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Analyzing Some Aspects of Robot-oriented Design Approach at Material Handling and Manipulation Systems of On-site Automated Construction Technologies

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Abstract

The construction sector is one of the fields of industries where automation and robotics are the least widely applied in our present day. This is in consequence of some characteristics of the construction industry, like the unique nature of the establishments, and the uncontrolled environmental circumstances on-site. However, with the present development level of robotics and with the spread of applications of AI-based technologies there is considerable chance for acceleration of development in this sector too. For the development of automated construction operations, it is essential to understand the most important principles in this regard, like robot-oriented design (ROD). In the present paper analysis of on-site automated construction technologies, which are already in use in the construction industry, is conducted, considering how the ROD approach prevails over the material handling and the applied manipulation types. In the case of material feed, there are still many technologies, where manual material handling is performed even if the technologies are applied on a relatively high level of autonomy. Regarding the automated construction processes the applied types of manipulations and the types of joints are analyzed. Robotic arms with various joint types are widely used in many industries. In the case of automated construction technologies, however, some joint types are more frequently applied than others. In the present paper, statistics are given about the occurrence of the various types, and an attempt is made to reveal the background of the observations.

Keywords

construction automation, construction robotics, robot-oriented design, joint and manipulation types, material handling

1 Introduction

The automation of the construction industry has become a more and more important issue of our time and can be considered as one of the most important challenges of the construction industry. Automated construction is a future-oriented area of the construction industry, which is characterized by the use of modern and experimental technologies. Some of the emerging solutions already have decades of industrial background, while others only date back a few years. Concerning construction automation, automated prefabrication, on-site automated construction with single-task construction robots, and multiple purposes construction robots in some cases have been used for decades [1, 2], but most of the automated construction technologies have tended to spread only in the last few years. Beyond the technology-related questions, the typical fields of challenges in construction automation are the elimination of environmental circumstances to assure accuracy and quality [2], the temporal harmonization of the processes like the material transport and handling for undisturbed workflow, the handling of the relatively large weights of construction and the assurance of safety of the human workforce who are present on the site, involving their exemption form monotonous heavy physical work [1].

The first attempts at automated construction technologies were either very embryonic solutions with complicated mechanical bodies like "Motor mason" [3] or focused on a relatively easy construction step like horizontal surface sanding e.g., Shimizu Flat-KN [1]. The application of teleoperated machines in Japan was also a very important step in construction automation [4]. In the past few years, the number of autonomous solutions has increased, as it is revealed by many interpretations [1–8].

Robot-oriented design (ROD) is an important approach to the planning and execution of robotic-based technologies.

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The principles of ROD provide a proper understanding of the facts that must be considered in the case of robotic-based production or construction to have an efficient and beneficial result. In the case of automated construction technologies ROD affects the management of the material supply, the organization of the automated construction sites, the development of the construction elements and processes, and even the final product which is the building itself [2, 9]. The related literature embraces a few decades. The concept of ROD in the construction industry dates back to the 1980s when the elemental principles of this approach were set [9]. Later these principles were analyzed in detail in the mirror of the applied robotics-based construction technologies and related research concepts [2]. Some further works are dedicated to some minor problems related to ROD [10, 11]. The conception has had determining importance up to now and predictably will accompany the development of the future construction industry [12, 13]. On automated material handling, as part of the organization of an automated building construction system, there were conceptions already in the 1990s [14]. Regarding compliance with the various kinematics systems for automated construction technologies, besides the above-mentioned works, there is a relatively early analysis on some of the most relevant types [15], and recently some detailed reviews were made on many aspects of automated construction with some reference to the kinetic body types, however, it was not the focus of these papers [7, 8].

In the present paper, supplementing the above literature, the focus is on some ROD aspects of the on-site autonomous construction technologies that are applied in real construction practice, and which are considered as an entire construction activity, not just a single automated step of the technology.

Regarding the technology conceptions, within the above-given focus, two-dimensional works (planar, surface treatments), and three-dimensional works (structure-producing technologies) can be distinguished [6].

The problem of on-site automated construction can be considered by many factors; however, the following typical fields are focusing on the most important issues regarding automated construction:

- transportation,
- material handling,
- construction process,
- disassemble.

