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Review

Feasibility study for drone-based masonry construction of real-scale structures

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A R T I C L E I N F O

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A B S T R A C T

The additive manufacturing of real scale structures using UAVs (drones) is a new discipline with challenges as wide as the possibilities it opens up for the future. UAVs must not be seen as the only way of robotizing future construction sites, but in combination with other kinds of robots. This adequate combination is indeed likely to reduce the influence of factors that usually badly affect the quality and profitability of construction projects, such as human factors, execution slowness, insecurity, insufficient communication between the stakeholders, weather conditions, strikes, lack of skilled labor, etc. The aim of this research, carried out jointly by MIT and UCLouvain since 3 years, was to lay the necessary groundwork, still not explored elsewhere, in order to prove the feasibility of building real-scale structures, in particular masonry structures, with big custom-built drones. In particular, the objective was to investigate the drones precision, their behavior while transporting, handling and laying loads, but also to draw the first guidelines for the design of “Drone compatible” construction elements: their shape, the way they should be assembled together, how to minimize their weight, how to connect them together, how to ensure their stability. This publication summarizes the work carried out so far in this field, provides the results of the laboratory tests and proposes development and improvement paths for the future. In particular, lab tests with a big drone assembling different kinds of more and more complex construction elements are commented. Several conclusions can be drawn from the study, the first one being that the research is worth going beyond the step of proving the feasibility. Indeed, it shows that using UAVs for the construction of future real scale structures is certainly not a utopia and is very promising. However, it requires further developments, not only about the drone themselves (guiding systems, handling systems, robustness, power supply), but also about the way to pass from the laboratory stage to the construction of real structures with a complex geometry, composed of slabs, walls, connections and finishing.

1. Introduction and objectives

The steady rise in labor costs, crossed with the decreasing prices of technologies has encouraged in recent years the development of new automatization processes in the field of construction. Technologies related to UAV (Unmanned Aerial Vehicle), also called drone, flying robot or UAS (Unmanned Aerial System) have undergone an exponential growth and have become much more affordable. Furthermore, this growth is far from being done, and projections show a flourishing future for the UAV industry [1].

For all the construction projects and still today, workers still use paper plans, which leads to mistakes, a lack of quality and a loss of time. In 2014, a survey from the ADEB (Association of Belgian contractors for major works) showed that, on construction sites, the lack of knowledge, of communication, of (auto) control and rigor is usually responsible for 5 to 13% of the total cost of a building.

Assembling buildings on a fully or partly automated process using UAVs, eventually combined with other kinds of robots, should allow a better construction management as far as the automated process can be directly linked to BIM models (Building Information Modeling/Management: [2, 3]). BIM is about gathering around a shared 3D model all the information concerning a construction project, in order to ensure a better communication and sharing of information between the stakeholders (Architects, engineers, contractors, clients, …). Linking BIM models directly to UAVs (and other types of robots, Fig. 1) should thus allow to bring many benefits to the constructions projects, such as:

- The reduction in construction time, and a better CO_2 balance;

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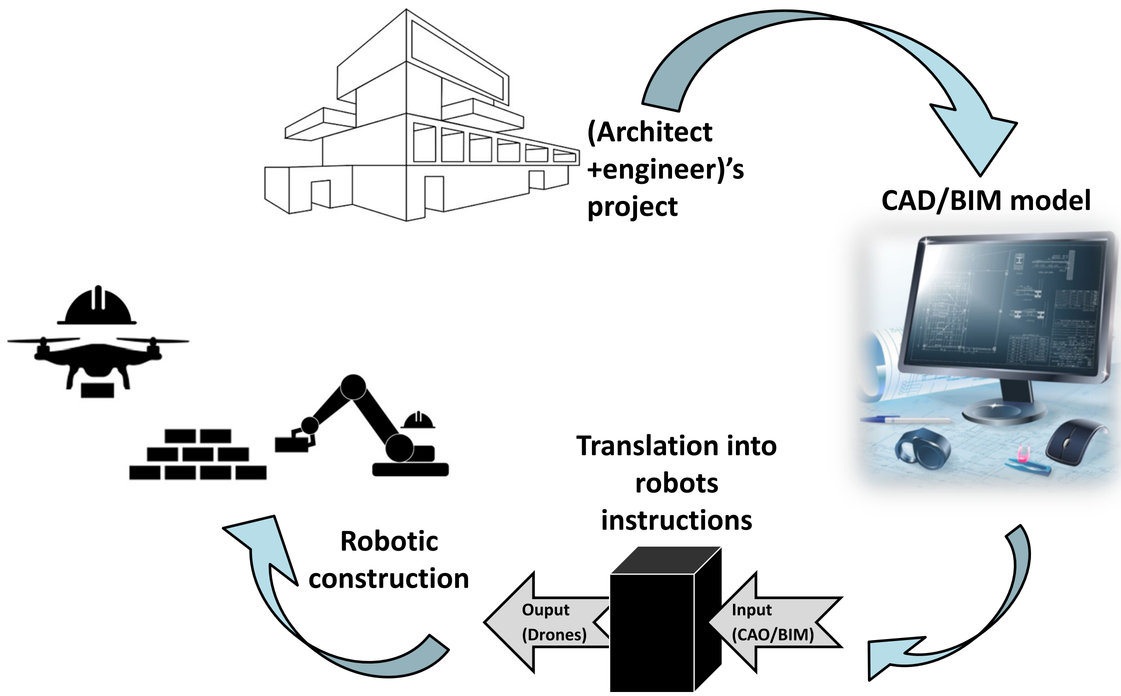

Fig. 1. BIM models could be directly translated into UAV flight (or other robots) instructions, allowing a fully automated construction process without the need to produce plans.

Fig. 2. Transportation of a long concrete beam by two synchronized UAVs.

