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Ground-based automated construction of droxel structures: An experimental approach

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ABSTRACT

This manuscript presents a recently developed automated robotic system for the deployment of block-based structures. The main structural component used for the construction of the specimens is the droxel: a universal building component recently developed by the authors. The herein presented work builds on such research to create new software and hardware capabilities to deploy droxel-based structures autonomously, by means of ground robotic operations. First, the paper describes the designed mechanical components and the experimental setup. Then, the main features of the ad-hoc designed software tools will be presented, together with the salient results of the experimental campaign. Different experiments on various types of structures (e.g., shelters and bridges) constructed by means of an ABB IRB120 robotic arm will be presented and quantification of the efficiency of the operations will be discussed. Quantitative description of the stability of the structures under construction, as well as capability of deploying full scale versions of different structural system is then discussed and conclusions and recommendations drawn.

1. Introduction

Research in automation in construction has experienced a dramatic increase over the last decades, due to scientific and technical advancements in different fields (e.g., mechanical and electronic engineering, computational modeling and hybrid digital-twin control of casting procedures, computer vision, robotics), making it an appealing possibility for the safe deployment of different types of structural archetypes at different scales [1,2]. The need for increased efficiency of construction operations is testified by the fact that workers still use paper plans and drawings, which increase the possibility of construction errors, general lack of quality and poor efficiency. In 2014, a survey from the ADEB (Association des Entrepreneurs Belges de grands travaux) showed that, on construction sites, the lack of knowledge, communication, (automated) control and rigor is usually responsible for 5 to 13% of the total cost of a building. Performing construction works with robots in fully or semi-automated fashion can allow for better construction management as far as the construction process can be directly linked to BIM models [3], also leveraging ever-growing capabilities granted by the adoption of parametric design procedures and digital twins [4]. Linking digital models directly to robots (see Fig. 1) can bring many benefits to construction projects, such as the reduction in construction time, lower total green-house gas emissions [5], reduction in construction defects, lower impact of human factors and errors, the reduction (or abolition) of paper plans and heavy manual work (with consequent increase in health and safety), and greater profitability. In this context, the universal building blocks object of this work, the droxels, satisfy two criteria that often limit the range of applicability and scalability of robotic applications: (1) the laying tolerance and (2) the weight of the construction components.

1.1. Literature review

The first mature attempts at developing automated construction operations were presented in the late 1990s, the most notable examples being the ROCCO project (Robot Construction System for Computer Integrated Construction) [6,7] and FAMOS BRICK (Highly Flexible Automated and Integrated Brick Laying System) [8]. All the precursor applications of automated bricklaying were mostly oriented towards the design of robotic arms capable of deploying masonry structures safely and efficiently, even though they often required the presence of an operator to function [9,10]. More recently, novel applications for

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automated construction have been proposed for in-space construction [11]. As a result of the vast technological advancements in robotics and computer vision, current attempts at automating on-site operations can be generally subdivided in three main groups: structural additive manufacturing, ground mobile robots and aerial robots [12].

The additive manufacturing of cementitious composites is a revolutionary concept for architects and engineers, as it opens up tremendous possibilities in the architectural and structural features that can be materialized [13–15]. The general framework for this type of applications is to upscale the disruptive advancements in digital fabrication and 3D printing to the level of common small-to-medium sized building. In order to materialize such structures, specific concrete mixtures are required to guarantee the proper intra-layer adhesion and workability throughout the additive manufacturing process [16]. One of the main drawbacks lies in the size of the required equipment, which is often several times bigger than the final built object. Large-scale monolithic 3D printing of fresh concrete is currently being investigated by many different research groups. The available works can be roughly subdivided in: (1) "structural" approaches, where the feasibility of deploying full-scale structural components and assembly by means of large scale printers is investigated [17,18], (2) "material" approaches, where the focus lies within the evaluation of the rheological properties and mechanical behavior of the constituent materials, with particular emphasis on increasing the performance of the built objects [19,20] or the efficiency of the casting process [21]. An intermediate approach between additive manufacturing and automated brick laying was taken with the SPIDER Robot project [22], in which a cable-suspended robot was constructed to perform automated construction operations. Even though the navigation system of the robot resembles 3D printing operations, the project aimed at building structures by bricklaying rather than deposition of raw materials.

The field of ground-based automated construction is arguably the one that is currently showcasing the biggest number of large-scale solutions. Bao and Li [23] investigated the potential of adopting flexible and bendable cementitious composites in the autonomous deployment of lego-like structures. Several recent industrial applications for ground-based operations can be found in literature, mostly focusing on deploying large-scale robotic systems for the automation of the laying procedure for different types of bricks and blocks. Bricklaying operations are, in fact, labor-intensive and repetitive tasks requiring a high degree of accuracy, therefore they are well-suited applications for automation. These approaches generally rely on the use of serial robot manipulator (i.e., arm-like actuators) designs and suffer from their inherent disadvantages. Notable examples are the SAM robots (United States) and Hadrien X (Australia), which are currently paving the way towards the application of automated bricklaying. Both these systems present advantages and disadvantages when compared to the additive manufacturing examples. The advantages consist of the relatively smaller size of the robotic actuators and the higher degree of autonomy in the full-scale casting process. Disadvantages relate to problems in the use of large end-off actuators, as well as the difficulties linked to the deployment of inter-brick mortar layers at large scales.

The third group regards autonomous aerial-based operations. At this time, this group comprises few examples of full-scale construction, seen the current technological limitations in deploying heavy-payload Unmanned Aerial Vehicles (UAVs) [24–26]. Advancements in near-earth flight [27], navigation systems [28] and the so-called Mobile Manipulating UAVs [29] in recent years have opened new possibilities for the deployment of swarms of drones to assemble and interact with built objects in different ways [30]. Aside from some pioneering work [31,12], however, this field remains largely unexplored at present.

Regardless of the specific automation approach chosen, the practicability of Single-Task Construction Robots (STCRs) for use in construction sites has become a reality in recent years, as a result of rapid advancements in the fields of computing and mechatronics. Notable examples in literature are represented by the work of Linner et al. [32] and Pan et al. [33], who developed an agile and flexible technology management system to deploy fit-for-purpose STCR robots based on inter-relations between engineering requirements, development, implementation and performance evaluation. The proposed technology management system was applied to multiple projects with satisfactory results.

1.2. Research plan and methodology

The research presented herein employs ground-based robotic operations in a controlled laboratory environment to create a scaled prototype of an autonomous terrestrial construction system. The novelty lies in the application of a special construction block, the droxel (portmanteau word derived from "drones" and "voxel"), which can dramatically increase the efficiency and quality of the process [12,34], by increasing the laying tolerance of each piece, while simultaneously granting greater structural stability without the need for mortar or fasteners [31]. This innovative construction component can be employed to materialize a wide range of structural systems (see Fig. 2), thanks to a parametric geometric design that is fully characterized by the 8 parameters reported in Fig. 3.