The automation of transportation to the site is developed as a part of the development of the automation of traffic and vehicles, and it is a problem that goes beyond the scope of research on the construction industry. Disassembly is a very important field of development, but it is not part of this present analysis. Two of these territories, however, the material handling and the manipulation area of the construction operation are analyzed in the present paper as fields of high importance, which are related to the ROD approach in the construction industry.

The goal of this research is to have a deeper and more systematic understanding of these questions for the further development of on-site automated building technologies, for supporting optimizing tasks of the application of automated construction activities on the construction sites in the future.

2 Methodology

In the present paper, as an extension of the preceding analyses of the introduced literature, a new analysis is made focusing on the on-site applied automated construction technologies from the perspective of the material feed and the construction operation (manipulation), considering some principles of the ROD approach in the construction industry. In the first part of the paper, the material feed is in question. In the frame of this investigation, the occurrence frequency of the human power-based, manual material feed was in focus. In the second part manipulation types are investigated with a focus on the relationship between spread and compliance. In both parts, an analysis is made to create an image of the present trends and solutions. In Section 5, some conclusions are deduced from the observations.

This research is not a literature review as far as the focus of the analysis is the already in-practice applied on-site automated construction technologies themselves, based primarily on the information which is provided by the producing companies online. Construction robotics is a rapidly developing field of the construction industry, however, many development technologies cannot be used in the industry in their present state. This paper focuses on the solutions only that have industrial scale applications too, because the question to be answered here is what lessons should be learned from the construction site challenges, opportunities, and problems. The related literature was evoked only for connecting the most important principles with the analyzed technologies. Having a few decades of past in the field of automation in construction, the opportunity arises to analyze more and more automated on-site construction technologies in practice, for which there were only fewer opportunities earlier.

3 Analyses

3.1 Material handling

Regarding material feed, there are many unsolved issues, which formulate limits at the level of autonomy of the automated construction technologies. From this point of view, classical-type construction technologies, where solid construction elements are handled (e.g., bricklaying), and additive technologies (e.g., 3D concrete printing) can be distinguished. The analysis of the material handling of the various automated technologies [16-32] is summarized in Table 1. In some other cases, the material handling is part of the automated workflow. In many cases of automated technology, however, the material feed is done manually (e.g., EZ Renda plastering machines [22], SAM, Semi-Automated Mason [28]), namely, the human workforce feeds continuously the required material to the machinery during the automated workflow. If the material feed is done before the construction activity, but the fill-up is not part of the autonomous workflow, the continuity of the automated work is limited by the stock. Most painting systems are equipped with a built-in tank, which enables a certain time of autonomous work, however, it also must be filled up regularly, which causes an interruption of the process. In the case of the HadrianX autonomous bricklaying technology [23], the material is transported by the machinery itself, but the working time is limited by the capacity of the container of the truck.

Regarding the material feed of the investigated automated construction technologies, we can distinguish the following categories:

- on-site manual material feed during the work process [18, 22, 28, 29, 30, 31],
- on-site manual material feed at the breaks of the work process [21, 24, 26],
- on-site material feed during the process with machinery [16, 17, 19, 25, 27, 32],
- built-in material feed (off site loading) [23].

Table 1 Applied material feed at robotic-based construction technologies

Name	Company	Technology	Material feed
Apis-Cor Frank [16]	Apis-Cor	Concrete 3D printing	Automated pumping (with an independent item) from the silo
Canvas 1200CX, 1500 [17]	Canvas Construction Inc.	Drywall spraying	Automated built-in spraying system, automated paint pumping
Chonho CH WP-5 [18]	Yantai Chonho Machinery Technology Ltd.	Wall plastering machine	Material sprayed (independently) on the surface to be rendered, before the rendering
Cobod Bod2 [19]	Cobod International	Concrete 3D printing	Automated pumping system (independent item) dry mix from a silo or transported concrete
Crane WASP [20]	WASP	3D-printed cob (clay)	Manual material feed to the pumping system
DF033 Residential [21]	DaFang AI	Concrete grinding, putty plastering, painting	Automated built-in spraying system
DF062 6-meter [21]	DaFang AI	Concrete grinding, plastering, painting	Automated built-in spraying system
EZ-Renda 1200 [22]	EZ-Renda Construction Machinery Ltd.	Plastering robot	Manual material feed
Hadrian-X [23]	Fastbrick Robotics	Automated bricklaying	Automated brick feed from a specialized transporter
MYRO Wall painting Robot [24]	MYRO	Wall painting	Automated built-in spraying system, manual material feed
NEXCON 1G [25]	Black Buffalo 3D	Concrete, clay 3D printing	Automated pumping system (independent item) dry mix from silos
OKIBO 2 EG6 [26]	OKIBO	Wall painting, plastering/rendering	Automated built-in spraying system, manual material feed
Phoenix [27]	Icon	Concrete 3D printing	Adjoining concrete pump
Semi-Automated Mason[28]	Construction Robotics	Automated bricklaying	Manual material feed
Shimizu CFR-1 [29]	Shimizu Corporation	Ceiling panel installation	Manual material feed
TUPO series (3, 8, 9) [30]	Tupo Machinery	Automatic plastering	Manual material feed
TyBot/IronBot [31]	Advanced Construction Robotics	Autonomous rebar tying	Manual rebar placement and material feed
Vulcan II [32]	Icon	Concrete 3D printing	Adjoining concrete pump