- The reduction in the number of construction defects;
- The decrease of the impact of human factors;
- The futility of making paper plans;
- No use of cranes, which reduces the congestion inside and outside the worksite areas and facilitates construction in cities or in hard-to-reach places;
- The reduction of the painful work;
- The increase of the safety;
- A better profitability;
- A very fast construction process, combined with a quick access at any height, outside and inside the buildings, and to inaccessible areas;
- The possibility to link the automatic construction process with on-site computer vision-aided systems. This could allow the automated detection of components during the construction phase, and provide real time information about the quality of the construction by the means of a comparison with the BIM model [34].

UAV-based construction could be considered for many different types of buildings and different materials such as timber, concrete, steel or masonry. However, whatever the construction process, it must respect at least 2 constraints that leaded us to first consider masonry-based construction, which still remains today, in Europe and in many countries of the world, a widely spread construction process.

First, the mass of the construction elements should be limited to 100 kg, unless the drone become heavy and dangerous helicopters. The challenge is thus to succeed in building real scale buildings made out of a large amount of small and light elements. A combination with other non-flying robots should then be foreseen in all the cases where elements with a mass larger than 100 kg remain unavoidable. Secondly, the assembling process should take into account a position inaccuracy of the UAV of several centimeters, as a consequence of the wind or the imperfection of the guiding system. This inaccuracy is discussed further in this paper. The terms "UAV-compatible", "Drone compatible" or "DC" are thus used, in this study, to designate construction elements that respect these two limitations.

This article has not to be seen as an evolution where we would try to automate some existing construction processes. Conversely, it has to be

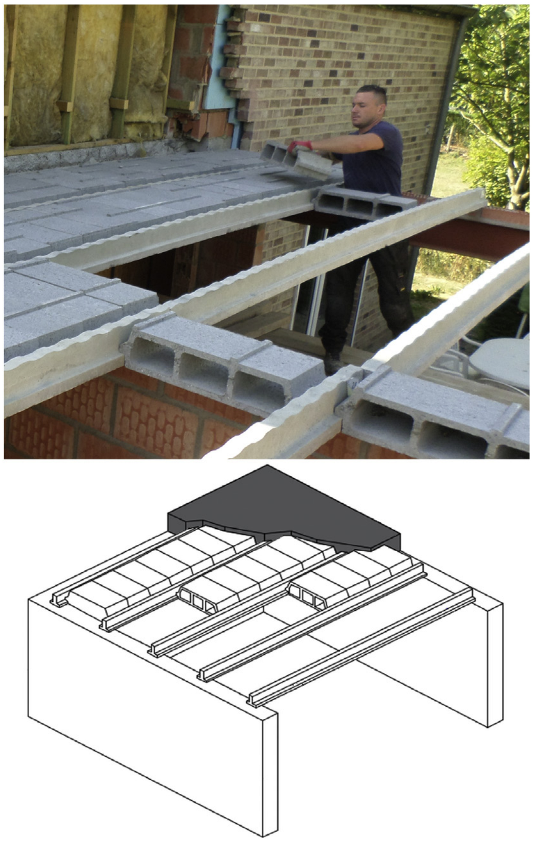

Fig. 3. Construction of a slab with the “Poutrain-claveaux” system.

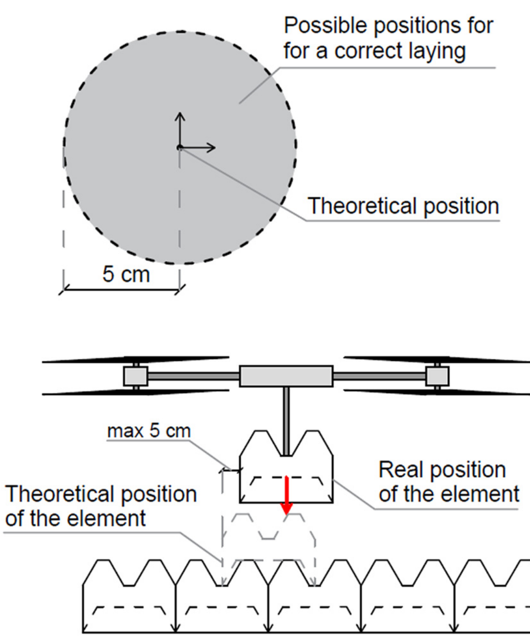

Fig. 4. Position inaccuracy allowed for the placement of UAV compatible element.

seen as a something that considers new construction processes directly impacted by new technologies. Globally, the objective of this research was to prove the feasibility of the UAV-based masonry construction and, in this field, everything was yet to discover. This is why this article focuses not only on the development of big drones or on the design of the blocks or on the construction processes, but on the three subjects at the same time, since they are intimately linked. In particular, the objective was to answer the questions listed below:

For the drones:

- What would be the size of a drone capable of lifting tens of kilograms?
- How would it behave while laying the mass (brutal leap upwards, instability, …)?
- Which system would allow an easy plug and play of the masonry blocks?
- What would be the tolerance needed for the blocks, depending on the oscillations of the drone around the theoretical position;
- What is the best guiding system?

Fig. 5. Stepoc block technology.

Table 1
Concrete compositions for dricks.

	Classical concrete	Composition 1	Composition 2	Composition 3	Composition 4
	Quantity for 1 kg of cement				
Expanded clay [kg]		0,4		0,3	0,4
Sand [kg]		1			
Crushed expanded clay [kg]			2	1,3	0,8
Polyurethane [Liter]					1
Water [kg]		0,3	0,7	0,6	0,6
Volumic mass [t/m^3]	2,3	1,7	1,4	1,3	1
Strength [MPa]	20 40	26,6	28,2	13	7,6
Mass of one block [kg]	31	23	20	18	14
Ratio strength over mass [MPa/kg]	0,65 1,30	1,16	1,41	0,72	0,54

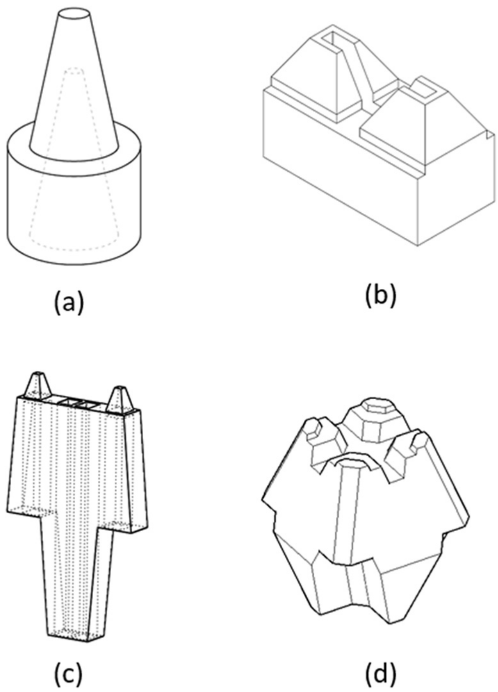

Fig. 6. The four families of dricks.

