# Construction Automation with Autonomous Mobile Robots: A Review

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# Construction Automation with Autonomous Mobile Robots: A Review

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***Abstract*—We review state-of-the-art research into automated construction by autonomous mobile robots. Today, space research agencies seek to build infrastructure without human intervention; and construction companies look to robots with the potential to improve in construction quality, efficiency, and safety, not to mention flexibility in architectural design.**

**This paper addresses and classifies the relevant studies in terms of applications, materials, and robotic systems. We also identify ongoing challenges and discuss about future robotic requirements for automated construction.**

## I. INTRODUCTION

In the absence of a general consensus on the clear definition for *construction*, we refer to it here as the work of building by fitting parts together [1]. In this review, we consider it as an activity that relates to the creation of physical artifacts. We differentiate construction from *manufacturing*, in which a product is designed for mass production; *construction* products are instead large and unique in form [2]. They have to be made on sites which are unstructured, cluttered, and where laborers might simultaneously work. We also limit the definition of construction as building a structure whose approximate shape should be predictable by a human user (e.g., building a structure based on a pre-specified blueprint). Moreover, we do not consider the maintenance and decommissioning of infrastructures in this review.

Construction automation is an interesting field focused on applying computer-controlled processes and mechanization concepts into industry. It deals with applying the latest automation technologies to construction subdivisions, whether in civil engineering (building, dams, bridges, etc.), or in prefabrication of construction components [3]. Construction automation has been progressing to reduce the time and be cost-effective. For instance, reducing the cost could be done by replacing human workers with robots. Apart from the economic aspect, construction robotics has technical features to enhance quality and efficiency of the operations. Moreover, robots could potentially perform construction tasks where human presence is impossible, undesirable, or unsafe. For instance, we would mention to construction in hazardous areas after natural or man-made disasters such as earthquakes and nuclear accidents, construction under difficult physical conditions such as undersea or outer space locations, and construction in areas that are not readily accessible to humans or that require an initial structure to prepare the environment for a human habitat. Robots can be used to build these structures for particular situations either in an autonomous mode without human intervention, or with some level of planning by or interaction with a human supervisor.

Research in construction robotics and automation started in the 1980s, and since then developments in robotics sciences have led to a wide range of robotic platforms. Due to this diversity, general categories of construction robots are considered [2]: the first one is teleoperated systems, in which machines are under the remote control of humans; a human operator interprets data and cognitive activities. The second category, programmable construction machines, enables the human operator to do various tasks by choosing a preprogrammed menu of function or by teaching the machine a new function. The third category is intelligent systems in which unmanned construction robots accomplish their tasks either in a semi- or fully-autonomous mode. In the fully-autonomous mode robots would be expected to complete the tasks without human intervention within a specific domain. In contrast, in the semi-autonomous construction, a robot accomplishes its tasks with some level of planning interaction conducted with a human supervisor, for instance.

In this paper, we study construction automation research limited to the use of autonomous *mobile* robots. The framework of the review consists of three main categories: applications, materials used in the construction, and robotic systems. In Section II-A, we study the applications. Section II-B discusses the materials from various construction applications. Section II-C presents robots and robotics systems. Finally, in Section III, we discuss challenges in construction with mobile robots and provides conclusion and future directions.

## II. RESEARCH AXES

### A. Applications

Recent developments in robotic systems have led to a wide-range of automated construction applications that are mostly based on civil infrastructure and house building, for instance, automation of road, tunnel and bridge construction, earthwork or house construction including building skeleton erection and assembly, concrete compaction, and interior finishing [4]. Typically, a pure construction consists of a finite number of sub-tasks such as handling, concreting, coating, attaching, and measuring. The robot can perform one or more of these sub-tasks depending on situations and robotic capabilities. There is no straightforward way to classify applications based on the sub-tasks or robotic types, however, we can classify the applications based on conventional processes as follows [2]:

