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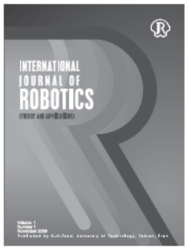

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Are Autonomous Mobile Robots Able to Take Over Construction? A Review

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ABSTRACT

Although construction has been known as a highly complex application field for autonomous robotic systems, recent advances in this field offer great hope for using robotic capabilities to develop automated construction. Today, space research agencies seek to build infrastructures without human intervention, and construction companies look to robots with the potential to improve construction quality, efficiency, and safety, not to mention flexibility in architectural design. However, unlike production robots used, for instance, in automotive industries, autonomous robots should be designed with special consideration for challenges such as the complexity of the cluttered and dynamic working space, human-robot interactions and inaccuracy in positioning due to the nature of mobile systems and the lack of affordable and precise self-positioning solutions. This paper briefly reviews state-of-the-art research into automated construction by autonomous mobile robots. We address and classify 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.

1. Introduction

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

Automation in construction is an interesting field that is focused on applying computer-controlled processes and mechanization concepts in this industry. In other words, it deals with applying the latest automation technologies to construction subdivisions, whether in civil engineering (building, dams, bridges, etc.), architecture or in prefabrication of construction components [3]. Construction automation has been

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progressing to prevent worker injuries, reduce the construction process duration, and be cost-effective. Apart from the mentioned aspects, robots could potentially perform construction tasks where human presence is impossible, undesirable, or unsafe. For instance, 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, construction in areas that are not readily accessible to humans, and construction where an initial structure is required to prepare a human habitat. In addition, advances in robotic systems and fabrication technologies have opened up new ways for architects to build sophisticated and elegant artifacts, as illustrated in Figure 1.

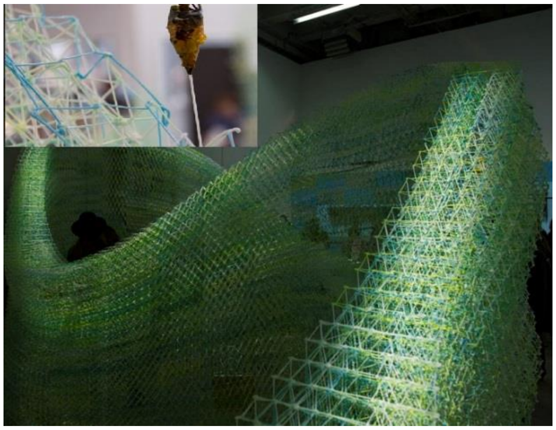

Figure 1. A spatial and multi-colored mesh was printed by robotic machines [4].

However, autonomous mobile robots for construction should be designed taking particular care with regard to some key challenges; for instance, construction requires precise positioning while mobile robots have no common frame of reference with the construction. Construction sites are also highly complex working spaces, where displacement and mechanical work requires a high dexterity. Moreover, one goal of automated construction is to prevent worker injuries; therefore, construction robots should ensure safe interactions with workers.

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, several general categories of construction robots were considered [2]: the first one consists of teleoperated systems, in which machines are under the remote control of humans; a human operator interprets the robot situations and applies his intelligence to solve the problem, transmitting orders that are transformed into actions by the robot. The second category, programmable construction machines, enable the human operator to do various tasks by choosing from among a list of preprogrammed functions or by teaching the machine a new function. The third category consists of intelligent systems: unmanned construction robots accomplish their tasks either in a semi- or fully-autonomous mode. In the fully autonomous mode, robots are expected to complete the tasks without human intervention within a specific domain. In contrast, in the semi-autonomous construction mode, a robot accomplishes its tasks with some level of planning made in interaction with a human supervisor.

In this paper, we limit construction automation research to the use of autonomous (or semi-autonomous) ***mobile*** robots. The framework of the review consists of three main categories: applications, materials used in construction, and robotic systems. In Section 2.1, we study the applications. Section 2.2 discusses the materials from various construction applications. Section 2.3 presents robots and robotics systems. Finally, in Section 3, we discuss challenges in construction with autonomous mobile robots and provide conclusions and future directions.