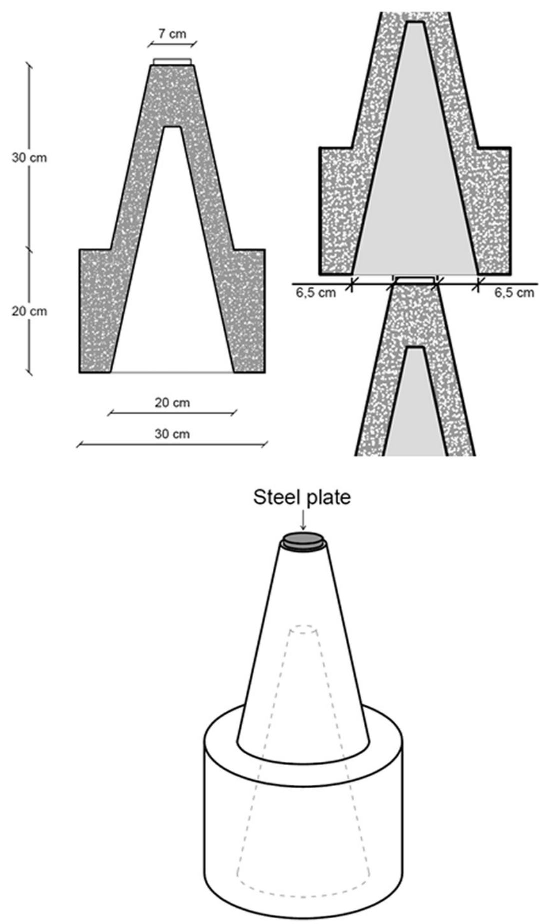

Fig. 7. The stackable conical dricks allow a tolerance of 6,5 cm.

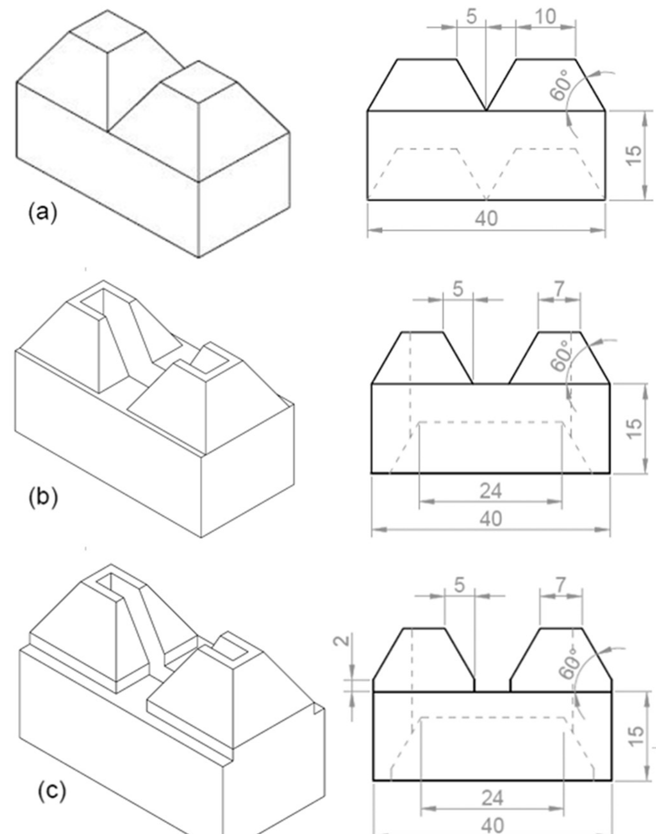

Fig. 8. A first family of rectangular dricks that were tested in lab.

For the masonry blocks:

- What should be their geometry and characteristics in order to be easily assembled, to maximize the laying tolerance, to minimize their weight and to be compatible with the laying system?
- Would it be possible to find "drone compatible" block geometries that allow the construction of a drone-based covering structure without scaffolding?
- What should their general design rules be?

For the construction processes:

- How to manage the successive embedment of the masonry layers?
- How to ensure the stability of the intermediate construction phases?
- Would it make finally sense, in terms of construction costs, to build masonry structures with drones?

This research needed the development of one UAV of big size capable of lifting masses up to 25 kg in addition to the 5 kg of batteries (see details in Section 6.1). Our laboratory tests showed that the construction time of a UAV-based masonry wall could allow a huge profitability thanks to a fast construction time (one drone being up to 5 times faster than a well-trained worker), leading to a construction cost up to 10 times cheaper, estimated to 4 euros/m^2.

Finally, this study paves the way for many future developments not only linked to the drones themselves (guiding systems, multi-flight, robustness, link with BIM models, etc.) but also to:

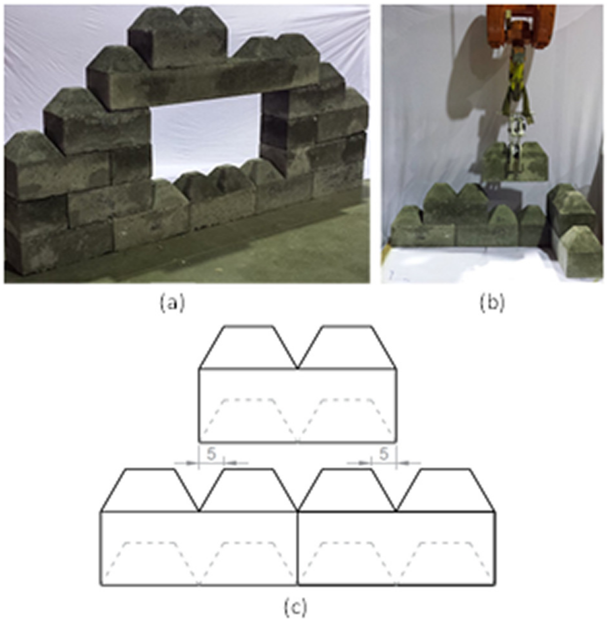

Fig. 9. Lab tests: (a) A concrete wall built with dricks; (b) The laying of a drick between two already placed dricks; (c) The laying tolerance of 5 cm for a rectangular drick.

