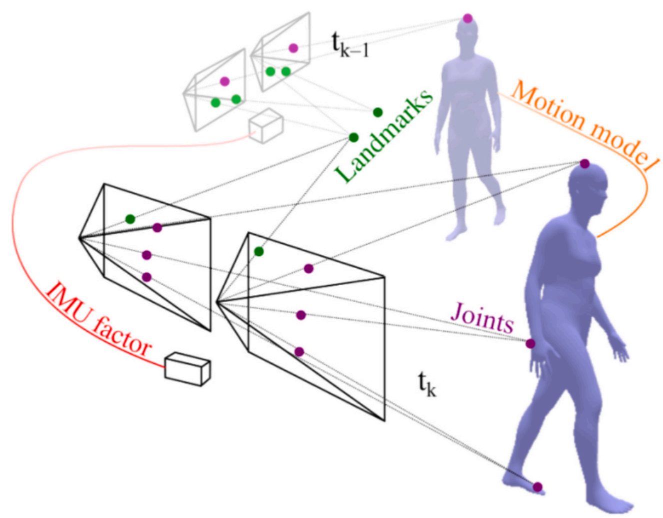

Fig. 14. The BodySLAM++ framework by Henning et al. [62] uses an IMU factor between frames and a human motion model to predict the displacement of the sensor and human, respectively, making it particularly apt to be integrated into mobile construction robots.

Control challenges of mobile 3DP robots

Mobile manipulators, equipped with a mobile base and a robotic arm, are designed to cover large workspaces and are sufficiently lightweight for field deployment of 3D printing (3DP) processes. However, employing mobile robots for in-place 3D printing on construction sites—particularly for continuous printing or “print-while-driving” in existing environments—presents a complex challenge due to the high level of autonomy required. This challenge can be divided into two main areas within control theory. The first is whole-body-motion control, which involves ensuring the precise, collision-free movement of both the mobile platform and the printing nozzle (end effector). The second challenge involves the adjustment of printing parameters to account for and mitigate any external disturbances effectively.

Whole-body motion control

Trajectory accuracy, particularly in whole-body motion, is vital for the success of continuous mobile printing. The quality of the final product is influenced not only by the exact positioning but also by the speed at which the material is deposited. Although current methods employ sequential near-nozzle multi-sensor approaches for continuous trajectory tracking, as described in Section 2.1, these are geared towards stationary settings and unsuitable for dynamic mobile applications. Instead, for continuous mobile printing, contour tracking techniques that utilise feedback from 2D profile data are being explored. These techniques promise to enhance the reliability and efficiency of mobile printing by providing more adaptable and responsive control strategies suitable for changing conditions [54].

In continuous mobile extrusion or spraying processes, the necessary combination of control of a mobile base and an articulated manipulator system requires advanced control strategies. Controlling such systems has multiple challenges such as redundant degrees of freedom, non-holonomic constraints in the drive system of the robot base, and imperfect motor command tracking as well as errors in state estimation. Model predictive control (MPC) has been shown to be an effective strategy for whole-body motion control of mobile manipulators [63]. In [64], instead of preplanning trajectories for all DoFs of the robot, a spraying job is defined as a task-space end-effector path. Tracking the path is the main MPC objective while the redundant null space is used to minimise joint velocities. In contrast to purely reactive control schemes, MPC can generate motion plans for non-holonomic wheeled bases such as skid-steer or differential drive vehicles where instantaneous motion in all directions is impossible. MPC continuously replans whole-body motion and generates motor commands for the mobile manipulators, thus adapting to tracking errors. Replanning prevents motor command tracking errors as well as state estimation errors from accumulating and ensures that the end-effector does not drift away from the desired spraying path.

In the typical context of extrusion-based 3DP, the act of material deposition on the ground substantially alters the robot's environment throughout the course of a printing task. This may lead to non-navigable or unreachable areas rendering some tasks infeasible. Hence, in [47] and [17], [48] specialised combined task-and-path planners were developed and used in combination with MPC—finding and executing feasible robot paths that take deposited material into account. When a mobile manipulator for spraying tasks operates in confined workspaces such as residential building construction sites, it needs a small base footprint to safely manoeuvre on-site and a long arm to reach all walls and ceilings. MPC can also be used to plan safe motion in such scenarios by considering the tip-over stability as a constraint [65]. The authors also show how a robotic base could dynamically change its footprint to fit through narrow passages like doors and enlarge the footprint during operation when stability is critical.