This work builds on an international research program, leveraging the expertise of the research group in the deployment of droxel-based structures by means of autonomous operations. Previous works by the authors have focused on the evaluation of stability of droxel-based structures and the definition of safe structural deployment techniques for aerial-based operations [12,31]. In the context of aerial operations, a large laying tolerance is required, since several factors such as wind and the guiding system do not always allow a perfect flight stabilization (see Fig. 4). Experimental tests were also carried out with 3D printed and concrete droxels (see Fig. 5). Outside of the general context of automated construction, droxels also offer a wide array of DIY and emergency management applications. Ongoing research also includes aspects related to the mechanical and geometrical characteristics of droxels and the search for the best combination of the eight parameters required to define their geometry. Finally, an ongoing research project concerns the calculation of droxel structures (in terms of stability, forces and stresses) and the search for stable laying sequences.

The present work stems from our belief that droxels can be efficiently employed in ground-based robotic operations. Aerial operations, in fact, bring interesting advantages with respect to terrestrial methods (particularly the capability of deploying the droxels on hard-to-reach areas), but are also accompanied by several layers of technical challenges (e.g., the resolution of the flight path in real-time for the accurate

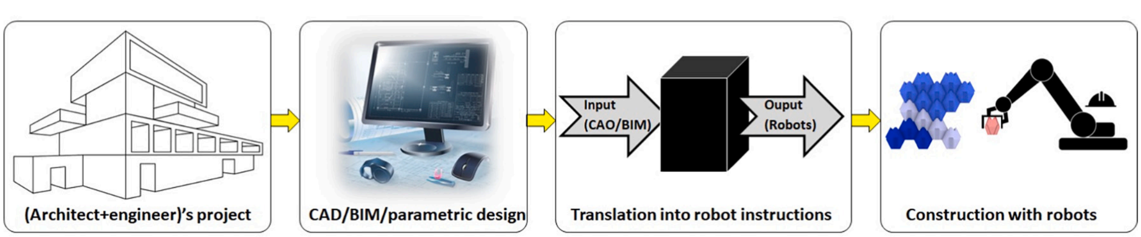

Fig. 1. Idealized workflow for the data exchange between BIM models and robotic construction components. No paper plans are produced in the process.

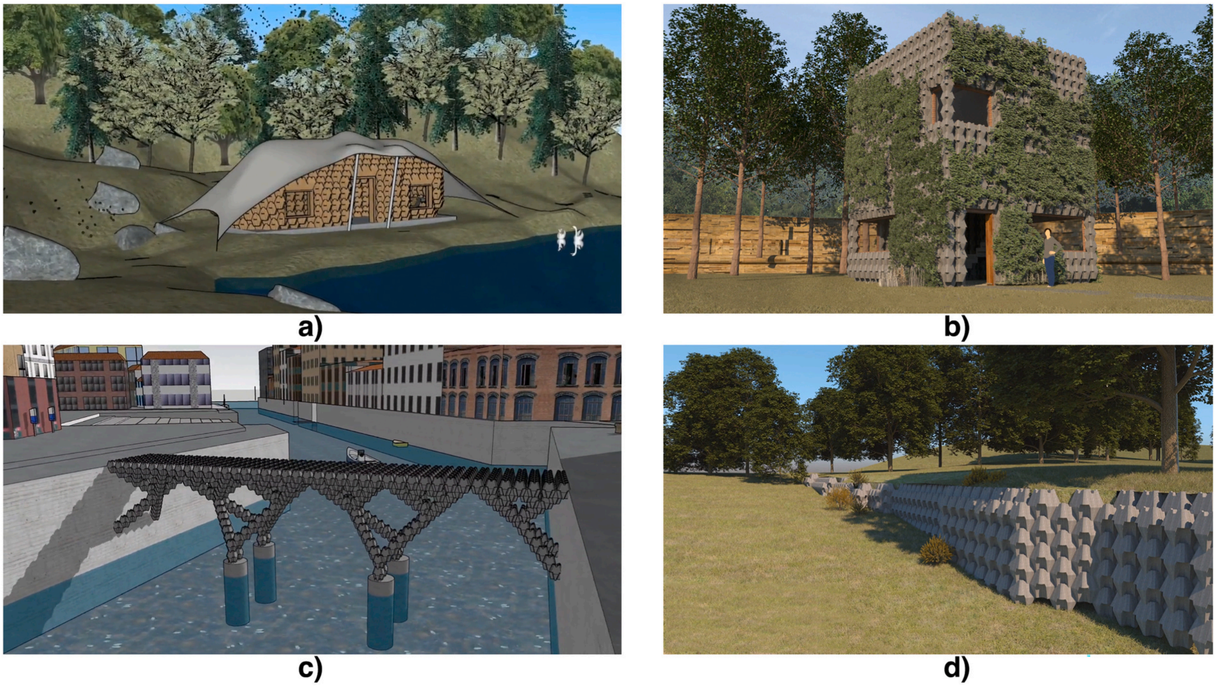

Fig. 2. Prototypical droxel structures: (a) timber droxel shelter, (b) concrete droxels multi-story house, (c) concrete droxel footbridge, (d) plastic or concrete droxel retaining wall.

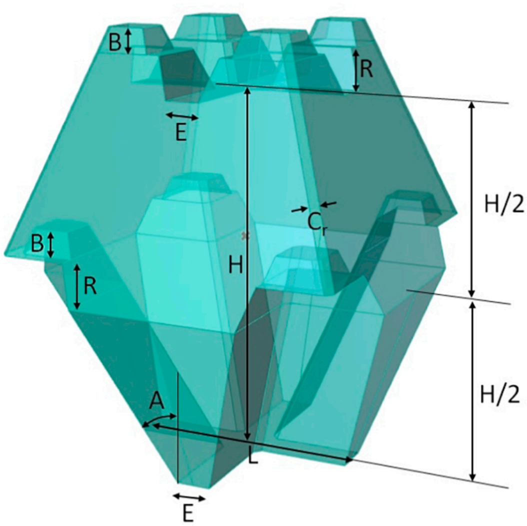

Fig. 3. Three-dimensional model of a droxel and definition of the parameters governing its geometry.

placement of the droxels, safety and efficiency of structural deployment). Also, we envision terrestrial robotic deployment of droxels to open up new interesting possibilities in the context of multi-mode automated construction operations, in which ground units can efficiently collaborate with aerial unmanned vehicles. In recent years, in fact, swarm robotics and corresponding decentralized control approaches were developed by several research groups. A thorough comprehensive review was recently published on the topic [35], which the interested reader is referred to. The focus of swarm robotics developments lies with the modularity of the robots and standardized building structures, and mobility of the swarm units during the assembly of the building structures. The concepts of these robots were proven to be successful in miniaturized models and they are currently object of further development for full-scale deployment.