- Masonry systems (Compression and shear resistance of walls, industrialization process, how to glue them together, best shapes, etc.);
- All the other construction processes, such as the making of slabs, the making of connections between walls and slabs, the integration of finishing and MEP techniques, the integration of concrete as linking material where necessary, the combination with other types of robots, etc.

2. Literature review

Research based on the use of robots to build structures on construction sites is not something new and various projects have been carried out in this direction since the 1980s. For instance, the ROCCO project (Robot Construction System for Computer Integrated Construction) started in 1992 and was about the development of an on-site bricklayer robot [5]. The developments of these avant-garde projects were uneasy because at that time, much of the technology known today still had to be developed: not only the robots themselves, but also the control systems, the sensors, the softwares and command algorithms [6, 7].

These last years, a significant increase of automation projects in the field of architecture and construction, that concern both prefabrication and on site construction, occurred. About on-site construction projects, three families of robots can be identified: large scale 3D printing, mobile robots and flying robots.

3D printing has revolutionized the way of producing very precisely geometrically complex objects in various fields. The construction field is not an exception to this [8–12], but the inconvenient is that the printer must be bigger than the structure that it builds. Among all these researches, the SPIDER Robot concept [4] uses a cable robot (a kind of gripper moved in a defined 3D space using cables). Although it can be assimilated to 3D printing, the approach is here different because it proposes the use of a kind of giant 3D printer to assemble building elements such as bricks, rather than successively depositing layers of liquid material.

Mobile robots have the advantage of being able to build much larger structures than themselves. However, they need enough space to move around the structure, which slows their progression, especially when the structure is high. Researches conducted at ETH Zurich still offer very promising results using this technique [13]. Indeed, compared to other robotic construction projects where the realizations are often far from real applications, this project allows the building of large brick walls. Another impressive project is the MX3D developed by the Joris Laarman lab, who succeeded in building in 2015 a steel bridge with the

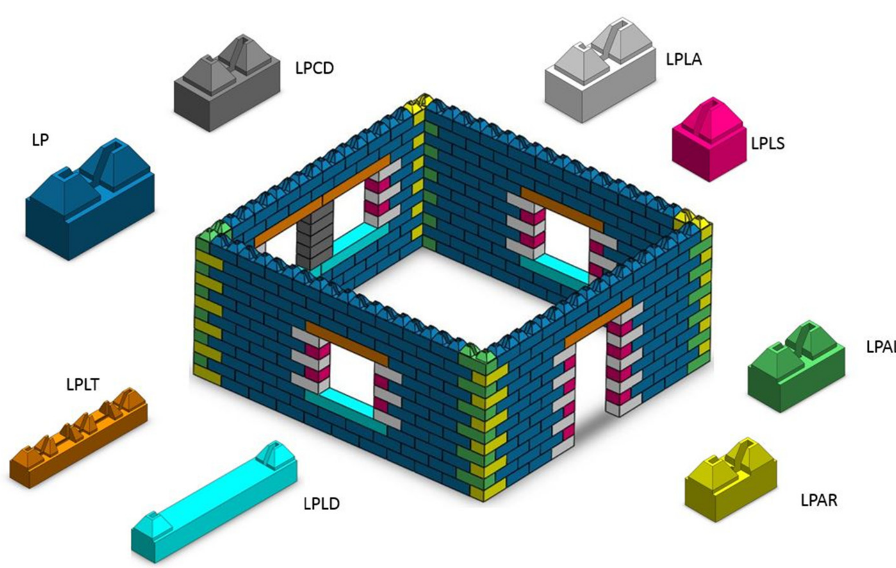

Fig. 10. Eight different dricks are needed to cover every straight wall configuration.