1) The handling process aimed at placing solid substances together or build based on a specific construction map (e.g., bricklaying).
2) The assembling and joining process for attaching rigid materials (e.g., welding).
3) The forming process leads to materials (or environments) with flexible shapes (e.g., cutting, machinery, liquid deposition, digging)

Several robots were developed for automated handling and assembly during last decades. The handling process would increase building efficiency of final structures composed of many big and monolithic parts. In this category, we study the applications in which mobile robots are used to lay rigid material for construction purposes. Helm et al. [5] presented the in-situ construction using a ground mobile robot equipped to the six DOF manipulator for a 3D structure made of same bricks. In [6], flying robots built brick-like tower by dropping block one by one. Wismer et al. [7] used robots to place cube blocks (cube with magnet component) with different dimensions for a roofed structure. These applications could open new ways for civil purposes such as masonry. Masonry is time consuming, repetitive and labor-intensive and often result in back injury, therefore it is excellent candidate to be performed by robots [8]. The elementary processes of the masonry such as the bricklaying was performed by the BRONCO robot [9]. Today, many companies employ robotic automation for onsite construction. The Tiger-Stone is designed for paving a road. Tiger Stone is placed in position with a remote control and it starts to fill the site [10]. A semi-automated masonry (SAM) system is invented to work with the mason. The operator moves the base of the SAM and it lifts and places each brick [11]. However, human-robot interaction is a challenging area, because the environment is unstructured and full of dangerous dynamic obstacles for a human being. The proximity and vulnerability of the human in the interaction imposes strict challenges on human and robotic activities in a shared environment [12]. In addition, fully automated construction using mobile robots is not ready for commercial markets because they need developments to be reliable, efficient, and cheaper in respect to laborers. For instance, an autonomous mobile robot has to tackle uncertainties and to take proper decision in failure cases for laying a straight wall in a site full of obstruction as mason does. In fact, autonomous mobile robots requirements need to be developed to get ready for fully automated commercial construction purposes.

In contrast to using a pre-specified blue-print, some research presents construction in interaction with environment or external inputs. Robots place blocks of alternating color along a straight line starting with a pre-placed seed block located underneath a beacon [13]. Soleymani et al. [14] take advantage of biological principles to deposit sand bags in front of a colored ground marker acting as radioactive source.

The assembling and joining process is an important aspect of construction and a critical issue for mobile robot installation as well. Laborers are usually employed to manually align parts together and connect them by using bolts, welding, or other types of connections, although the automated (or even robotic) construction needs more effort and redesign of connectors to be employed as a common and reliable way for assembling and joining structures. In [15], aerial robots were used to construct a truss-like tower with magnet nodes and members. In [16], the robot moves autonomously and untethered through a truss structure to assemble and dissemble rods. The KUKA MOIROS, which is a mobile industrial robot system, can be equipped with advanced manipulators to handle welding processes [17].

An exemplary application of the forming process is contour crafting, which is a layered fabrication technology developed for building a structure in a single run [18]. Napp and Nagpal [19] apply a mobile robot which is embedded by foam tube to deposit foam for creating a ramp. The long-term goal of this application is to enable robots to perform a construction processes in emergency situations. Building large structures without being confined by dimensions is another challenge for current technologies. Mobile robots inherently provide the flexibility to construct artifacts that extend beyond fixed-based system constraints (e.g., size of a 3D printers frame constraint). Jokic et al. [20] have developed technologies to build 3D shape structures by using amorphous material deposition with mobile heads. This method allows an object to be printed independent from its size.

### B. Materials

For autonomous robotic construction, material properties need to be taken into account because the type of the material can determine what kind of a robot is needed to perform construction processes. Diversity of material based on the expected goal motivates the unique design of a robot and algorithms; factors such as shape and application of the structure, construction precision, construction speed, simplicity of the construction, amount of required material and cost. The nature of social animals provides impressive construction instances; ant workers dig earth to make the nest; termites build mound structure with paste of the water, sand, clay and deposit the mud stuff while wet; some birds construct the nest structure from small twigs and grasses without the help of binders. However, human structures usually are complex and needs combinations of materials while simple materials were used in the most of the research around involving robot construction.