For all of the aforementioned reasons, and in order to evaluate the capabilities and efficiency of ground-based automated droxel construction, a small-scale prototyping environment has been developed at the University of Waikato, where two different types of traditional structures (namely shelters and bridges) have been testedto define and validate a robotic toolchain to perform automated construction of droxel assemblies. The experimental campaignis used to assess performance and capabilities of available robotic solutions, and requirements for the software interfaces for the correct data management and exchange between a given 3-D model of a structural design, the "droxelization" procedure (depicted in Fig. 6) and the subsequent machine operations to

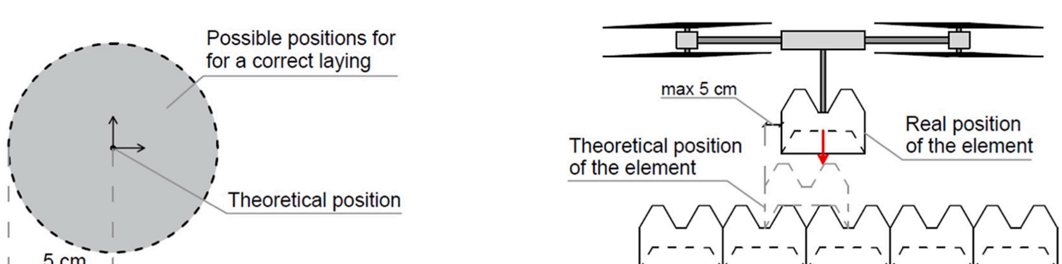

Fig. 4. Spatial laying tolerance allowed for the placement of UAV-compatible elements.

Fig. 5. On the left, small-scale tests on FDM 3D printed droxels. On the right, a 15 kg concrete droxel, under one of its possible geometrical forms.

be performed. We devoted particular attention to the selection of the robotic arm to be used, with specific reference to the required positional accuracy. The proposed 1:5 scaled system uses an ABB IRB120 robotic arm, placed at the center of the construction site (see Fig. 7). The arm, which has full reach in the entire portion enclosed by safety walls, was equipped with an ad-hoc 3D printed mechanical actuator and a vacuum pump for the correct acquisition and deployment of the building blocks. Different types of droxels, having different weights, are hosted on two different foundation plates (the NE and NW plates respectively, see Fig. 7) while the South plate is intended to host the constructed objects. This work also represents the first attempt at producing droxel-based structure with blocks of different weights to maximize stability of the assembly throughout the construction phase.

The remainder of the document is organized as follows: a description of droxels and their capability of materializing different structural shapes will be given first. Based on this information, the novel features of the terrestrial automated construction procedures object of the experimental campaign will be given, followed by salient results, open challenges and paths for further research.

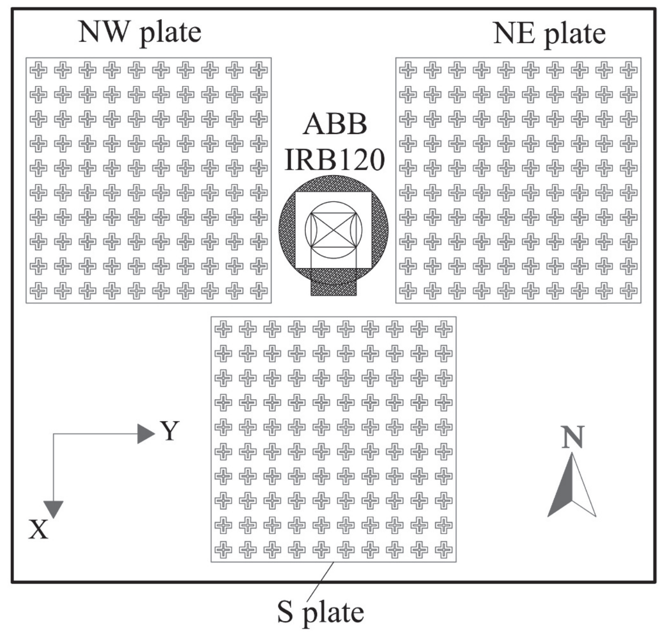

Fig. 7. Schematic representation of the controlled experimental environment. Definition of NE, NW and S foundation plates and global coordinate system.

2. Droxel-based structures

The geometry of the droxels is presented in Fig. 3, where the main characteristics and the parameters that govern their geometry and aspect ratio are reported. A thorough description of the geometrical and mechanical features of the droxels is outside the scope of the present manuscript, in which only the salient characteristics relevant to the ground-based automated operations will be presented. For what concerns their constructablity, in particular, droxels have two planes of symmetry (i.e., the two planes by the vertical direction), which make them relatively easy to build by casting one fourth of the final object by means of the preferred casting technique and subsequently adjoining the different portions. A total of 200 droxels were used in this study. The

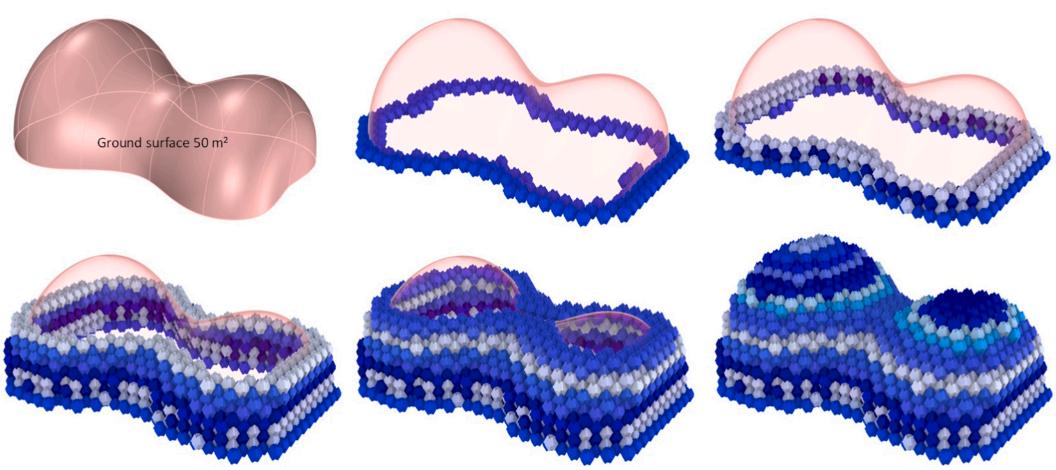

Fig. 6. Examples of different structural shapes materialized by “droxelization” of their geometrical forms.

elements, which have been constructed by means of SLA additive manufacturing, were cast as hollow blocks with a constant thickness of 3 mm. The 200 blocks were then divided in two groups, the first one of which was left "as-is", with a weight of ~22 g per droxel, while the others were filled with fine sand to reach a weight of ~66 g per block (the variation in weight between the blocks is lower than 3%). The 3:1 weight ratio between the blocks was chosen to resemble the conditions attained in a full-scale setting.