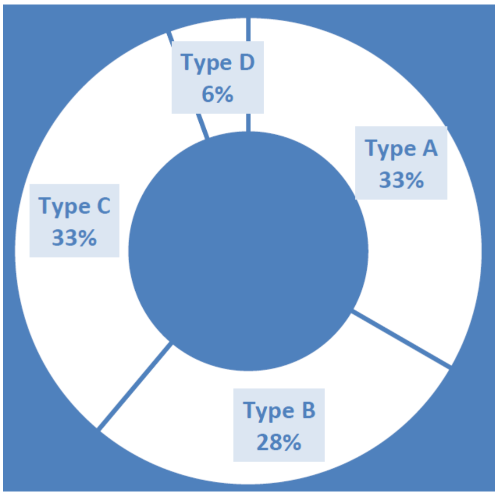

Fig. 1 Percentage of the occurrence of material feed A) on-site manual material feed during the work process; B) on-site manual material feed at the breaks of the work process; C) on-site material feed during the process with machinery; D) off-site material feed

The occurrence of the various types of material feed in the case of the investigated automated construction technologies can be seen in Fig. 1.

3.2 Applied manipulation systems of the automated construction technologies

Regarding the manipulation types and the work envelope of the construction technologies, a compilation and an analysis were made. The analyzed technologies are autonomous, or at least a sequence of phases of those are autonomous. The applied kinematic system is developed according to the requirements of each construction technology. In the field of construction robotics, the applied joint types are the following:

- prismatic (translational) joint,
- planar hinge/revolute joint (planar rotational joint),
- spherical hinge (spatial rotational joint).

The known kinematic base bodies [2, 33] of robotic manipulation systems are:

- rectangular (cartesian): that operates with prismatic connection, (3 translational joints),
- overhead gantry: it is similar to the rectangular one and operates with prismatic joints, but it is normally installed on a frame structure above the manipulation area,
- cylindrical: usually operates with one support involving a central planar hinge and two further prismatic connections (1 rotational and 2 translational joints),
- spherical (polar): this type can be built up in various ways, but normally a combination of prismatic joint and planar hinges (2 rotational and 1 translational joint),
- SCARA system: planar hinges in combination with a lifting prismatic joint (1 translational and 2 rotational joints),
- articulated (anthropomorphic): a series of planar hinge joints or spherical joints (with an analogy of the human arm: shoulder, elbow, wrist).

The kinematic base bodies can be seen in Fig. 2.

In Tables 2 and 3 data was collected, about the name, the producer of the robot, the technology, the applied manipulation system, and the type of joints. The aim was here to reveal the frequency of the occurrence of the various robot and joint types in the construction industry. Among the technologies two categories are distinguished in the present study: surface preparation machines like painting robots, where the manipulation area is two-dimensional, and structure-producing machines like 3D concrete printing or bricklaying. Within planar, surface-treating construction