2. Research axes

2.1. 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 using large machinery and earthwork or house construction including building skeleton, erection and assembly, concrete compaction, and interior finishing [3]. Typically, a complete 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 construction 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 leading to artifacts (or environments) with specific shapes (e.g., cutting, machinery, liquid deposition, and digging)

Several robots were developed for automated handling and assembly during the last decades. The handling process would increase building efficiency of final structures composed of many big and monolithic parts. In this category, we can find 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 with a six DOF manipulator for a 3D structure made of bricks. In [6], flying robots built a brick-like tower by dropping blocks one by one. Wismer et al. [7] used robots to place cube blocks (cube with magnetic alignment/attachment) with different dimensions, creating 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 results in back injury. Therefore it is excellent candidate to be performed by robots [8]. The elementary processes of masonry such as bricklaying were performed in a study on the BRONCO robot [9].

Today, many companies employ robotic automation for onsite construction, but on very specific subtasks. 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 designed to work with the mason. The operator moves the base of SAM and it lifts and places each brick [11]. However, human-robot interaction is a challenging aspect, because the environment is unstructured and full of dynamic and heavy obstacles dangerous for a human being. The proximity and vulnerability of the human in the interaction imposes strict restrictions on human and robotic activities in a shared environment [12]. Because of these and other challenges, such as positioning, fully automated construction using mobile robots is not ready for commercial markets. Human workers are still, in most situations, more reliable, more efficient, and cheaper. For instance, an autonomous mobile robot will face many uncertainties and will have a hard time taking the proper decision when laying a straight wall in a site full of obstruction, as a mason does easily. Autonomous mobile robots still require additional development to get ready for fully automated commercial construction purposes.

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. These connection techniques are often not well adapted to automatization, pushing roboticists to redesign the connectors and joining mechanisms. In [13], aerial robots were used to construct a truss-like tower with magnetic nodes and bars. In [14], the robot moved autonomously and untethered through a truss structure to assemble and dissemble rods. KUKA MOIROS, which is a mobile industrial robot system, can be equipped with advanced manipulators to handle welding processes [15].

Another application is material shaping. This is one of the most interesting processes leading to ***digital fabrication***. The most known method of digital fabrication by material shaping is additive manufacturing, also called ***3D printing***. An exemplary application of additive manufacturing in construction is contour crafting, which is a concrete-based layered fabrication technology developed for building a large structure in a single run [16]. Advances in robotic systems applied to digital fabrication of large structures have opened new ways for architects to build elegant artifacts. ***Digital fabrication*** intends to fill the gaps between digital technologies and the physical construction process, because design restrictions can be relaxed allowing artifacts to be fabricated with high customization and sophistication [17]. In space applications, digital fabrication processes can be useful because space agencies could launch raw materials and reduce the transported volume. Volume, mass, and cost are significant factors in space systems to ensure successful missions, so decreasing size and mass is very important, particularly in space systems with large components, such as antennas or panels. SpiderFab is used to employ techniques of fused deposition modeling with methods derived from automated composite layup. SpiderFab will fabricate components on-orbit, enabling NASA to escape the volumetric limitations of launch [18].

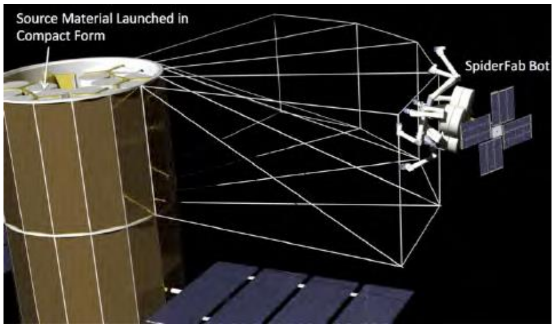

Figure 2. SpiderFab fabricates a support structure onto satellite [18].