Figure 1 shows a wide range of materials used, which confirms that the design and development of the robots has to be adopted on the material properties and target environments. The injection sprayer for creating foam needs a different design compared to an end-effector for grasping rigid materials. Accordingly, amorphous materials can be applied by a robot with the simple sensory system and controller while they provide inaccurate structures. In contrast, structures made from rigid substances like blocks or rods are more precise. Moreover, rigid structure provide the robot to better build structures according to a blue-print.

Three types of materials for amorphous construction were investigated regardless of robotic activities in [21]: stiff pre-fabricated components and adhesive (toothpicks and glue), compliant pre-fabricated components (sandbags), and liquid depositions (casting foams). Largest expansion ratio of casting foams is an attractive point but sufficient time is necessary to cure foam. Compliant bags comparatively need low mechanism complexity to be carried but they have no expansion and do not create permanent structures. Adhesive covered objects, such as toothpicks and glue, have intermediate characteristic attributes such as lower cure time rather than casting foams and lager expansion ratio rather than sandbags. Soleymani et al. [14] addressed the deformable pocket (compliant bags) to construct a protective linear wall. The properties of compliant bags have allowed employment of a simple mechanism and simple controller to deposit them but the wall is not really linear. Napp and Nagpal [19] [22] presented a model of construction to build an arbitrary shape with casting foams in unstructured environments.

Autonomous construction is also a complex application in which many failures can occur. These failures can propagate from one step to another, for instance, if the robot incorrectly grasps the block, it could destroy the built structures, thus, it is important to avoid or to correct these faults. Using self-aligning objects could be a way to decrease misalignment errors; for instance, bricks are made from expanded foam, with physical features to achieve self-alignment and magnets for attachment [23]. In [7], foam bricks with several magnetic pins on the adjacent faces bricks were used to build a roofed structure. Terada and Murata [24] presented a particular robotic assembler that builds autonomous manipulates, transports, and assemble the modules with automatic connectors. Today, companies are designing and manufacturing prefabricated components to increase construction speed and efficiency. New prefabricated components could be designed and made for robotic use in automated construction. For example, components with male–female connectors allow for automatic assembly in a more robust way [2].

Truss-like structures are composed of cube-shaped nodes, and bar-shaped members. Members may be attached together to create a simple cubic lattice structure. In this way, each level is constructed on a former plane and it grows to build a tower. In [15], each face of a node has four circular slots and there are protrusions at the two ends of each member to provide features for assembly. The magnets at the center of each face provide a snap fit connection. In [25], they reduced the number of magnets and the mass of the parts because the truss is constructed by aerial robots. In [16], the novel bidirectional geared rods and connectors have been used to build a truss structure with female bidirectional and a male bidirectional connectors.

For materials that do not have self-align mechanisms, advanced robotic systems are needed to meet requirements of construction automation. In [6] glued polystyrene bricks were carried by flying robots. A network of intercommunicating computer programs used a real-time camera system that helped the robots to find specific locations to pickup and then drop the blocks. Helm et al. [5] presented the dimRob equipped with the ABB manipulators. A 3D laser scanner scans the placed wooden bricks during fabrication then sends this mapped measurement to the controller software to obtain next commands. These research shows non self-alignment blocks require more accurate position systems.