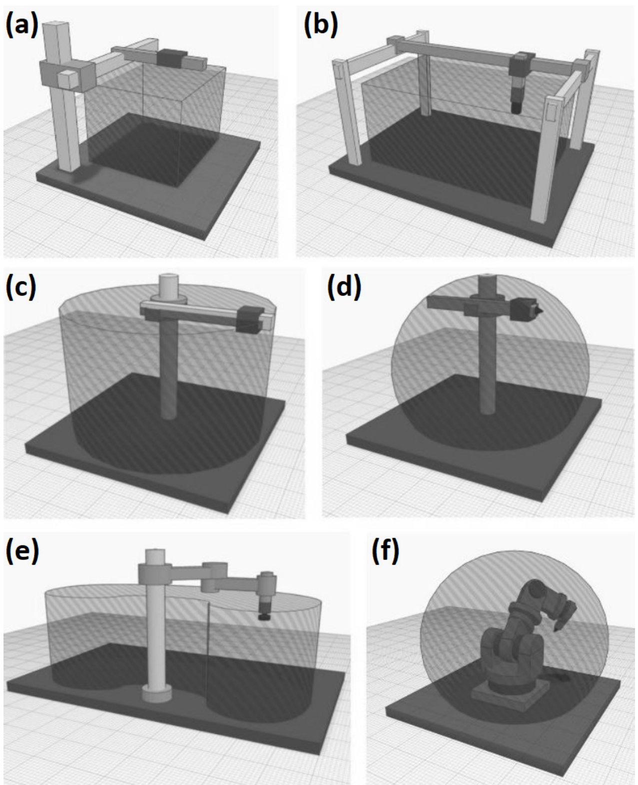

Fig. 2 Types of robotic manipulators (illustration is prepared by the author); (a) rectangular; (b) overhead gantry; (c) cylindrical; (d) spherical; (e) SCARA system; (f) articulated

Table 2 Applied robotic-based construction technologies and robotic manipulation types of surface preparation technologies

Name	Company	Technology	Manipulators	System joints
Canvas 1200 CX, 1550 [17]	Canvas Construction Inc.	Drywall spraying/saning	Sliding rail and robotic arm on a mobile platform	Prismatic base and planar hinge
Chonho CH-WP5 [18]	Yantai Chonho Machinery Technology Ltd.	Wall plastering machine	Mobile platform, sliding rail manipulator	Prismatic joints
DF033 Residential [21]	DaFang AI	Concrete grinding, putty plastering, painting	Rectangular manipulators (mechanical "rail-arm"), on a moving platform + hinge attached head	Prismatic joints, planar hinge at the end-effector
DF062 6-meter [21]	DaFang AI	Concrete grinding, putty sanding, putty plastering, painting	Rectangular manipulators (mechanical "rail-arm"), on a moving platform + hinge attached head	Prismatic joints, planar hinge at the end-effector
EZ-Robot 1200 [22]	EZ-Renda Construc-tion Machinery Ltd.	Plastering robot	Rectangular manipulators on a moving platform	Prismatic joints
MYRO Wall painting Robot [24]	MYRO	Wall painting	Telescopic head, mobile platform	Prismatic joints
OKIBO 2 EG6 [26]	OKIBO	Wall painting, plastering/rendering	Mobile platform, sliding rail for height, robotic arm-based end effector	Prismatic joints, planar hinges
TUPO series: 3/8/9 [30]	Tupo Machinery	Automatic plastering	Double sliding rail frame	Prismatic joints

Table 3 Applied robotic-based construction technologies and robotic manipulation types of structure production technologies

Name	Company	Technology	Manipulators	System joints
Apis-Cor Frank [16]	Apis-Cor	Concrete 3D printing	Cylindrical manipulator, prismatic head alignment	Central planar hinge, prismatic joints
Cobod Bod 2 [19]	Cobod International	Concrete 3D printing	Overhead gantry manipulator, sliding head alignment	Prismatic joints
Crane WASP [20, 37]	WASP	3D-printed cob (clay)	Cylindrical manipulator, sliding head alignment	Central planar hinge, prismatic joints
Hadrian-X [23]	Fastbrick Robotics	Automated bricklaying	Articulated manipulator and head + inside conveyor belt system	Planar hinges
NEXCON 1G [25]	Black Buffalo 3D	Concrete, clay 3D printing	Overhead gantry on sliding rails, and sliding head alignment	Prismatic joints
Phoenix [27]	Icon	Concrete 3D printing	Articulated manipulator and parallel manipulator head on a moving platform	Planar hinges, and prismatic joints
Semi-automated mason (SAM) [28]	Construction Robotics	Automated bricklaying	Sliding rail, articulated robotic arm manipulator, and head	Prismatic joints, spherical hinges
Shimizu CFR-1 [29]	Shimizu Corporation	Ceiling panel installation	Sliding rail system on mobile platform	Prismatic joints
TyBot/IronBot [31]	Advanced Construction Robotics	Autonomous rebar tying	Gantry manipulator, telescopic height management system	Prismatic joints
Vulcan II [32]	Icon	Concrete 3D printing	Overhead gantry on sliding rails, and sliding head alignment	Prismatic joints