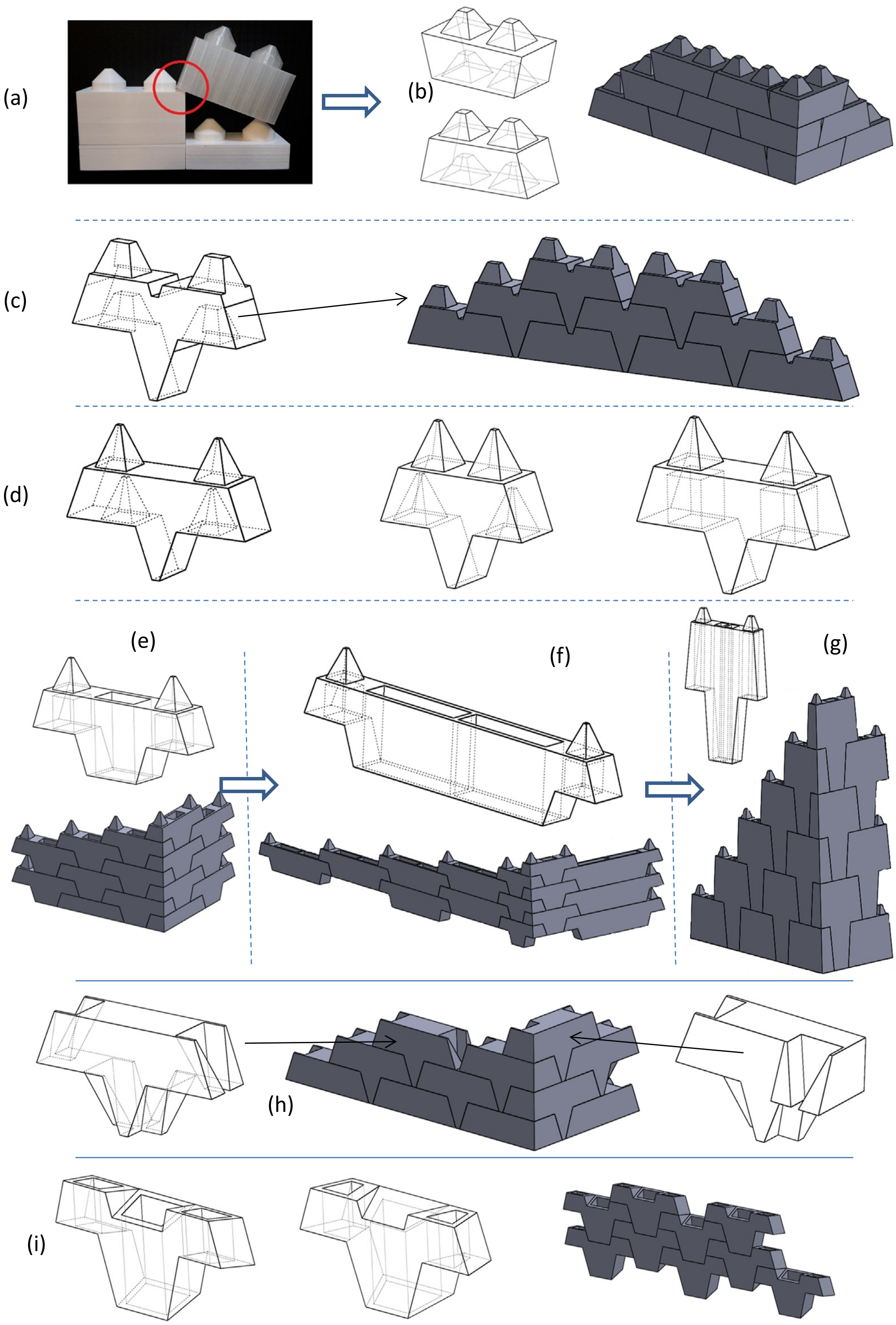

Fig. 11. Possible future developments for dricks.

use of a climbing robot equipped with an automated welding station [14]. This kind of 3D mobile steel printer makes it possible to produce large resistant structures despite the relatively small size of the robot.

Regarding the use of flying robots, several recent studies have highlighted the feasibility of the process for lightweight structures, such as a fascinating project from ETH Zurich (F. Augugliaro et al. [15]) where 4 flying robots were used to assemble a 6 m high indoor tower made out of foam bricks. Also at ETH Zurich, another project [16] uses

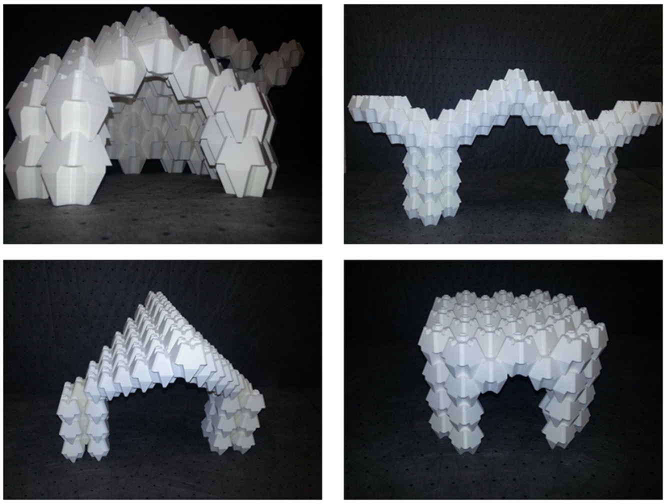

Fig. 12. Several structures composed out of 3D printed droxels.

flying robots to assemble cable structures. At the University of Pennsylvania, Q. Lindsey et al. [17] have used a quadrotor team to assemble small scale columns and beams structures fixed together with magnets. Another research, the one of G. Hunt and al. [19], concerns 3D printing using a UAV for the building of small structures made out of foam. Other initiatives also exist such as the ARCAS project (Aerial Robotics Cooperative Assembly System, [18]).

Finally, the three families of robots have their own advantages, and however their limitations:

- The 3D printer has the disadvantage to be bigger than what it builds;
- The mobile robot has to find its way inside, outside and around the structure, which slows the execution;
- The flying robot cannot lift heavy masses and its accuracy depends on several factors as wind and the technology used for the spatial positioning.

Therefore, in the future, construction projects will probably see the combination of these three complementary families of robots.

3. Philosophy of real scale Uav-based construction

As already mentioned above, the UAV-based construction has to take into account both the limited payload and the position inaccuracies of the UAVs. This requires to completely rethinking the construction processes, the shape of the construction elements and their connections. It is thus the entire process, from the design to the execution, which needs to be rethought in order to take intelligently advantage of the potential positive aspects of the UAV-based construction.

The constrain on the payload cannot be bypassed, in order to keep robots of reasonable size, to limit their noise pollution, and the wind they create. However, long elements could be lifted and put in place by several synchronized UAVs (Fig. 2).

The use of light construction elements runs counter to the tendency where, in countries with an expensive workforce, buildings are built with large and heavy precast components assembled by cranes. But, due to the very fast execution of the UAV-based construction, it is relevant to think that the building of big structures composed of many light elements would be more relevant. As a source of inspiration, Fig. 3 shows the “Poutrain-claveaux” system, commonly used in some countries especially for renovations, which allows the construction of slabs with elements that can be lifted by one or two workers.