Despite this rapid evolution in construction processes, most robotics systems used in digital fabrication are not mobile. Mobile robots inherently provide great flexibility for digital fabrication, because they can build artifacts that extend beyond fixed-based system constraints (e.g., size of a 3D printer's frame constraint) but require innovative solution for positioning. Jokic et al. [19] have used a compact and mobile head positioning device to build 3D shape structures by using amorphous material deposition with mobile heads. This method allows an object to be printed independently from its size. Rétornaz [20] developed a two-levels approach for precise positioning mixing of a long-range/low-precision localization with a short-range/high-precision positioning that is based on shared referential with the construction. With this approach, he designed a special extruder mounted on a miniature mobile robot to deposit raw material on rough surfaces or create free-standing structures. In the near future, mobile robots may be used in construction like we use commercial 3D printers. The company MX3D, for instance, plans to fabricate a steel bridge based on additive manufacturing, as illustrated in Figure 3. In this project, robots will be targeted to print a bridge by welding molten metal to an existing structure while they move on what they built. For instance, two teams of robots will start building a bridge from opposite sides of a canal to meet together at the middle [21]. In contrast, Napp and Nagpal [22] designed a mobile robot that is equipped with a foam tube to deposit foam for creating a ramp for inaccurate construction. The long-term goal of this application is to enable robots to perform a construction processes in emergency situations to make a way (e.g., filling a ditch to cross it).

Figure 3. Robots are going to autonomously create a steel bridge [21] .

2.2. Materials

For autonomous robotic construction, material properties need to be taken into account because the type of the material can determine what kind of robot is needed to perform the construction process. Diversity of material based on the expected goal motivates the unique design of a robot and the related algorithms; additionally, factors such as shape and application of the structure, construction precision, construction speed, and simplicity of the construction, and amount of required material or cost can heavily impact on the robot structure.

The nature of social animals provides impressive construction instances; ant workers dig earth to make their nest; termites build mound structures with paste made out of water, sand and clay and deposit the mud stuff while wet; and some birds construct nest structures from small twigs and grasses without the help of binders. However, human structures usually are more complex and need a combination of materials, while simple materials are used in most of the research on robotic construction.

Figure 44 shows a possible taxonomy for the 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 a 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 structures enable the robot to build faster structures according to a blue-print.

Three types of materials for amorphous construction were investigated regardless of robotic activities in [23]: stiff pre-fabricated components and adhesives (toothpicks and glue), compliant pre-fabricated components (sandbags), and liquid depositions (casting foams). The 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 than sandbags. Soleymani et al. [24] addressed the use of deformable pockets (compliant bags) to construct a protective linear wall. The properties of compliant bags have allowed the use of a simple mechanism and simple controller to deposit them, but the wall is not really linear. Napp and Nagpal [22, 25] presented a model of construction to build an arbitrary shape with casting foams in unstructured environments. In [26], a mobile robot fills a ditch by two types of polyurethane foam: one- and two-components polyurethane foam. One-component foam needs 1 hour to cure and is expandable in a horizontal direction. In contrast, two-component foam cured within 2 minutes and is expandable in vertical direction. These different properties pushed the researchers to implement two different construction algorithms. The result has shown that two-component foam seems to be a more efficient material for construction purposes.

Autonomous construction is also a complex process in which many failures can occur. These failures can propagate from one step to another: for instance, if a robot incorrectly grasps a 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 [27]. In [7], foam bricks with several magnetic pins on the adjacent faces' bricks were used to build a roofed structure. Terada and Murata [28] presented a particular robotic assembler that autonomously 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, one can build several layers on top of each other to build a tower. In [13], 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 [29], they reduced the number of magnets and the mass of the parts because the truss was constructed by aerial robots. In [14], the novel bidirectional geared rods and connectors have been used to build a truss structure with female bidirectional and a male bidirectional connectors.