Future advancement will aim towards increased autonomy of mobile printing robots [54]. Therefore, the integration of extended environmental perception is indispensable to allow for a more stable localisation within highly dynamic construction environments as well as to maintain safety for individuals within the workspace [66]. Additionally, varying ground conditions will significantly affect the localisation and printing accuracy when transferring the current state-of-the-art mobile robot motion towards construction sites with dirt, gravel or even soil terrain [67].

Control methods for dynamically changing conditions

In addition to using robot mounted sensors for localisation and perception, especially near-nozzle sensing systems implemented for relative robot localisation, material property assessment and perception of the printed component, play a crucial role in compensating dynamically changing printing conditions. While current approaches already try to minimise the influences of varying material properties, process parameters, temperature and humidity [68], [69], mobile on-site renovation or repair also adds sunlight, wind and possibly even rain to the list of disturbances. Therefore, it is expected that for the successful deployment of mobile robots in concrete-based 3DP, a significantly increasing range of fresh material property monitoring and control will be necessary. On the one hand, this requires specific tests that can quickly and accurately determine the material properties relevant for additive manufacturing [70–72]. On the other hand, these tests must be suitable for integration into the mobile platforms as well as for integration into a digitally controlled closed loop of material property control, such as within a mixing nozzle or during the processing stages.

Aside from pure print strand recognition and material property monitoring, expanded object perception (Fig. 15 left), as well as reinforcement integration (Fig. 15 right), must be considered in the future development of mobile printing systems. While the first requires excessive material application control to ensure printing as planned, the latter is especially inevitable to ensure the connection to existing building substance in the context of renovation and repair. Given that existing construction objects inherently have positioning tolerances, future research must focus on enhancing current control algorithms with advanced object detection and recognition capabilities to maintain a seamless and robust printing process in attachment or expansion to existing structures [68].

Material delivery

In the domain of mobile ground robots engaged in 3DP tasks, the critical components comprise power, data, and material supply. While power and data management present challenges that are generally manageable, material delivery poses challenges that require careful strategic considerations. For example, in relation to concrete or earth-based 3DP, the procedural stages encompass the mixing of material, its deposition in an intermediate storage, the pumping of the material, and material application or deposition. The spatial disposition of these processes plays a significant influence on the technical design and mobility attributes of mobile 3DP robots. Notably, the selection between on-board (untethered) or off-board (tethered) material storage configurations profoundly influences the design and operational dynamics of the robot.

Illustrating the onboard material storage approach, fully onboard systems such as those shown in [18], [19], [21], [52] often result in larger robot sizes, increased payload capacity requirements, and the incorporation of heavy, power-intensive components such as compressors or pumps for material conveyance. The decision of where to allocate material storage—either on the robot body [19], [21] or on the manipulator [18] — has significant implications for the overall design, influencing both material delivery distances and power consumption. Storing material on the robot body leverages its robust carrying capacity but requires material to be delivered over longer distances, necessitating larger pumps. Conversely, placing material storage on the manipulator brings the storage closer to the extruder, reducing delivery distances but substantially increasing the payload demands on the manipulator, thereby impacting power consumption.

In contrast, tethered systems opt for the off-board storage of materials. While this choice provides the advantage of static material pumping systems, the protracted distance that the material must traverse from the pump to the extrusion nozzle introduces complexities in the realms of path and task planning. In shared workspaces featuring multiple robots, the inclusion of tethers introduces an additional layer of complexity, necessitating the formulation of coordinated plans [73].