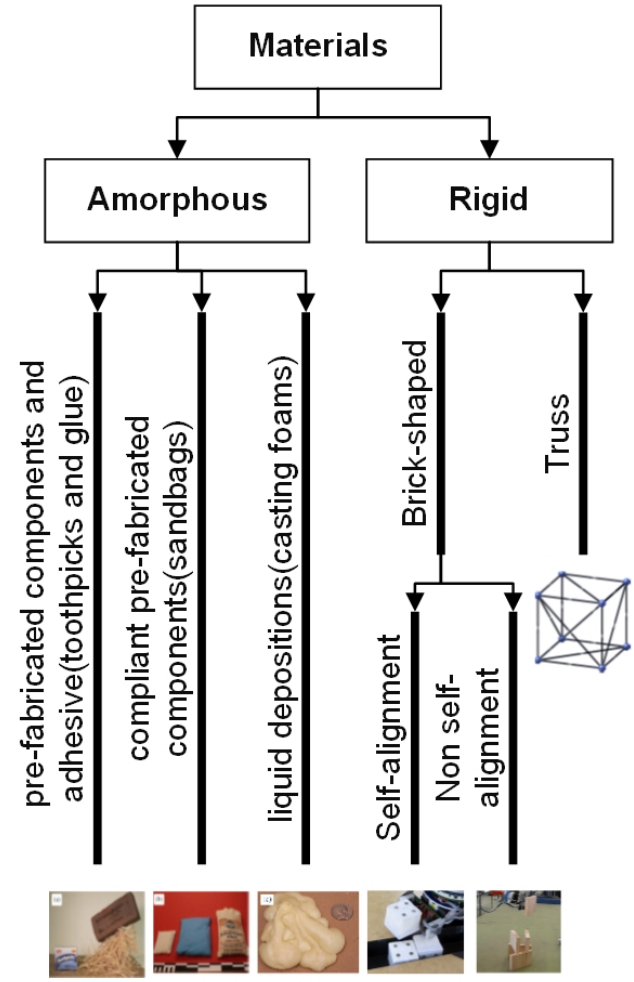


Fig. 1. Diagram of the materials used in automated construction

### C. Robots and robotic systems

*1) Robotic systems:* Generally speaking, robots have been designed and developed based on human requirements but autonomous robots need to be more intelligent to tackle more complex issues such as uncertainty and unpredictable situations. Due to technical limits facing autonomous robot development, most of autonomous construction robots are on experimental scales and they are far from the commercial stage, although mobile robots are extremely useful in the field of architecture [6].

Robots are typically divided by ground robots and aerial robots regard field. Aerial robots such as helicopters and quadrotors are a branch of small unmanned autonomous vehicles fields (UAVs) that considerable number of research groups have been working to develop and improve. Construction systems target to integrate these achievements for performing complex construction autonomously. For instance, an accurate positioning system is necessary in construction and an external localization system is employed to provide high-accuracy flight for construction tasks. Aerial robots fly in space and place bricks directly to their required position without scaffolding. Structures can also be built according to highly complex designs because the aerial robots benefit from powerful external localization systems therefore they can place and manipulate material according to a precise digital blueprint. Each of these characteristics provides the potential for spatial structures. On the other hand, at the moment, most aerial robots have limited payload capabilities. Another limitation concerns to aerodynamic considerations because the shape of modules affects the performance of control and stability, so modules must be designed such that satisfy the aerodynamic constraint. In a branch of research which has been done at ETH Zurich, four quad-rotors are exploited to construct a brick-like tower. They benefited from the real-time camera system to guide robots according to digital design,allowing the robot pickup and deposit objects[6]. The robot is a hummingbird quad-rotor which is approximately 55 cm in diameter, weighs approximately 500 g including battery and providing approximately 20 minutes of operation. The maximum payload is around 500 grams. The VICON motion tracking system was used to estimate the position and orientation of the picked objects, and aerial vehicles states. It provides position feedback at 150 Hz with marker position accuracy on the order of a millimeter. The low-level controller can execute three maneuvers, hovering at any specified position, and traveling the trajectory between any two desired points. Currently, a higher level is needed to perform the assembly task with multiple quad-rotors in coordination [15].