The placement of a new droxel on a pre-generated sub-assembly is called a basic construction mode [12,36]. Previous works have identified the 11 basic modes of stacking (see Fig. 8). Such modes are defined by a combination of numbers and letters, which identifythe number of droxels supporting the new piece and the type of structural connection, respectively. One important feature of the droxels stacking modes is the interlocking action between the 4 convex pins at the top of the block and the 4 concavities placed at the mid-heigh of the element (see for example Modes 1A or 1AB in Fig. 8). This feature allows for a series of interesting features and advantages: (1) a newly-placed droxel stacked in any "A" type mode will have its bottom half resting on the top half of a previously placed block; as both surfaces have the same inclination, this guarantees the maximum placement tolerance, as the top element will automatically adjust to the correct position, (2) by varying the geometrical appearance of each block, the "mid-height interlocking" allows for the final structure to be free of gaps in-between the droxels, (3) as the center of gravity of the top element does not fall on the same vertical axis as the bottom one, this allows for global overturning moments to be counteracted by proper placement of droxels of different weights, as in the experimental tests presented in the following. The staggered final position of the droxels in a typical construction, as described in Fig. 8, has strong implications in the definition, implementation and operation of the optimal construction technique.

Foundation systems play a vital role in the deployment of droxel-based structures [37]. The stability of the system is, in fact, the most important parameter for the design of the automated operations. A properly designed foundation must be able to support the actions resulting from the casting of the system throughout the entire construction process and, in terms of principle, should allow for its own construction to be automated as well. In this context, droxel structures can be supported by either "negative" or "positive" foundation systems. In the experiments presented herein, three acrylic foundation pads constructed by means of a 3-axis CNC machine with dimensions of $50.8 \times 50.8 \times 2\ \mathrm{cm}^3$ were used as a negative foundation (see Fig. 9).

3. Ground-based automated construction

This section presents the novel features of the terrestrial-based automated construction tools developed in this research. The required hardware components consist of: (1) an IRB120 robotic arm equipped with an ad-hoc manufactured end-actuator, (2) three acrylic foundation pads used to store and deploy the droxels, (3) 200 SLA 3D printed droxels. The software specifically developed for this project comprises: (1) an interactive Graphical User Interface (GUI), in which the user defines the layering of the different droxels on different levels across the vertical axis, (2) a RAPID code compiler that translates the information provided through the GUI in machine-ready instructions. The software needed to perform the experiments also comprises the proprietary RAPID robotic arm control software, for which no modifications were needed. The general arrangement of the prototyping environment was

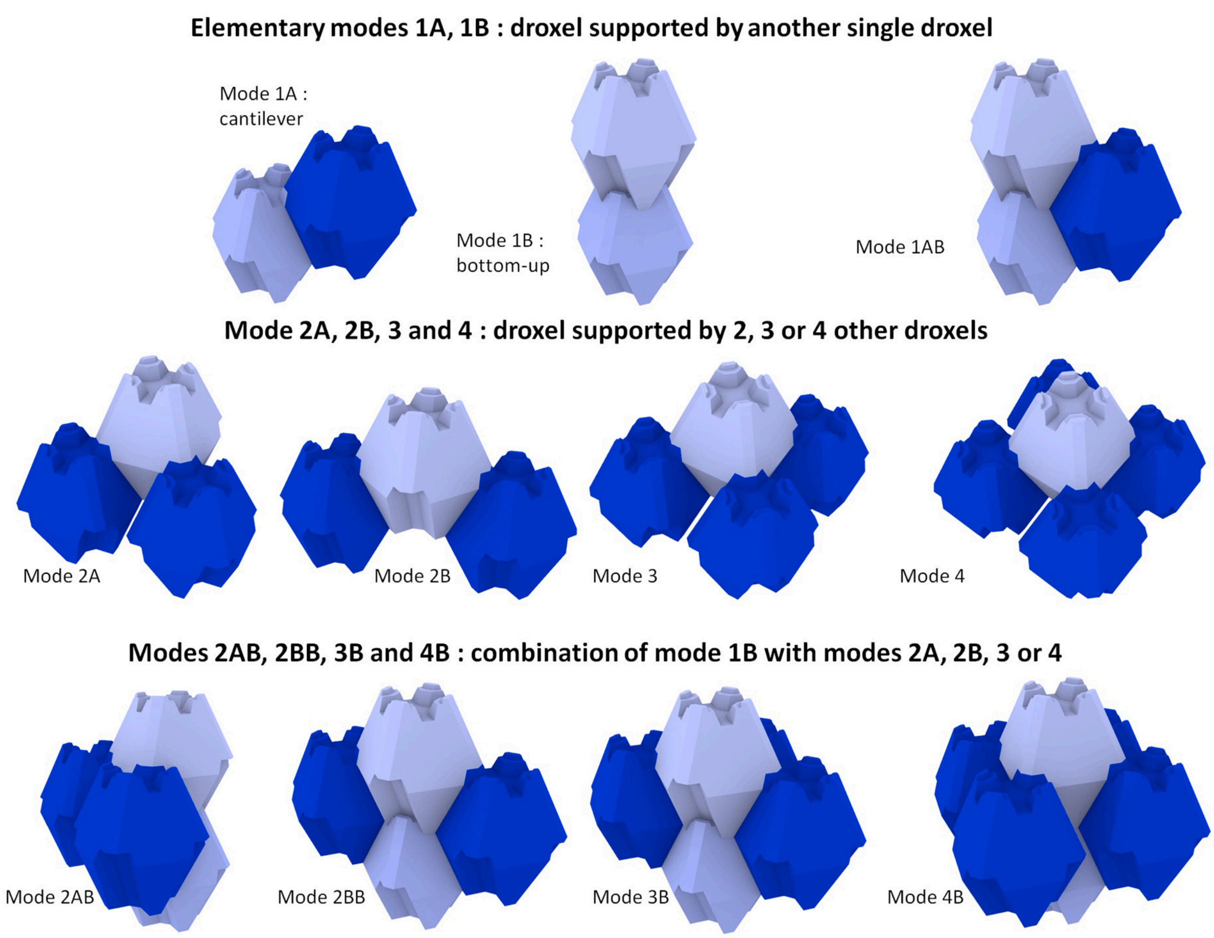

Fig. 8. Graphical description of all the possible droxels stacking modes.