Furthermore, the material properties must be carefully considered in relation to the specific 3DP technique being employed. For extrusion-based 3DP, such as FDM or concrete 3DP, the material needs to be liquid enough, i.e., have sufficient pumpability, to be transported through hoses or tubes yet strong and stiff enough to ensure stable build-up upon deposition [74]. The rheological requirements for printable concrete, in particular, are critical. These include yield stress, viscosity, elastic modulus, critical strain, and structuration rate, all of which play crucial roles at various stages of the time-critical 3DP process and its

Fig. 15. Building installation integration during SC3DP at ITE TU BS with implemented process control height compensation (left). AI-based object detection and recognition using Intel RealSense data to ensure correct rebar positioning (right). Source: L. Lachmayer,

related sequencing and coordination [75]. Additionally, controlling the viscosity and structuration rate is essential to maintain the geometrical dimensions of each layer and the overall object, minimising risks such as buckling stability issues or surface cracking [76]. This contrasts with other techniques like spraying and plastering methods, where the material may not require the same level of stiffness, or Wire Arc Additive Manufacturing (WAAM) of steel, where the material properties and delivery requirements differ substantially.

Short delivery distances, achieved through on-board intermediate material storage or on-board mixing, emerge as advantageous strategies. Empirical evidence indicates the successful application of on-board intermediate storage in both small-scale experiments, such as in FDM [52] or clay extrusion mobile printers [18], [19], and in cement-based materials exemplified by Baubot X1 beta [77]. To reconcile the conflicting requirements of workability during delivery and the requisite structural maturation post-deposition, innovative strategies, such as inline mixing of concrete mixtures directly at the nozzle, are under exploration [78], [79].

Potentials in multi-robot cooperation

Multi-robot processes can increase the range, speed, and efficiency of a process, where multiple robots can support each other or take on individual tasks leading to new possibilities that one robot alone could not handle [80], [81]. There are two primary modes of multi-robot deployment, that is, heterogeneous and homogeneous systems. Heterogeneous systems employ robots of varying scales, capabilities, and other attributes, collaborating in a synergistic manner to enhance the overall operational capability of the system. Conversely, homogeneous systems comprise robots with similar capabilities, aiming primarily to augment efficiency and throughput.

In the case of homogeneous systems, particularly concerning mobile ground robots equipped for in situ additive manufacturing, the focal point lies in addressing the vast workspace volume and often substantial material volumes required by target geometries, as, for example, depicted by Cutajar et al. in Fig. 16 for the cooperative printing of an earthen formwork for concrete casting [81]. The ability to parallelise any task, be it in computing, construction, or other domains, is not universally assured. Even when parallelisation is feasible, intricacies such as subtask dependencies or resource contention dictate that efficiency gains will not straightforwardly scale with the number of deployed robots. In [20], [21], [81], the parallelisation of large-scale printing tasks via a multi-robot system is preliminarily examined. It was shown that initial challenges of task allocation may be tackled using established strategies such as voting or ensemble methods, similar to heuristic methods shown in [46]. However, it was observed that the aforementioned problem of inherent coupling between robot navigation and the derivation of print trajectories was significantly amplified. As