The second major constraint that strongly influences the design of UAV-based construction is the positioning inaccuracy of the UAVs, that can be due to many factors: the inherent inaccuracy of the positioning system (local or global), the ability of the flight controller to maintain the desired position, the external disturbances such as wind or self-created wind, the dynamic behavior of the UAV and its load in motion, the possible movements of the handling system, etc. As shown in Fig. 4 and according to our lab tests, the overall inaccuracy of the UAV can therefore be, depending on the situation, of the order of a few centimeters (typically 5 cm), while the precision required for the laying of classical masonry blocks is of the order of a few millimeters. It is thus necessary to design new kinds of construction elements and their associated smart handling systems.

Up to now in this research, the DC units have been designed to be assembled without mortar. This has advantages, such as fast execution, ease of implementation and low impact of weather conditions. Many research projects already address the issue of interlocking dry masonry such as [21]. In 1995 already, researchers from the University of Karlsruhe (Germany) carried out tests on the automatic assembling of mortar-free masonry [22]. More recently, many researches focus on the mechanical behavior of dry assembled constructions [21, 23]. These studies generally do not deal with the automated assembling or the search for a maximum laying tolerance but rather with the resistance to compression [24, 25], with the fatigue behavior [26] or with the behavior during earthquakes [27].

However, in order to build more resistant structures, one must not exclude the use of UAVs in such way that the masonry blocks are more than just nested in each other. For instance, the use of hollow blocks like “stepocs” that can be filled afterwards in order to create a monolithic structure is possible and allows furthermore the insertion of reinforcement bars (Fig. 5). Another possible solution consists in covering some faces of the DC units with glue before they are transported by the UAV.

Concerning the UAV's autonomy and energy supply, the significant and constant progresses in the technology of batteries make it reasonable to assume that the current limitations will no longer be relevant in a few years. Furthermore, it is also possible to consider that UAVs could be powered by cable, as we did for some of our lab experiments. In this case, an AC/DC converter must be foreseen on the drone in order to allow the supply with high tension with a small diameter cable.

Concerning the environmental impact of the UAV-based construction, the authors supervised a first study [20] that showed that the impact of a UAV-based masonry construction (typically, a house) is lower than the “hand-made” one. One the one hand, the fast execution and, on the other hand, the negative CO_2 impact of the daily transportation of the workers between their housing and the work site, can explain this. The same study also showed that the profitability of a UAV-based construction could be higher, especially where the cost of the workforce is high.

Finally, it is evident that the robotization of the construction should

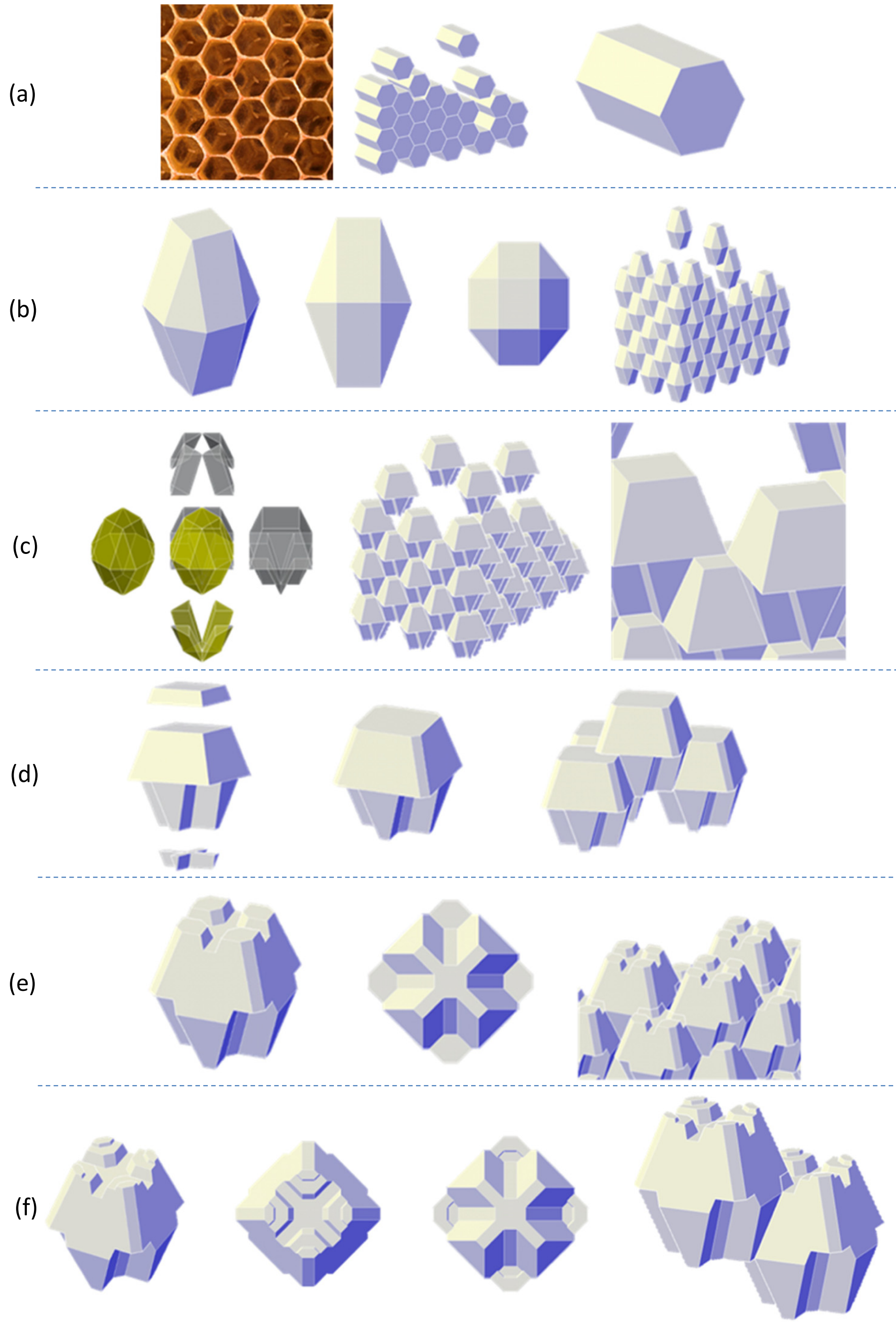

Fig. 13. The step-by-step design philosophy of the droxels geometry.

affect the low skilled handforce on construction sites, but should create high added value employment in the robotic sector.