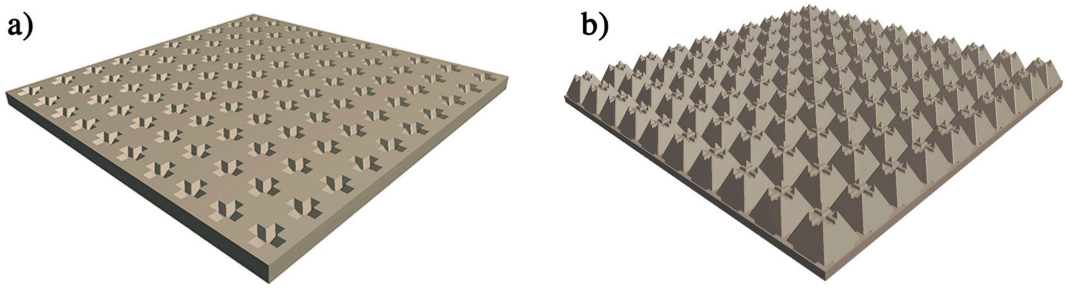

Fig. 9. Two possible arrangements for foundation pads of droxel structures: (a) “negative” foundation, (b) “positive” foundation.

presented in Fig. 7. During the calibration stage, a local set of coordinates is identified for each of the three plates used in the study (see Fig. 7) in accordance with the global coordinate system reported in Fig. 10.

3.1. Actuator and robotic arm

The arm used for the experimental campaign presented herein is the ABB IRB120. The robot, with a payload of 3 kg, is tasked with moving the blocks from source (i.e., the original position at which the droxels are stored, NW and NE foundation plates) to sink (i.e., the designated destination for the specific pieces on the S foundation plate) by means of an end actuator which allows for the activation of an external vacuum pump. The actuator was designed by extrapolating the top surface of the droxel and allowing for the blocks to have a clearance of 0.5 mm on the four sides, to account for imperfections in their fabrication and allow for re-adjustments of the droxels inside the actuator during the pick-up process. To facilitate the building operations, the actuator is constructed by two portions connected by a spring of appropriate stiffness, to allow for the part of the device in contact with the droxel to accomodate for its geometry. Fig. 11 shows the details of such design. The end actuator is connected to a vacuum pump and the controller in the robot arm can enable and disable the vacuum pump using a digital output. The coordination of the robot arm motion to perform the task can be developed in RobotStudio (see Fig. 12), and can be translated to the proprietary RAPID code [38].

3.2. Checkerboard positioning system

As described in Section 2, the peculiarities of the interlocking between adjacent droxels create complex three-dimensional arrangements

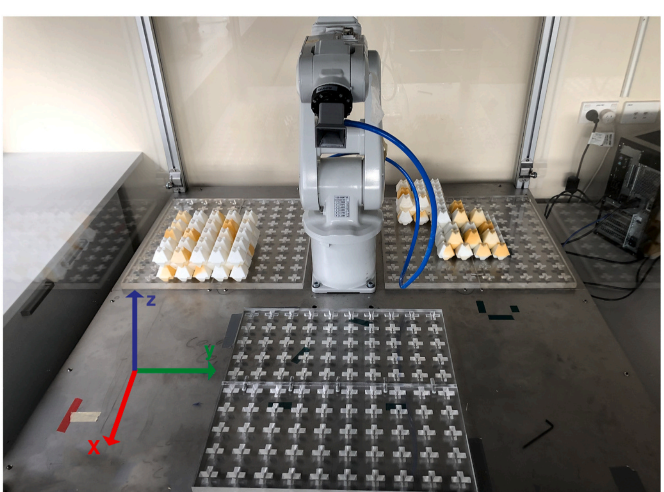

Fig. 10. ABB IRB120 robotic arm used in the experiments and positioning of the foundation plates hosting the source droxels.

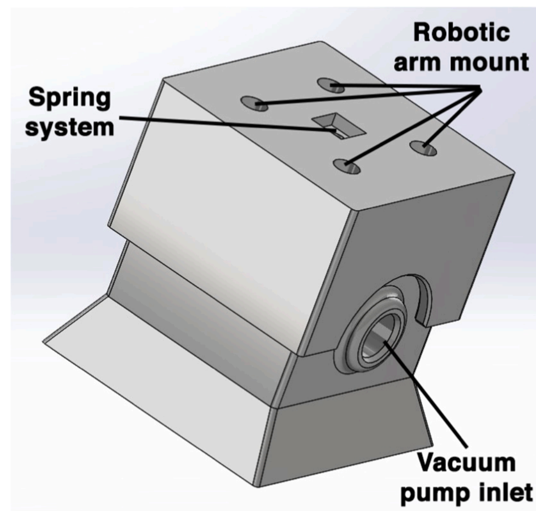

Fig. 11. The designed 3D printed end-actuator used in the experimental campaign.

of blocks, interacting on different contact surfaces and through locking of the 4 top pins with the 4 mid-height concavities. This creates a honeycomb-type of structure that has all of the centers of gravity for the different blocks aligned on two different gridline systems, based on the level of the droxels. Remembering the information reported in Fig. 8, the first layer of droxels (i.e., the one that is housed directly on the foundation pad) and all the subsequent odd-numbered ones will have the centerline of each block aligned with the gridlines A-H and 1-10 reported in Fig. 13. Conversely, the second layer and all the subsequent even-numbered layers will have their centerlines lying at the mid-points of the same gridlines. This aspect is crucial in the definition of a user-friendly positioning system software (i.e., to obtain the correct spatial arrangement of the blocks in space), with implications on the structural stability of the construction. To further clarify this aspect, the position of all the droxels in the first two layers for the construction of the shelter presented in the following is graphically represented in Fig. 14.

3.3. Collision avoidance

The information reported in Fig. 14 also describes the order of placement of the droxels in each layer. This aspect is of great importance for the execution of the tests, as it affects both the stability of the system and the total fabrication time. For this purpose, a “no collision” positioning scheme is adopted. This process resembles that of additive manufacturing, by slicing the structure into a finite number of layers (i.e., the well-defined droxel layers), which are constructed in sequence from bottom to top. This choice of the construction method guarantees that the sub-system composed of the arm, the end actuator and the currently lifted droxel will never collide with any previously placed block. This is achieved by imposing that the arm performs the collection