In contrast, ground robots are more stable and controllable than aerial robots. In addition, they can carry heavier and more complex objects in terms of shape, although they hardly access each point of the space without a scaffold or a big manipulator. Werfel et al. [26] presented a ground mobile robot (TERMES) to perform automated construction inspired by the building activities of termites. TERMES are climbing to build a structure using passive solid building blocks. The TERMES robot is equipped with four small whegs which allows the robot to climb the tallest blocks and align itself mechanically with the structure as it climbs. For positioning, the robots use just 6 active infrared (IR) sensors and blocks which are colored black with white stripes. Magnenat et al. [27] used the marXbot robot to grasp ferromagnetic self-alignment blocks. It employed the odometry and laser data to perform SLAM and employed the front camera and proximity sensors to provide the required data for dropping blocks. A roofed structure was built using a VICON to estimate the position of the marXbot [7]. Ardiny et al. [28] presented an autonomous construction system for building separated artifacts with simple blocks. The approach was based on the combination of a self-positioning system (SLAM) to find the construction place in an unknown environment and stigmergy[1] to build coherent artifacts. Stroupe et al. [30] presented construction by two robotic platforms: SRR and SRR2K in an outdoor environment. Each rover is economically equipped with a forward-facing stereo cameras and a four DOF arm. A 3-axis force-torque sensor on the gripper helps the rover to peform manipulation for transporting and placing rods. They used a model which is precise for manipulator positioning but may be inaccurate for world coordinates. Helm et al. [5] presented dimRob which has a mobile base and is equipped with the ABB IRB 4600 manipulator. It has a 2D line scanner on mobile base as well as a 3D scanner to detect objects. Two vacuum grippers are embedded to grip the object either from the top or the side. Unlike other mobile robots discussed here, this robot was designed for in-situ construction but the robot moves and localize itself based on the CAD map and two metal disks as markers. In each step, the robot is fixed and supported by side-hinged telescopic outriggers [5].

[1]Robots can use stigmergy by looking at the local configuration of the building material to determine where to add additional materials [29].

This research shows that existing robotic construction processes need precise positioning, which can be achieved by machines that have a fixed mechanical link with the construction and therefore rely on absolute positioning. Mobile robots, by nature, do not have a fixed referential point, and their positioning systems are not as accurate as fixed-based systems. Therefore, they need to employ external tracking systems (e.g., camera, GPS) or short-range relative localization. Moreover, this research is rarely performed in unstructured environment where there are many dynamic obstacles to relatively build an accurate structure. The cluttered and unstructured nature of construction environments limits robot mobility, communications and map building. In addition, various ambient conditions, for instance working under adverse weather conditions including variations in humidity and temperature or the existence dust and dirt, will affect robot performance. Therefore, automated construction needs more development to be exploited as fully as possible.

*2) Multi-robot systems(MRS) :* MRS is relatively a new field focused on control of and collaboration between robots which can either be homogeneous or heterogeneous. In fact, the remarkable characteristic of the MRS is the ability for robots to work with one another to reach a common goal. Robots can have similar or different tasks depending on their roles and environmental conditions. Several works have presented MRS which take their inspiration from social insect behaviors like bees, ants, schools of fish or flocks of birds [31]. MRS have some advantages like parallelism, robustness, scalability, fault tolerance and low-cost operation compared to a single robot [32]. They also have very high potential in solving complex tasks which a single robot cannot accomplish individually. Main issues include communication (implicit communication and explicit communication), control approach (centralized and distributed), mapping and localization, object manipulation, motion coordination and task allocation. Moreover, there are many studies in MRS in various topics, for instance, aggregation, chain formation, self-assembly, box-pushing, foraging, collection, exploration and construction. In fact, construction is a complex task that requires the combination of several collective behaviors, such as object clustering and material assembling, collective transport of material, and collective decision-making to allocate the robots to the different sub-tasks of the construction process [33].