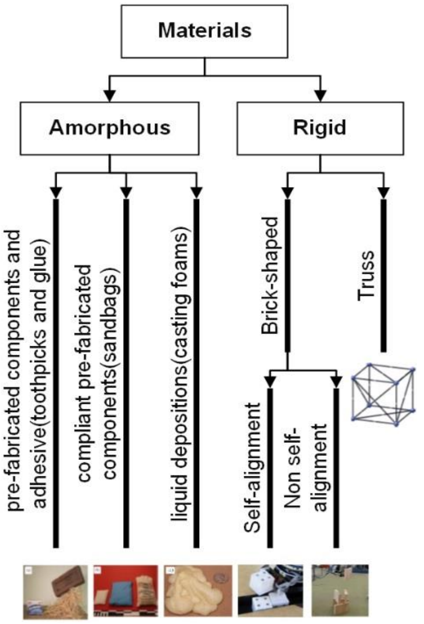

Figure 4. Taxonomy of materials used in automated construction.

For parts that do not have self-alignment mechanisms, advanced robotic systems are needed to meet the requirements of construction automation. In [14], 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 pick up and then drop the blocks. Helm et al. [5] presented dimRob equipped with ABB manipulator. A 3D laser scanner scans the placed wooden bricks during fabrication and then sends this mapped measurement to the controller software to obtain next commands. These examples show how the use of parts without self-alignment require more accurate positioning solutions.

Research on the use of amorphous materials targets mainly digital fabrication, either considering continuous deposition or removal. Gershenfeld et al. [30] have addressed the implications of this kind of material in digital fabrication. In addition to continuous deposition techniques, one can use digital materials that are composed of many discrete and self-aligning voxels that can be placed in specific locations within a lattice structure. Digital materials can open new doors for the automated and coherent fabrications where functionality is integrated with the form [31].

2.3. Robotic systems

Generally speaking, robots have been progressing toward autonomous operation, independently from human controls, requiring a more advanced control to tackle more complex issues such as uncertainty and unpredictable situations. Construction sites are highly complex and dynamic working spaces, very far from the highly predictable factory environment found in car industries. On the other hand, robots can be powerful and precise systems that reduce cost, operation time, and increase efficiency. Moreover, robotic systems can be extremely flexible. In the field of construction, architects can, for instance, use these features to build fascinating and elegant artifacts, as illustrated in Figure 1. At present, although most autonomous construction mobile robots are at an experimental stage and far from commercialization, promising developments in the robotic field are addressing the challenges and technical limits that robots are facing in complex working spaces. In this section, we briefly survey robots that have been used in the construction field and discuss challenges in their sub systems.

Robotic platforms

In this field, robots are typically divided into ground robots and aerial robots. To our knowledge, there are no underwater robots for construction. Aerial robots such as quad-rotors, which are a branch of unmanned autonomous vehicles fields (UAVs), have been developed by a considerable number of research groups. Construction systems benefit from their latest achievements by performing complex construction autonomously. As accurate positioning is necessary in construction, where external localization system is employed to provide high-accuracy flight for construction tasks. Aerial robots fly to the construction point and place bricks directly in the required position without scaffolding. Structures can also be built according to highly complex designs because the aerial robots move in the 3D space, and therefore, they can place and manipulate material according to a precise digital blueprint. On the other hand, at the moment, most aerial robots have limited payload capabilities but several aerial robots can grasp and carry a heavy object in cooperation [31]. Another limitation concerns the aerodynamic considerations because the shape of the construction parts can affect the performance of control and stability, construction parts must be designed such that they satisfy the aerodynamic constraint. In addition, control of aerial robots with significant disturbances (e.g., gust, variability in the parts) is not an easy task [32]. At ETH Zurich, four quad-rotors were exploited to construct a brick-like tower. The positioning of the robots was ensured by a real-time camera system guiding the robots according to a digital design, allowing the robot pickup and deposit of objects [6]. The robot is a hummingbird quad-rotor that is approximately 55 cm in diameter, weighs approximately 500 g with the battery and provides 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. A higher level was needed to perform the assembly task with multiple quad-rotors in coordination [13].