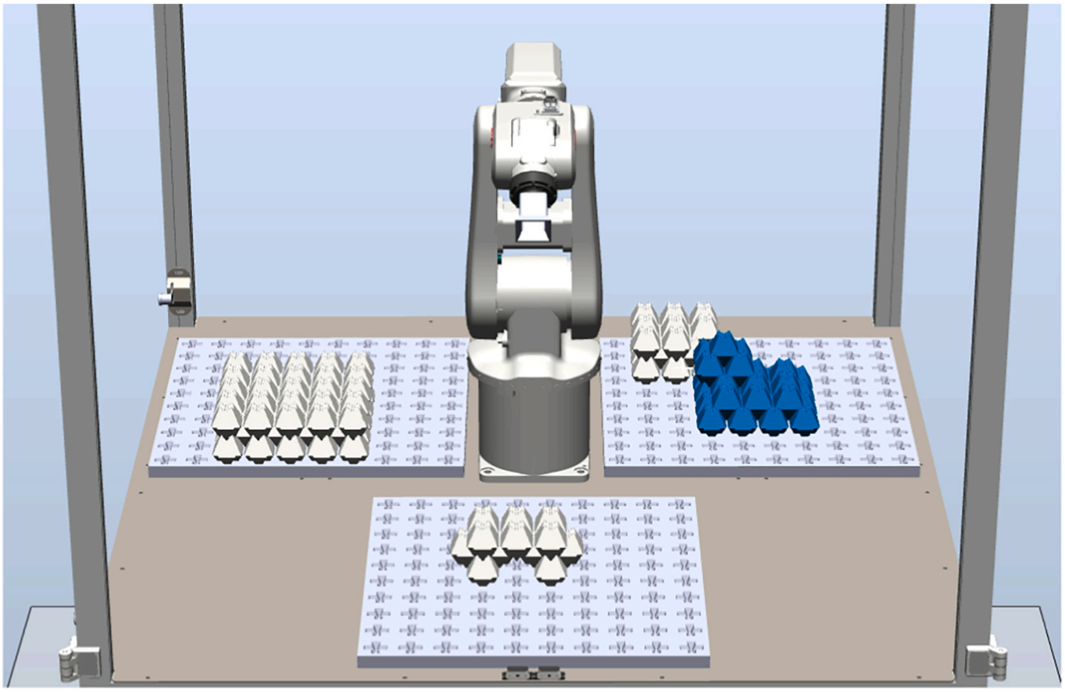

Fig. 12. Screenshot of the Robot Studio model used for the simulation of the construction procedures.

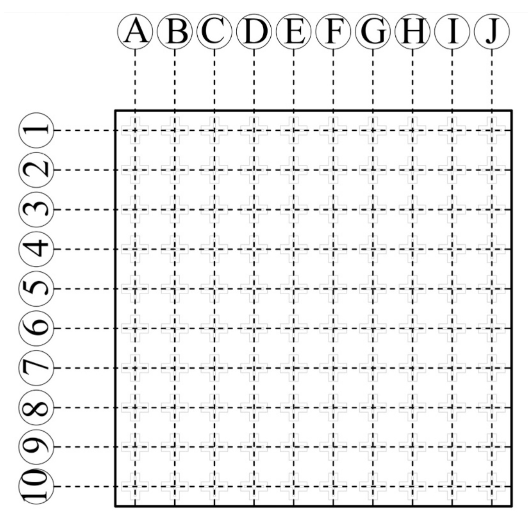

Fig. 13. Definition of the checkerboard scheme for the identification of the sink location for each droxel.

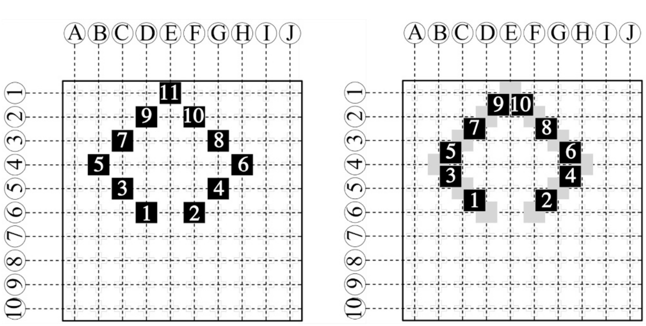

Fig. 14. First two layers of a square-based shelter construction: the order of placement of each droxel is given by the numbers reported.

and subsequent dropping sequence always approaching the final position of the blocks with a straight vertical motion (parallel to the Z-axis), greatly simplifying the construction operations, without significant increase of the total build time. The order of placement of the various blocks in each layer is defined by an “outwards first” scheme: the blocks are placed in reverse order with respect to the numbered alignments (see Fig. 13), and within each of them the construction proceeds from outwards to inwards. As depicted from Fig. 14, by adopting such positioning scheme, the second layer of the shelter construction results in Mode 2B placements only. This is an “always stable” configuration for each of the placements and therefore the entire construction process is stable.

3.4. Software architecture

The deployment of structural assemblies through the ABB IRB120 robotic arm requires accurate instructions to be completed efficiently, while on the other hand the user needs to be able to define the shape of the structural assembly to be built in an intuitive and efficient fashion. For this reason, a C++ program was developed (see Fig. 15) to serve as an interface between the droxel-based design and the robotic arm. Fig. 16 shows the GUI of the software, in which the user can define the

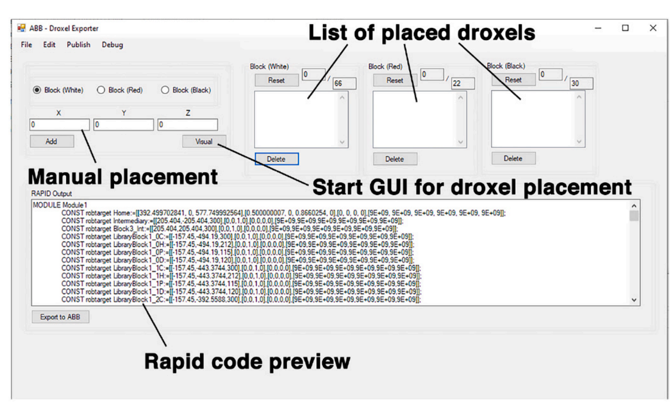

Fig. 15. Screenshot of the main window of the developed software.

droxel placement for each layer of the construction through the checkerboard scheme presented earlier. The code accepts such information and proceeds to build the RAPID code required to transfer instructions to the robotic arm. Such code can then be uploaded to the arm controller and the different programs executed by the robot.

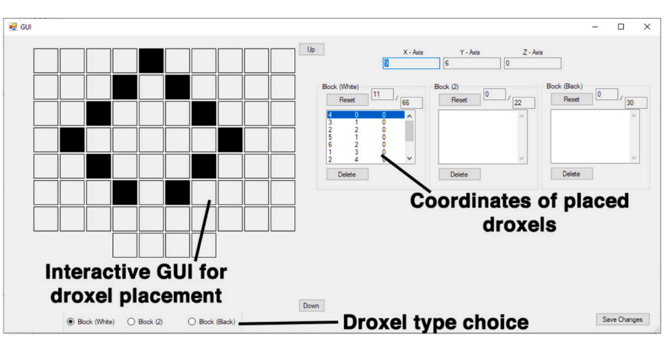

Fig. 16. Interactive GUI for the visual placement of droxels.

4. Experimental tests

4.1. Shelter construction

The first set of tests interested the construction of square-based tetrahedral structures representative of a simple shelter that can be materialized by means of droxels. The structures present a frontal opening to represent the main entrance, and are composed of 8 layers of droxels, for a total of 57 blocks. As depicted in Fig. 17, only the NW plate was used in this set of experiments. This is due to the fact that the structure has a convex shape and all the layers are concentrical. This results in an "always stable" construction schedule, so that heavier blocks are not required for this test. Fig. 17 shows different instants of the construction procedure, specifically the times at which each of the 8 layers was completed. This experiment was repeated 3 times to assess accuracy and efficiency of the proposed system. This resulted in 171 consecutive placements of droxels, with no failure recorded in any of the attempts. As expected, the total construction time was almost identical between different builds, and equal to approximately 19 min and 20 s, for an average deposition speed of ~3 blocks/min. No human intervention was required at any time during the experiments. A video recording of the full construction procedure is also included for reference in the supplementary data available in the online version of the manuscript.