Some construction-related studies do not have the goal of building any specific target structure and they apply minimal sensory systems without any awareness about other teammates. Parker and Zhang [34] presented a swarm construction algorithm to control robotic bulldozers in the creation of a clear region in a field of gravel (nest). Robots used a technique known as blind bulldozing which has been inspired form of the ant nest building strategy. These robots use minimal sensory and mechanical constraints imposed by the algorithm. They clear away debris in order to build their circular nest.

Some research presented the construction of specific structures which shape is fully pre-specified and requested by a user, who provides only a high-level description. Werfel [35] proposed, and demonstrated in simulation, a method by which robots are able to build two-dimensional structures of desired shapes by blocks. A robot acts as a stationary beacon and leader. Many robots take on the role of a corner. Other robots then build linear or curved walls between the corners. The leader also provides information about the building of this structure. In another research, Werfel et al. [26] presented 3D collective construction in which large numbers of autonomous robots build large-scale structures. Robots are independently controlled, and coordinate their actions implicitly through manipulation of a shared environment.

Some research explicitly took inspiration from biological concepts like stigmergy. Werfel and Nagpal [36] presented algorithms by which robots build user-specified structures without human intervention. Robots apply stigmergy concept and independently deploy to collect square blocks. In the another work [37], they presented algorithms for adaptive structures. The shape of the final structure can be defined by environmental elements. For instance, a team of robots may be tasked to build a protective barrier of a given thickness around a hazardous chemical spill. In contrast, some construction algorithms use a external guider. Melhuish et al. [38] reports simple wall building by groups of robots inspired by nest construction behaviors in ants. Two templates were used by the robots to build their wall. In other cases, where building a particular structure with centralized system is the goal, a team of quad-rotors assembled structures from simple structural nodes and members equipped with magnets [15].

A few pieces of research have presented interaction between robots. In [30], two heterogeneous robots coordinate together to place a rigid component into a fixed structure. The idea is to use force-torque sensing in order to provide indirect feedback. The amount and direction of these forces and torques provide information about relative position of the team-mate. In another study, the scenario was the construction of a square frame using four beams and four connectors with a team of heterogeneous robots. This team consisted of robots: roving eye (a mobile robotic base with a stereo camera pair mounted on a pan-tilt unit), a mobile manipulator, and a crane [39]. In summary, researchers have tried to take advantage of multi-robot systems but complexity has limited to studying simple scenarios.

## III. CHALLENGES AND CONCLUSIONS

### A. Challenges

1) Autonomous construction requires robots to make decisions in reaction to rich sensory input. These decision are made challenging by the unstructured nature of construction environments coupled with the unpredictability of physical interactions with construction material. Much of the work into autonomous construction sidesteps this challenge, either by giving up on construction precision or by imposing unrealistically-pristine structure on the environment. In order for robots to be eventually used in fully automated construction sites, there is a need to adopt more sophisticated decision-making techniques that treat autonomous construction with the richness that it deserves. In particular, there is an absence of construction planning methods that model uncertainty in robots' actions, and of reasoning methods that clarify complex construction situations.

2) Existing construction processes need precise positioning, which can be achieved by machines that have a fixed mechanical link with the construction and therefore rely on absolute positioning. Mobile robots, by nature, do not have a fixed referential point, and their positioning systems are not as accurate as fixed-base robots. Therefore, they need to employ external tracking systems (e.g., camera, GPS) or short-range relative localization. The precision of the current self-positioning system of mobile robots is not sufficient to support construction processes, therefore, mobile robots have to employ new technologies to progress in this domain.

3) As we discussed in II-C for the ground robots and flying robots, each robotic platform has its own restrictions which confine the functionality and versatility of an autonomous robot. Physical characteristics of a robot may not allow it to handle a complete construction process. Depending on the shape, type, and size of a structure or environment, we need specific robotic behaviors which may not be handled by an autonomous mobile robot at all. Therefore, we need either to improve the versatility of construction robots or to use a group of heterogeneous mobile robots to handle several situations.