4. Design of Uav compatible masonry

In this paper the denomination drick, portmanteau of drone and brick, is used to designate DC masonry blocks. Several kinds of dricks have been developed, each of them helping successively to identify challenges to solve and improvements to make. Shaping and designing a drick is a complex process that must integrate many parameters, sometimes contradictory:

- The laying tolerance;
- The ease with which they glide over those already in place, which

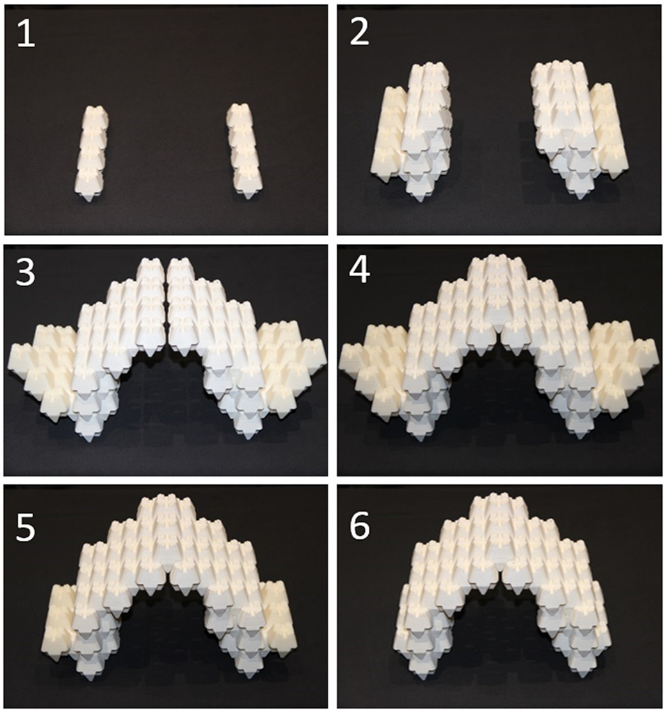

Fig. 14. The droxels allow creating an arch without formworks or support.

depends on the surface rendering of the material. Indeed, due to the

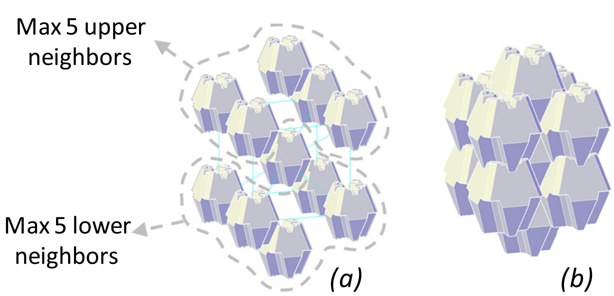

Fig. 15. A droxel may have up to 10 neighbours: (a) an exploded view of a droxel and it's 10 possible neighbours (b) the equivalent non exploded view.

friction coefficient between the faces that have to touch, a drick which is dropped could stay in a bad position;

- Their dimensions, their weight, or the ratio between their dimensions and their weight or the ratio between their strength and their weight;
- The shape, for instance the ratio between the height and the length, that can have an influence on the rotational stability of the UAV;
- The shape, in terms of simplicity, in order to facilitate the productions at low price. This can be of course contradictory with some preceding criteria;
- The shape, in the way that the existence of thin edges makes them fragile;
- The fact that they can be hollow and eventually filled with concrete after laying;

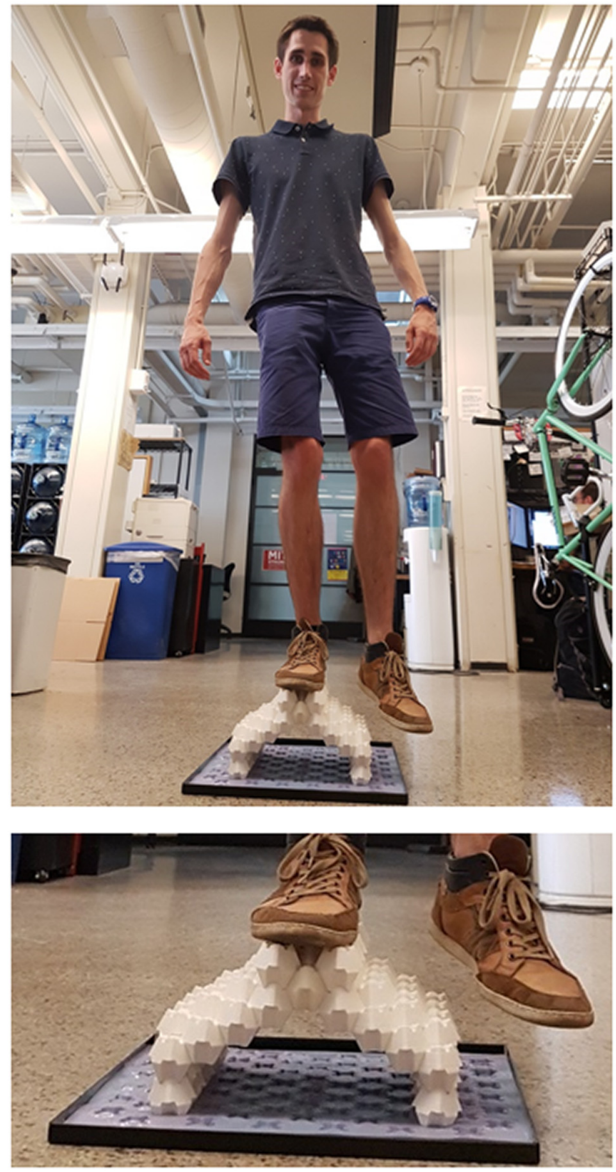

Fig. 16. The droxels are mortarless UAV compatible units capable of supporting heavy loads.