works there are two categories, horizontal (moving on floor surface) and vertical plane (wall treating) technologies. The first ones are normally freely moving single-task construction robots (e.g., concrete grinding robots), which are introduced in detail in the literature [1]. The second category [17, 18, 21, 22, 24, 26, 30] is more relevant in the here analyzed context, is listed in Table 2. Spatial works, i.e., structure-producing technologies [16, 19, 20, 23, 25, 27–29, 31, 32, 34], are demonstrated in Table 3.

3.3 Analysis of the manipulation system elements

The frequency of occurrence in the cases of different kinds of kinetic base bodies that are used for manipulation among the analyzed technologies can be seen in Fig. 3.

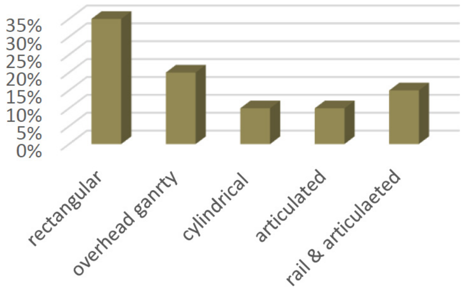

Fig. 3 Percentage of occurrence of the various types of robotic manipulators (rectangular, overhead gantry, cylindrical, and articulated type mounted on a rail) in the cases of the investigated automated construction technologies

The application of rectangular systems is the most frequently used one. Overhead gantry is also can be considered as a common solution, and cylindrical and articulated types are applied in some cases too. The latter is more often combined with a horizontal or vertical linear rail than used as a stand-alone solution. It is also can be observed in Tables 2 and 3 that these manipulators are combined with mobile platforms in somewhat more than half of the cases.

Regarding the joint types, prismatic joints are applied most frequently, and spherical hinge joints are the least common ones (Fig. 4).

Planar and spherical hinge joints allow much more freedom in moving however, prismatic joints have the advantage from the point of view of tractability and accuracy even in the case of heavy elements, which are characteristics of the construction industry. Even though prismatic joint-based manipulation systems (like linear rails or overhead gantry systems) and physically controlling passive compliances are common in robotics-based construction technologies, there are many solutions for the sensor-based autonomous controlling of newly designed technologies. Dynamic stabilization and computer vision-based work at the proper printhead movement [27] at Icon's new Phoenix system is an example of the sensor-based correction of the work process.

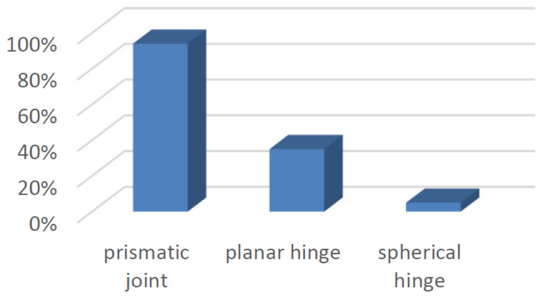

Fig. 4 Percentage of occurrence of joint types (spherical hinge, planar hinge, prismatic joints) at the investigated construction technologies (multiplied occurrence at the same technology calculated only ones)

4 Discussion

The unstandardized structure of the construction sites [4] and the uncertainty of various kinds are common problems to be considered in the development of the kinematic systems of construction. Of course, some unsteadiness can occur at the control too (computer freezes, end-effector malfunctions, instability of controlling network connections, etc.), however, standards and careful planning can mitigate these risks. Another disturbing effect is the irregularities of the physical characteristics of the materials and unevenness of the surfaces, which results in small differences in surface qualities, and material composition. These uncertainties have many impacts on the automated processes of the construction and the automated technologies should be robust enough to neutralize all these effects.