Fig. 17. Automated construction of a droxel-based shelter. From left to right, top to bottom, the placement of the 8 layers composing the structures.

4.2. Bridge construction

The second set of tests involved the construction of a complex 3-dimensional structure that represents a deck arch bridge composed of a main structural arch. This structure is composed of 5 layers of droxels, for a total of 40 elements (12 "heavy" droxels, painted in black, and 28 "lightweight" droxels, painted in white). Differently from the construction of the shelter discussed previously, the bridge structural assembly requires different stacking modes, resulting in potential instabilities at different stages of the construction. For this reason, both types of droxels (i.e., both the light and heavy blocks) were used in this experiment. Fig. 18 shows the completion of each of the 5 layers composing the scaled bridge, as well as the final structure holding a total weight of 7 kg applied by means of a plastic container filled with sand (5 times the total weight of the structure). Similarly to the previous test, the experiment was executed 3 times, resulting in 120 consecutive placements of droxels, with no failure recorded in any of the attempts nor any requirement for human intervention. The total construction time was of approximately 25 min and 10 s, for an average deposition speed of ~1.6 blocks/min. The reduced average speed obtained in this test is a result of the increased path length that the arm has to cover to collect the droxels of different weights from both the NW and NE foundation pads. A video recording of the full construction procedure is also included in the supplementary data available in the online version of the manuscript.

Fig. 18. Automated construction of a droxel-based bridge. From left to right, top to bottom, the placement of the 6 layers composing the structures.

5. Discussion of the experimental results

Based on the findings obtained from the experimental tests, several conclusions can be drawn on the capabilities of ground-based automated operations for the deployment of droxel-based structures. Both the software and hardware tools developed will serve as a base for the development of algorithms and equipment capable of deploying full-scale structures. The controlled environment used for this study allowed, however, for some simplifications that would not be present in a real-life case, such as the capability of describing the position of each possible sink location on a fixed global coordinate system and the absence of external disturbances such as wind and vibrations during construction. All of these aspects must be considered when deploying outdoors ground-based automated construction processes, therefore more research is still needed to quantitatively address these aspects.

5.1. Structural optimization

The designed code is inherently capable of analyzing any given droxel assembly and construct the corresponding RAPID instructions to be passed to the robotic arm. Structural optimization for any given structural system (i.e., the droxelization) is performed by means of parametric form generation tools, such as Rhinoceros 3D and Grasshoper [39]. Once this operation is completed, it is trivial to input such information in the given GUI, either by manual input or automated scripting. It is also worth noticing that due to geometrical constraints in the laboratory setting, a maximum of 12 droxel layers can be cast with the presented setup. Even though this limitation did not influence any of the presented tests, it will be taken into account in the upscaling of the technology.

5.2. Weight optimization and structural stability during construction

The set of experiments presented in the previous sections allowed to test the hypotheses and theories used to evaluate the stability of the droxel assemblies during construction. Results of this experimental work and future extensions of their results will also be instrumental in the validation of the novel computational tools required for the parametrization of the block-based structures. The simulation of the dropping procedure for each droxel is, in fact, described by a complex dynamic problem [40], that presents several layers of technical difficulties, requiring non-standard descriptions of the discrete kinematics of the blocks [41], non-linear friction and contact forces at each boundary between the droxels [42], and non-standard constitutive laws for the constituent materials [43]. Availability of such high-fidelity computational models will also allow for the formal description of the sensitivity of the process to the different parameters (e.g., optimal drop height, preferential stacking modes), as well as help with the quantification of the optimal weight ratio between light- and heavy-weight droxels, with the potential final goal of controlling and optimizing the total weight for each droxel (and as a result that of the complete construction).

5.3. Positional accuracy and laying tolerance

The experimental campaign presented herein was also used to validate analytical solutions obtained for the laying tolerance guaranteed by the adoption of the droxels. The obtained information can therefore be scaled to estimate the required positional accuracy required in large-scale robotic arms for the deployment of full-scale droxels, as a function of their weight. Table 1 reports the computed weights for droxels of different sizes and materials. By cross-referencing such information with the geometrical tolerance for the specific droxel shape used (see Fig. 19), it is therefore possible to obtain accurate information on the payload and positional accuracy required for a specific construction.

5.4. Order of placement and minimum time of construction

As discussed in the previous, a no collision algorithm has been implemented in the software to define the order of placement of the droxels. For each layer, the order of placement is derived as follows: (1) the total number of droxels to be placed and their position in space is retrieved from the software (through the designed GUI), (2) using the previously presented checkerboard system, the blocks are ordered both for the letter (reverse order) and number (linear order) associated with their position. With this information, the software proceeds to compile the RAPID code used to control the IRB120 arm. This choice for the order of placement is dictated by the specific conditions for the experiments: indoors small-scale environment and absence of a closed feedback control loop. This ensures that no potential collisions can happen between a new block that is being transported by the arm and all the other elements that have already been successfully placed. Even though this approach is appealing, it does not allow to control the total construction time nor the total path that the robotic arm covers during the operations. These aspects are currently being investigated and will be the object of future research.

Table 1
Mass of droxels (in kg) for different sizes and constituent materials.

H (cm)	Concrete	Timber	Plastic (1 cm thickness)	Plastic (2 cm thickness)
5	0.15	0.03	–	–
10	1.19	0.24	–	–
20	9.5	1.9	–	–
30	32.3	6.5	4.6	9.4
40	76.3	15.3	8.0	16.2
50	149.0	29.8	12.6	25.3
60	257.5	51.5	18.2	36.4
70	408.8	81.8	24.7	49.6

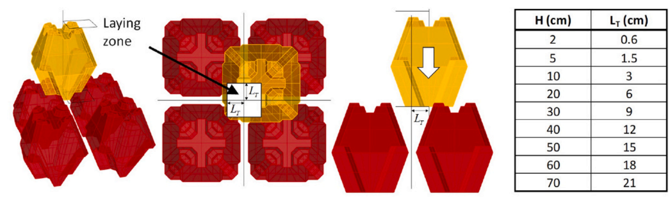

Fig. 19. Geometrical definition and quantitative description of the laying tolerance.

6. Upscaling and industry adoption

The capabilities that we envision will be granted by the adoption of droxels in the construction industry are numerous: (1) droxels are smart components that are easy to assemble and allow large geometrical tolerances, which is fundamental in the context of autonomous deployment (particularly in real-life cases where external agents like weather conditions and/or mechanical vibrations play a significant role), (2) interlocking provided by the droxel geometry allows for stable structures without requirements for scaffolding or intermediate supports, greatly simplifying robotic operations, (3) the efficient parametrization of their shape and infill characteristics allows for tailored properties to be obtained in view of specific requirements of a given project. In our vision, ground-based operations could be integrated with aerial operations, leveraging swarm robotics capabilities to optimize efficiency and quality of construction.