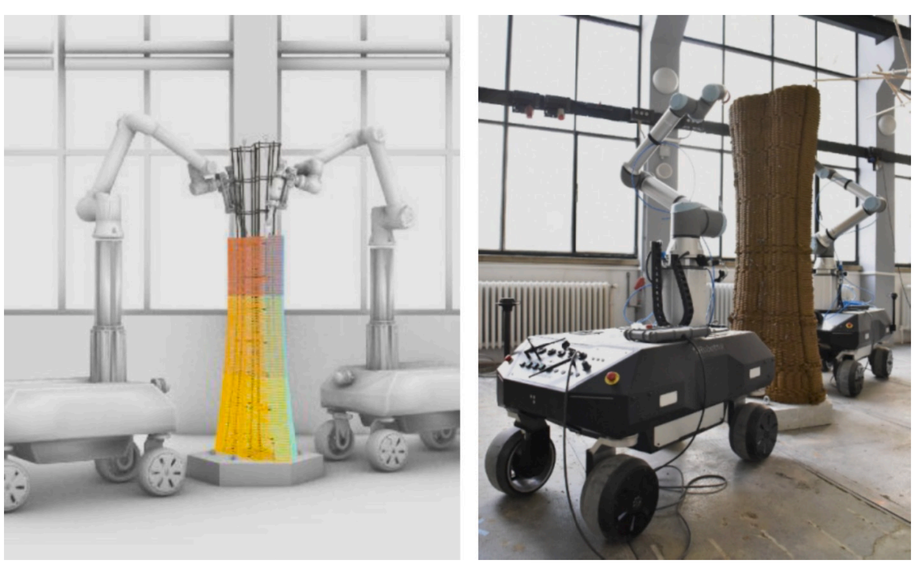

Fig. 16. Cutajar et al. 2024 [81] show a homogeneous dual-robot setup utilised to 3DP an earthen formwork for concrete casting cooperatively from opposite sides with finger joints in between the meeting points of the segments.

multiple robots populate the environment through printing, they alter the context within which future operations unfold—potentially creating bottlenecks and areas of congestion, amplifying the complexity of planning tasks, and diminishing robot utilisation.

In the case of heterogeneous systems, they could provide a robust framework for scalability. Unlike homogeneous systems, where scalability is often constrained by the uniform capabilities of the robots, heterogeneous systems can dynamically assemble a team of robots with complementary skills, ensuring optimal resource utilisation and adaptability to a wide range of scenarios [82], [83]. For example, in Aerial Additive Manufacturing, where a scan-drone maps the structure and a build-drone carries out layer-wise material deposition [22], the collaborative efforts of robots with diverse capabilities have been demonstrated to open up new possibilities. Here, the heterogeneous deployment has allowed for a specialised distribution of tasks based on individual strengths. The scan-drone, equipped with advanced sensing and mapping capabilities, efficiently navigates and surveys the designated area. Simultaneously, optimised for precise material deposition, the build-drone focuses on executing the construction process. This complementary division of tasks and specialised task allocation capitalises on the unique strengths of each robot type, enhancing the overall system performance. The collaboration between robots with distinct capabilities thus introduces a level of flexibility that succeeds the one of homogeneous systems.

The varied attributes and capacities of different robots enable the system to scale operations according to the complexity and size of the task at hand. This adaptability and scalability inherent in heterogeneous multi-robot systems make them particularly promising for applications in diverse fields, particularly for robotic repair and strengthening. In the context of repairing structural components, mobile robots with various capabilities can be utilised to cover the entire process chain. This includes removing deteriorated areas through subtractive surface removal of concrete and reprofiling cross-sections through additive processes, such as depicted in Fig. 17. For strengthening measures, linear reinforcement channels, e.g., bars or cables, can be milled, or surfaces can be roughened for planar reinforcement, including lamellas and meshes. This is again followed by the formation of the bond to the reinforcement through additive processes.

Human-robot co-deployment and cooperation

The current emphasis on deliberate coordination and task distribution in heterogeneous multi-agent systems within building construction mainly centres on interactions between machines. Although human involvement is often vital to the success of robotic fabrication processes—through intervention, reprogramming, initiating actions, or addressing unexpected events—existing research predominantly focuses on developing fully autonomous processes that reduce human interventions, effectively substituting humans with robots rather than promoting collaborative synergy between them [84], [85]. Incorporating human agents into the fabrication process could serve as a valuable and sustainable objective, while also taking advantage of the efficiency, speed, precision, and repeatability offered by mobile construction robotics. By sharing diverse tasks within the same building site environment, skilled workers and robots could collaborate towards common goals, blending their complementary abilities and strengths for optimal outcomes [86].

Fig. 17. Vision for a heterogeneous dual-robot setup aimed at strengthening structural components, including milling channels for reinforcement, and forming the bond between reinforcement and concrete through concrete 3DP. Source: D. Lowke

To achieve human-robot co-deployment and cooperation, instead of aiming at replacing human workers on construction sites, novel methods of how humans can be assisted by robots and vice versa will be required [87]. Advanced perception capabilities and spatial AI, enabling scene-level, object-level, and human-level understanding, as shown, for example with [56], [61], coupled with safe control methods, will allow robots to take on individual manufacturing tasks in direct or indirect cooperation with humans and thus allow for novel robotic construction processes to be carried out in a cooperative and collaborative human-robot manner.