In contrast to aerial robots, ground robots are more stable and controllable. In addition, they can carry heavier and more complex objects in terms of shape, although they hardly access each point of the construction space without a scaffold or additional tools like a manipulator. Magnenat et al. [33] used the marXbot robot to grasp ferromagnetic self-aligning blocks. They employed odometry, camera, and laser distance data to perform SLAM and employed the front camera and proximity sensors to provide the required information for picking and dropping blocks. An extension to this work was used to build a roofed structure. In this task, they used a VICON system to estimate the position of marXbot [7]. Stroupe et al. [34] presented construction by two robotic platforms: SRR and SRR2K in an outdoor environment. Each rover is equipped with a forward-facing stereo camera and a four DOF arm. A 3-axis force-torque sensor on the gripper helps the rover to perform manipulation for transporting and placing rods. They used a model that is precise for manipulator positioning but may be inaccurate for world coordinates. Authors in [5] presented dimRob, which has a mobile base and is equipped with a manipulator [i]. It has a 2D line scanner on the 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. Jung et al. [35] employed humanoid robots for floor tiling to avoid back injury and overall injuries in the construction industry. They hope that the use of this system becomes feasible within the next five years at small locations where this operation is too time consuming for a human worker.

Moreover, this kind of research is rarely performed in unstructured environments, where many dynamic obstacles are encountered when building an accurate structure. The cluttered and unstructured nature of construction environments limits robot mobility, manipulation, and map building. In addition, various ambient conditions, such as working under adverse weather conditions including variations in humidity and temperature or dirt and dust, will affect robot performance. Therefore, automated construction needs more development to be exploited to its best potential.

Positioning systems

Construction processes almost need precise positioning systems, especially where a structure has to be built based on a blueprint. Currently, the accuracy of positioning technologies ranges from meter to sub-millimeter precision. Depending on situations and hardware limitations, good accuracy might not always be achievable. Research shows that the required accuracy for traditional construction can be easily achieved by machines that have a fixed mechanical link with the construction and therefore rely on absolute positioning (e.g., contour crafting). In contrast, 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 to compensate for this shortage. The GNSS [ii] could be used for outdoor construction but its precision is not sufficient for some construction activities like bricklaying. In addition, this system does not work for indoor space, and robots might use their own localization systems. Proprioceptive systems such as odometry, as well as IMU systems, have accumulated and drift errors, so they are not reliable. Exteroceptive systems such as laser range finders and cameras could be helpful. In [36], a mobile robot was equipped with a manipulator, which had a laser range finder. The robot sweeps its arm to create a 3D map of its surrounding. Then, the robot finds its location by comparing this map with an initial scan of the environment. Moreover, by updating a map based on the CAD model of the structure, the robot is able to make adaptions during construction. Elapsed time is one challenge encountered by this method as the robot needs much more time to build a small brick wall. A similar robot, dimRob, has already done construction of a wall brick. The robot moves and localizes 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. In fact, dimRob should be anchored to the ground, which prevents the robot from moving many times during construction. It should be also repositioned manually in each step [5]. In [20], Rétornaz uses a two-steps methods, depositing part of the material in the first step, measuring the positioning of this first deposition to recalibrate the whole system and perform the final deposition with high precision. Ardiny et al. [37] 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 short localization system to build coherent artifacts.

External cameras like motion capture systems provide the precise position of the objects. As we mentioned, some studies used this system to localize robots [6,7,13]. Additionally, inaccurate external system such as GPS can be used for some construction activities. In [38], an autonomous excavator equipped with a GPS receiver and IMU was targeted to shape the complete construction site by mobile excavation. To achieve this task, in addition to the position system, it needs a path planning algorithm that is an extended A* path planning algorithm. Nevertheless, the precise self-positioning system is still generally a challenge for autonomous mobile construction systems. If robots would have better self-positioning systems, they could build sophisticated artifacts as well as 3D printers but without the printer size constraint [20].

Bio-inspired or engineering approach?