The results obtained from the experimental campaign allow to draw conclusions on the possibilities of upscaling such technology to the full-scale size, particularly in the following contexts: (1) the admissible droxel weight, and the stability of droxel structures composed of blocks with variable weights, (2) overall placement capacity, machine trajectory and construction sequence. The experiments were also designed to replicate real-life conditions on a construction site, where the droxels could be stored in the initial stacked configuration, which is easy to manufacture in precast facilities and deliver as-is on the construction site by means of shipping containers. Technical infills and finishing of droxel structures can bring several layers of complexity, with solutions mostly depending on the specific material used to build the droxels. For their production, concrete droxels require special formwork, timber droxels require CNC machines or robotic arms, while plastic droxels need specific production techniques such as injection molding. For hollow plastic droxels that can be produced in two stackable parts or with a filling hole, insulation can be placed inside the blocks. Insulation can also be placed either outside or inside, by projection or application of soft insulation materials such as rock wool. In a general framework, a waterproofing membrane is required to wrap the structure from the outside. This can be achieved by either placing it on the structure directly, or on the finished surfaces, similarly to application of traditional fabric membranes. At this stage, the robotic placement of insulation, waterproof membranes, or components such as electric cables or water pipes are out of our current research scope and will be object of subsequent works.

For what concerns the production of concrete droxels, the major challenge lies in the definition of cost-efficient production technologies, mainly in view of the complex formwork required. For timber droxels, the main research questions lie within the cost of the requirement equipment, such as 5-axis CNC machines and the rapidity of production. Plastic droxels (which we envision to be entirely made of recycled plastic) represent the most cost-efficient solution, also bringing the advantage of the possibility of filling the blocks with materials such as insulation or ballast. Beyond these aspects, the widespread use of robots on construction sites is still in its early stages and it is highly likely that the technology required for the full automation of the construction of droxel structures will be readily available to companies and equipment providers over the next decade. The Technology Readiness Level (TRL) is dependent on both the construction process, the type of structure, and the chosen structural material. The droxel technology itself has been extensively tested with a large number of 3D printed droxels, and a small number of full-scale concrete droxels, and corresponds to a TRL between 5 and 6. We are currently working on developing novel design and calculation algorithms for the stability check at each step of the construction process, including consideration of material characteristics and offset cumulating problems. For automated UAV-based construction, a relatively low number of tests have been performed and therefore the technology still needs further developments in terms of spatial positioning and computer vision, as explained in our previous work [12] (TRL 3–4). Lastly, concerning a construction process that includes robotic arms which is the focus of the proposed research, the TRL is around 3. Indeed, tests performed with small-scale robotic arm can only confirm the principle of building a droxel structure autonomously, but need to be extended to real structures and full-scale robotic arms. For real structures with dimensions of several meters or tens of meters, the weight of the droxels and their laying distance with respect to the extremity of the arm will have an influence on the laying accuracy. We are currently working to construct 50 cm high plastic droxels by means of injection molding, and to test their assembly with a large-scale ABB robot currently used by the research team in complementary research projects [44]. If these experimental tests will prove conclusive, the next major step will consist in investigating how the technology can be transposed to a construction site, and with what kind of robotic arms.

In the context of real-life deployment of full-scale structural system, this manuscript presented a general framework for data-exchange between a BIM model and the parametric droxelization of any structural form by means of parametric design. Future research will also investigate the possibility of employing Machine Learning forthe optimization of the geometrical and material density parameters of the droxels based on the specific project in exam, to maximize structural stability and minimize energy required for the assembly. Machine learning and AI will then be applied to optimize the robot path planning due to criteria set by the generated construction schedules and slice layers. One consideration would be the optimal locations of the robotic arm attached to a mobile robot platform if a platform is required to complete the construction blocks. This is based on the specific structure to build, such as linear paths for bridge building, or square or rectangular path of the platform for pyramidal structures. Another constraint to be considered is the collision avoidance between the robot and the droxel structures at the initial stacked configuration and the system throughout the construction operations. The feature-rich geometry of the droxels is ultimately expected to greatly increase capabilities provided by AI and Computer Vision algorithms to perform semantic segmentation and clustering, and therefore improve placement accuracy. The herein developed digital tools will serve as the basis to create an automated toolchain for the generation of the machine code to construct a given structure. Given a Building Information Model of the structure to build, the 3-D model is then imported in a parametric design software (e.g., Rhinoceros), where the droxelization is performed, as a discrete representation of continuous piecewise surfaces (see Fig. 6). This procedure can allow for any structure to be materialized with droxels of different sizes and with different geometrical arrangements. The location of each droxel is then exported into a Matlab file, to perform the required slicing (i.e., the layers subdivisions) operations. This information can then be fed into the newly develop software that was described in the previous to obtain the machine-readable code to materialize the structure. There currently exists a wide selection of industrial robotic arms capable of carrying the weight of full-scale droxels with sufficient accuracy positioning. One example is the IRB4600-60/2.05 arm that can hold a 60 kg payload with position repeatability of 0.06 mm and maximum arm reach of 2.05 m [45]. Another example is the IRB7600RX that can hold an 80 kg payload with maximum arm reach of 4.95 m and similar positional accuracy [46]. It is also foreseeable for the robotic arm to be fixed on a mobile scissor lift platform, with the mobile robot platform moving to the designated fixed locations, via linear or circular motion paths, to complete the construction. In these regards, the development of automated cranes [35] can also be adapted with droxel structures end actuators to replicate the presented experiments.

7. Conclusions and future research

With the set of indoors experimental tests, we have presented a prototype for the construction of droxel-based structures by means of ground robots. The experimental setup comprises an ABB IRB120 robotic arm equipped with a vacuum pump and an ad-hoc 3D printed end actuator. A total of 200 SLA 3D printed droxels were used in the study. The blocks were cast hollow, so that a portion of them were used “as-is” (~22 g per block), while the remaining ones were filled with sand, to reach a 3:1 weight ratio between the two groups. The stability of droxel-based structures with blocks of variable weight has been extensively studied by constructing different structural archetypes (i.e., shelters and bridges) in a controlled laboratory environment. The research presented herein aims at paving the way for the full-scale deployment of automated construction of droxel-based structures by means of ground robots. Ongoing work that is a natural extension of this research aims at investigating the optimization of the construction times and the introduction of feedback closed-loop for the evaluation of the correct placement of each block. Moreover, numerical predictions by means of ad-hoc designed computational models will be investigated for the hybrid control of the arm for the assessment of stability of the droxel-based structures during construction.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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