4) For realistic automated construction, robots must be able to work in an unstructured and cluttered environment where there are many dynamic obstacles. Usually in a construction site, there may be laborers or other material transportation and building activities which change the environment configuration. Mobile robots should tackle the problem of dynamic environmental uncertainties. For a fully autonomous robot, it needs a powerful high-level planner to predict and recognize the situation and take correct decisions. Additionally, various ambient conditions, for instance working under adverse weather conditions including variations in humidity and temperature or existence dust and dirt on the site, will affect robot performance.

5) To the best of our knowledge, collaboration between autonomous mobile robots and human laborers in construction has never been studied. Although some research addresses the use of semi-autonomous robots for on-site construction, collaboration between laborers and autonomous mobile robots (even in the close proximity) could be a big challenge, especially in terms of safety.

6) In joining processes the robots are usually expected to align parts together and connect them by using bolts, welding, or assemble prefabricated components. The problem is that specifications for tolerances in the construction are not always achieved in practice. In

the real situation, laborers will possibly fix problems rather than wait for replacement components to be fabricated and delivered because most construction projects are under tight schedules [2]. In automated construction, the goal is to increase productivity, and waiting for new components will decrease speed of the construction. If robots are to, one day, replace human construction workers, new methods should be developed to tackle tolerance problem during construction.

7) Today, companies are designing and manufacturing prefabricated components to increase construction speed and efficiency. New prefabricated components could be designed and made for robotic use in automated construction. For example, components with male-female connectors allow for automatic assembly in a more robust way [2]. Additionally, adopting gripping mechanisms design to the component design would yield a more efficient and more precise automated construction.

8) Automated construction consists of sequential and repetitive tasks which can be executed through a group of robots but the area of MRS is still in its infancy to be used in real construction applications. For instance, the variety of construction tasks requires heterogeneous robots in cooperation to build a structure. In dealing with heterogeneity, determining how to design and optimally integrate a robot team working in a shared area with shared material is an ongoing challenge.

9) Additionally, sometimes, a construction process consists of a sequential tasks which should be performed by interaction between robots. Task failures can propagate from each step to another and robots should be able to tackle the failures caused from previous step. Therefore, The reliability of MRS amidst faulty interaction is another challenge. Although, other open research questions of MRS such as robustness, learning, scalability are not limited to the construction field, they are a relatively big challenge in many automated construction applications especially where different types of robots are used [40].
10) Automated construction inherited challenges from autonomous robots. For instance, dealing with uncertainty in sensing, reasoning, and acting are critical competencies impacting the robot performance.

### *B. Conclusions*

Construction automation has been progressing to improve the quality of construction and has a great potential to be applied where human presence is impossible, unsafe, or intensively expensive. One aspect of automation is the utilization of mobile robots in construction. In fact, construction presents a unique for robotic applications because the construction environment is cluttered, unstructured, and sometimes teaming with human workers. In this survey, we have presented four interesting axes of automated construction with mobile robots. Firstly, we clarify what kind of construction is considered because construction consists of wide range elementary processes. We carefully define autonomous construction based on what has been done in this field to help focus in on the promising areas of research as well as to categorize the applications of robotics to construction. We have described different materials types used by robots. Materials influence the design of robots and concerning algorithms because of materials properties. Additionally, some research was based on biological inspiration to mimic behaviors of animals. From a hardware point of the view, robots and related auxiliary systems were studied. Robots were categorized into ground robots and aerial robots. Auxiliary systems like external cameras have proven to help robots tackle uncertainty and to compensate inaccurate positioning. However, autonomous robots are still far from being employed in commercial construction. Construction performed by a group of robots is an interesting topic because it can take advantage of multi-robot systems, but their increased complexity has caused researchers to target only simple multi-robot construction scenarios or to treat robots independently to decrease complexity of multi-robot coordination.

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