You might see fascinating structures built by animals which seems to be talented architects. More than the artistic aspects, animals consider functional features such as ventilation, temperature regulation, multiple escape routes and structural strength. For instance, a study on termite mounds shows that their nest construction process is influenced by thermoregulation and gas exchange properties of the nest itself, generating different mound architectures [39]. Nests may be built by individuals or by social animals working together based on specialized roles. Construction activities by social insects show how a complex structure can emerge from actions of many independent workers using simple rules and local information, even if there is no experimental data to prove that something like mental blueprints are used by a single insect [35, 36]. One idea is that animals use a mental image, but researchers believe also in another totally opposite approach, with animals building a structures based on local interactions [42]. Werfel et al. [27] presented a ground mobile robot (TERMES) to perform automated construction inspired by the building activities of termites. The robots climb to build a structure using passive solid building blocks as landmarks for local interactions. The goal of this research is to use insect principles to build a user-defined structure for human purposes. An offline compiler generates traffic rules depending upon a user-defined blueprint and then robots have to follow these during construction. Soleymani et al. [24] used two biological mechanisms, stigmergy [iii] and templates [iv], to guide a robot. The robot has to deposit sandbags to build a protective wall without relying on a central planner, an external computer, or a motion capture system. The interactive system is another approach in which agents not only use environmental feedback but also two-way dynamic feedback with the environment. This means that agents change the environment while simultaneously the environment impacts the ongoing actions, generating a two-ways feedback loop to construct structures based on functional blueprints [43].

Figure 5. (A) A termite mound (B) Robots try to construct complex structures based on bio-inspired methods [27].

Indeed, bio-inspired construction principles and human architecture have fundamentally different approaches. Humans build structures based on a blueprint, and the construction processes are centrally driven by the plan. To follow this approach, robots must have a global representation of the environment to be able to build a structure based on pre-specified blueprints; again, this approach needs many more computations in respect to bio-inspired ones. In contrast, in bio-inspired construction, agents perform tasks in a decentralized, self-organized manner. Bio-inspired approaches are elegant because simple mobile robots are able to run the automated construction by following compiled rules and performing reactive algorithms. Each individual acts independently, and interaction among them and interaction of each agent with the environment ensures an automated construction without a conventional blueprint. Compared to engineering strategies, the bio-inspired approach can be more robust to failure because of its decentralized methods, which can be very flexible and even include self-repair mechanisms.

Multi-robot systems (MRS)

MRS are relatively new fields focused on control of and collaboration between robots, which can either be homogeneous or heterogeneous. In fact, the remarkable characteristic of 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 research works have studied MRS, taking their inspiration from social animal like bees, ants, fish, or birds [44]. MRS have some advantages like parallelism, robustness, scalability, fault tolerance, and low-cost operation compared to a single robot [45]. They also have very high potential in solving complex tasks that a single robot cannot accomplish individually. Most studies address communication (implicit communication and explicit communication), control approach (centralized and distributed), mapping and localization, object manipulation, motion coordination, and task allocation. There are studies on several behaviors related to construction, such as aggregation, chain formation, self-assembly, box-pushing, foraging, collection, and exploration. In fact, construction is a complex task that requires a 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 [46].

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 team-mates. Parker and Zhang [47] 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 the ant nest building strategy. These robots use minimal sensory and mechanical resources required by the algorithm. They clear away debris in order to build their circular nest.

Some research presented the construction of specific structures whose shape is fully pre-specified and requested by a user, who provides only a high-level description. Werfel [48] 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 process of this structure. In another study, Werfel et al. [49] presented 3D collective construction in which large numbers of autonomous robots built 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 [50] presented algorithms by which robots build user-specified structures without human intervention. Robots apply the stigmergy concept and are independently deployed to collect square blocks. In the another work [51], they presented algorithms for the adaptive construction of 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 an external guide. Melhuish et al. [52] 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 a centralized system is the goal, a team of quad-rotors assembled structures from simple structural nodes and bars equipped with magnets [13].

A few pieces of research have presented interactions between robots. In [34], two heterogeneous robots coordinate 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 the 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 [53]. In summary, researchers have tried to take advantage of multi-robot systems, but the complexity of tasks has limited studies to simple scenarios.

3. Challenges and conclusions

3.1. Challenges

I. Autonomous construction requires robots to make decisions in reaction to rich sensory input. These decisions are made by challenging 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 configurations 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.