In the present paper, analyses were made on two territories related to ROD in the construction industry: material feed and the impact of the requirements of the construction technologies on the chosen kinetic body types. Regarding material feed it should be realized that there is still human workforce-based manual feed in 33% of the investigated cases of automated technologies, the majority of which is a continuous manual activity all along the execution process. In these cases future development goals can be envisaged for reducing the amount of monotonous heavy physical human activities in the construction industry by the automation of the construction processes. At one-third of the analyzed technologies the material feed is not parallel with the construction work, which means no occupied human workforce during the construction, however, the activity is interrupted, and still requires human workers for the feed. There is a relatively small part (33%) of the cases (mostly additive technologies) when the material feed is automatized, or machine-based, and in one case we could speak about off-site upload of the construction material, which means no interruption of the work processes.

Regarding the analyses of the relation of requirements of the construction technologies and the application of the kinetic body types, it can be assumed, that spherical joints are rare, as far as these joints are the least suitable at large weights, and they can cause the most problems of inaccuracy.

Planar hinge joints are less frequent than prismatic ones, even if there are some examples regards automated construction technologies. They cannot be abandoned where turning or rotation motion is required. Articulated manipulators are usually applied directly or close to the end-effectors, to reduce the applied force on the system.

Partially for these reasons, in the case of robotic-based construction technologies prismatic joints are the most frequently applied ones. Prismatic joints are the most trustable ones even in case of large weights and are the least sensible to the random occurrence of dislocations, and this is the joint type where supplementary control of external sensors is the least required.

It can also be stated that manipulator types that operate with prismatic joints (rectangular and gantry typed) are the most frequently applied ones among the analyzed examples. This is concordant with the opinion that gantry systems are more power efficient less complex to control and enable higher precision than mobile systems [7]. The frequent application of mobile platforms could contradict this statement, but in most examined cases, it is not involved in autonomous technology. Namely, it is applied for the repositioning of the machinery for the new location of work. This replacement can be manual (moved by human power), or it can work with teleoperation. At HadrianX [23] technology, the mobile platform is a human-driven truck, that is for the transportation of equipment and materials to the construction site. In some rare cases the mobile platform autonomously repositions itself (e.g., MYRO Wall painting Robot [24]), however, this requires an external reference system for the coordination, like an already existing building structure (in this case the reference is the wall).

The scope of this research is limited to the automated construction technologies, that are already used in the construction industry in their present state and that are used for an complete construction activity, consequently, automatization of a single step of a technology, and technologies, that are in an early phase of development are not analyzed here. As far as the focus of this paper is the material feed and the manipulation area, technologies, like linear working equipment (e.g., tunnel boring and paving machinery), multitasking robots, automated earth moving and transporting machinery (e.g., forklifts, excavators), and measuring/surveying robots, are not analyzed here either.

5 Conclusions

In summary, in the frame of the above analyses, the following statements can be established:

1. In the case of material handling of on-site automated construction technologies manual material feed is still very often, which is in contradiction with the long-term goals of ROD. Research focusing on this problem would be necessary.
2. In the present paper, it was ascertained that regarding the kinetic systems of the existing automated construction technologies, the application of prismatic joints is dominant. It is because these joints enable easier handling of large weights, and ensure higher steadiness against environmental effects. The application of rotational joints is mostly can be observed close to the end-effectors, where the loads are smaller.
3. As an extension of the above statement regarding the kinematic base body types of the present automated construction technologies in practice, the prismatic joint-based ones (rectangular, overhead gantry-typed, and the ones, that are equipped with a linear rail) are the most frequently used ones, namely in the investigated cases a preference of prismatic joint-based kinetic systems can be observed.

The practical benefit of the present analyses can be seen in two ways. On the one hand, it highlights the automation needs expressed in terms of building material-feeding solutions in the cases of several technologies. On the other hand, the analyses related to the manipulation area point to the mechanisms of selection related to the kinematic system, validating the more frequently used solutions and providing good examples for future developments.

The novelty of the present research can be identified in the new aspects of the analysis, namely that it focuses on the solutions used in practice from the perspective of future developments. Similar analyses carried out earlier aimed at slightly different goals.

In the future, the range of the here analyzed on-site construction techniques predictably will be expanded with some technologies that are under development in our present days, like cable-driven robots, unmanned aerial vehicles (UAVs), and self-organizing, multi-robotic systems (robotic swarms) [2, 35–37]. These might make significant changes in this field.

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