4. Upscaling: from the laboratory to the site

Considering the significant environmental impact of demolishing and reconstructing buildings, it is critical to promote sustainable practices. This includes prioritising corrective maintenance and repair of existing structures instead of their demolition with the help of advanced and alternative construction technologies.

Mobile robotic platforms, well-suited for these tasks, can access confined spaces, operate in hazardous work sites, and reach difficult locations, such as significant depths or areas with extreme temperatures, potentially redefining the efficiency and effectiveness of building repairs. Their enhanced sensing and manipulation capabilities will enable repair operations to surpass human-level precision and effectiveness. The research presented in this paper highlights the potential of 3D Printing (3DP) with mobile robots as a promising approach to achieving these objectives, thereby enhancing resource efficiency and sustainability in the construction sector.

The mobile robotic processes reviewed herein, encompassing extrusion-based and spray-based 3DP with mineral materials like concrete, plaster, and earthen materials, as well as deposition-based 3DP processes for metals (e.g., WAAM), represent an initial exploration of leveraging such processes and machinery for on-site building repair. However, transitioning from the laboratory to the site necessitates further research in various areas.

Concerning the 3DP processes, one of the critical areas for future research lies in the understanding of material processing and material-process interactions in integration with the deployed mechanical systems. The rheological properties of the materials, such as yield stress, viscosity, elastic modulus, critical strain, and structuration rate, must be thoroughly understood and optimised to meet the specific requirements of on-site applications. This involves not only ensuring proper flow and buildability during the 3DP process but also addressing the interaction between the material and the existing structural elements. The interaction between the deposited material and the underlying layers or substrate plays a vital role in the overall structural integrity and durability of repair and reinforcement tasks. As such, future research challenges lie in exploring custom structural and non-structural connections between existing building elements and novel 3DP elements. This involves the nuanced integration of separate connecting surfaces through 3DP, especially in areas where multiple building elements meet and converge, such as corners or intersections between ceilings and floors. The objective will be to facilitate seamless transitions and augment structural capacity. The potential of fully mobile setups, encompassing both aerial and ground-based robots, equipped with whole-body motion planning and control, emerges as a key enabler for realising the full scope of mobile 3DP in diverse on-site printing applications at a 1:1 scale within extended workspaces. These setups will need to account for material-process interactions in real-time, ensuring that the printed material meets the structural and aesthetic requirements of the repair tasks in question.

Additional challenges from conceptualisation to practical application include the precise evaluation and survey of intrinsic building characteristics and conditions, including as-found geometry, connection details, deterioration type, and age, amongst other factors. Complementing the proposed robotic 3DP processes, semi-automated on-site surveying is necessary to systematically collect objective data on building structures for the precise estimation and evaluation of as-found conditions. For example, processes such as non-destructive testing (NDT) can aid in building condition assessment, considering factors like material aging and deterioration. Furthermore, complementing 3DP processes will also entail a variety of manipulation procedures such as surface preparation for additive repair tasks, including cleaning, treating the substrate surface, applying adhesive primers, or incorporating mechanical connectors.

Finally, the effectiveness of the proposed automated building repair procedures using mobile 3DP robots relies on an array of extrinsic factors. These include the cost and effort associated with refurbishment, encompassing cleaning and preparation efforts, architectural impacts, and adherence to applicable building regulations. The successful navigation of these external considerations will ultimately determine the viability and success of the envisioned robotic building repair processes in real-world scenarios. In conclusion, the future of 3D printing in construction lies not only in technological innovation for new constructions but also in the successful integration of these advancements into the complex fabric of existing structures and environments.

CRediT authorship contribution statement

Kathrin Dörfler: Writing – review & editing, Writing – original draft, Conceptualization. **Gido Dielemans:** Writing – review & editing. **Stefan Leutenegger:** Writing – original draft. **Selen Ercan Jenny:** Writing – original draft. **Johannes Pankert:** Writing – original draft. **Julius Sustarevas:** Writing – original draft. **Lukas Lachmayer:** Writing – original draft. **Annika Raatz:** Supervision. **Dirk Lowke:** Writing – original draft.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 4 in order to improve language and readability at selected locations. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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