II. 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 because of the common reference frame with the construction artifact. 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.

III. 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.

IV. As we discussed, for ground robots and flying robots, each robotic platform has its own restrictions that 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 that may not be handled by an autonomous mobile robot at all. Therefore, we need either to improve the versatility of construction robots, or use a group of heterogeneous mobile robots to handle several situations, or rely on human-robot cooperation.

V. 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 workers or other material transportation and building activities which change the environment constantly. Mobile robots should tackle the problem of dynamic environmental uncertainties. For a fully autonomous robot, there is a need for a powerful high-level planner that predicts and recognizes the situation and takes 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 the robot performance.

VI. To the best of our knowledge, collaboration between autonomous mobile robots and human workers in construction has never been studied. Although some studies address 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.

VII. In joining processes, the robots are usually expected to align parts together and connect them by using bolts, welding, or assembling prefabricated components. The problem is that specifications for tolerances in the construction are not always achieved in practice, resulting in assembly failures. In the real situation, human workers 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 the speed of the construction. If robots are to, one day, replace human construction workers, new methods should be developed to tackle the tolerance problem during construction.

VIII. 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.

IX. Automated construction consists of sequential and repetitive tasks which can be executed by a group of robots, but the field of MRS is still too immature to be used in real construction applications. For instance, the variety of construction tasks would require heterogeneous robots working together to build a structure. Dealing with heterogeneity, and determining how to design and optimally integrate a robot team working in a shared area with shared material is an ongoing research challenge.

X. When a construction process consists of a sequence of tasks that should be performed by robots, task failures can emerge from one step to another, requiring from robots the ability to address the failures caused from previous steps. Therefore, the reliability of robotic systems amidst faulty interaction is another challenge. Although, other open research questions of robotic construction systems such as robustness, learning, and scalability are not limited to the construction field, they are a relatively big challenge in many automated applications, especially where different types of robots are used.

XI. Automated construction inherited others challenges from autonomous robots. For instance, dealing with uncertainty in sensing, reasoning, and acting are critical competencies impacting the robot performance.

3.2. 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. Among the several possible approaches, autonomous mobile robotics seems to have great potential but also presents many challenges. In fact, construction presents very hard conditions for robotic applications because the environment is particularly cluttered, unstructured, and requires collaboration with human workers.

In this survey, we presented the existing research on automated construction with mobile robots under different perspectives. Firstly, we clarified what kind of construction is considered because construction consists of wide range elementary processes. We carefully defined autonomous construction based on what has been done in this field to help focus on the promising areas of research as well as to categorize the applications of robotics dealing with construction operations. We described the different material types used by robots. Materials influence the design of robots and the construction algorithms because of the materials' properties. Additionally, we looked at some bio-inspired research aiming to mimic construction behaviors of animals. We also looked at robots and related auxiliary systems from a hardware point of the view. In particular we studied ground robots and aerial robots. Auxiliary systems like external cameras have proven to help robots tackle uncertainty and positioning.

However, autonomous robots are still far from being employed in commercial construction. Construction performed by a group of robots seems to be the ultimate goal in the field as this system could take advantage of the distributed heterogeneous approach, but the complexity of the whole task and system has pushed researchers to target only simple multi-robot construction scenarios or to treat robots independently to decrease complexity.

Despite the negative answer to the original question: "***Are autonomous mobile robots able to take over construction?***" there is still a dream to be able, in the future, to reach a technological level that allows ones to drop off robots and come back several months later to see a huge and fantastic building. Although this is quite far from current robotic capabilities, it is clear that research is progressing across this highly interdisciplinary field, trying to provide solutions to the demand for robots to be used in construction.

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Notes

i. ABB IRB 4600

ii. Global Navigation Satellite System

iii. Stigmergy is indirect communication through the environment by which agents can work in coordination.

iv. Templates are heterogeneities of the environment that may influence agent behaviors if the agent is able to detect it (e.g., a temperature gradient) [24].

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Biography

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