- The possibility of using light materials, for instance aerated concrete;
- The possibility of making a wall with corners and openings with a limited number of different dricks;
- The compatibility with an efficient handling system;
- The stability and strength without (and with) mortar between the dricks;
- The possibility to easily place a drick between two existing dricks;
- The possibility of creating space structures without the need of scaffolding.

Concerning the ratio “strength over weight” and the surface rendering/friction coefficient, several concrete compositions where tested,

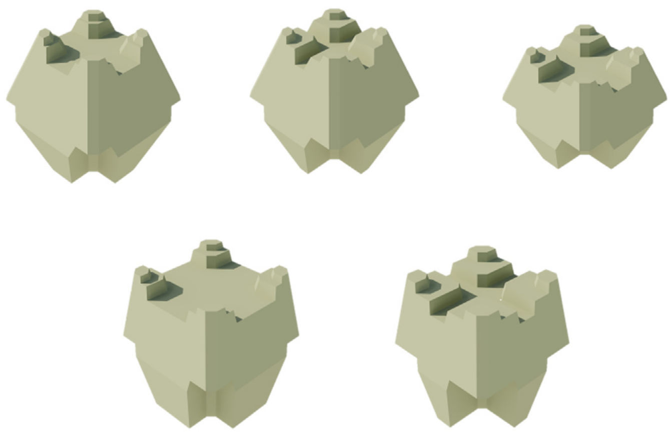

Fig. 17. A few different Droxel shapes.

and compression tests were made, as shown in Table 1. It shows that the use of expanded clay is relevant, although these concretes have a rougher surface finish, which makes more difficult the sliding of the dricks on each other. The addition of “crushed expanded clay” instead of regular expanded clay makes smoother surfaces and a better compression strength.

The dricks that are presented in this section can be classified into four families. The first one concerns conical blocks for the making of columns (Fig. 6a). The second and third ones are DC masonry used for straight walls, (Fig. 6b and c). The last family concerns the *droxels* (Fig. 6d), which are dricks with a more complex shape, with a less good laying tolerance, but with the great advantage of making it possible to create without scaffolding, structures of very complex architectural forms, such as arches and cantilevers (Fig. 12).

4.1. Conical dricks

At the beginning of this research project, everything was yet to discover concerning the behavior of big size UAVs and the possibility to use them in order to assemble concrete blocks with an adequate lifting system. In these circumstances, very simple shape stackable conical concrete blocks of diameter 30 cm were designed, in order to assemble columns and proceed to the first tests.

The dimensions of the blocks are given in Fig. 7. Their maximum laying tolerance is about 6,5 cm and their weight between 14 kg and 20 kg, depending on their concrete composition. A small metallic plate is embedded at the top of each block, which makes it possible a lifting system with an electro-magnet. The results of the tests performed with these blocks are presented in Section 6.2.

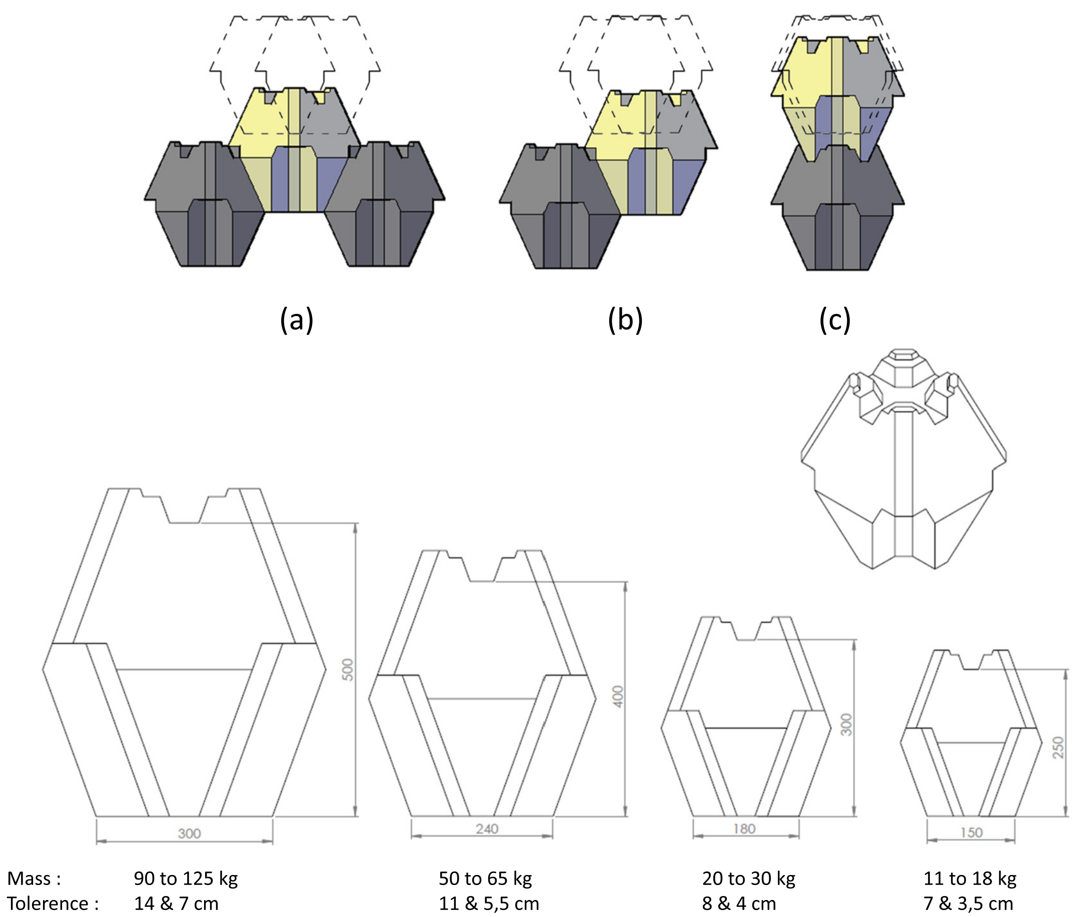

Fig. 18. Dimensions, weight and laying tolerance for various sizes of droxels.

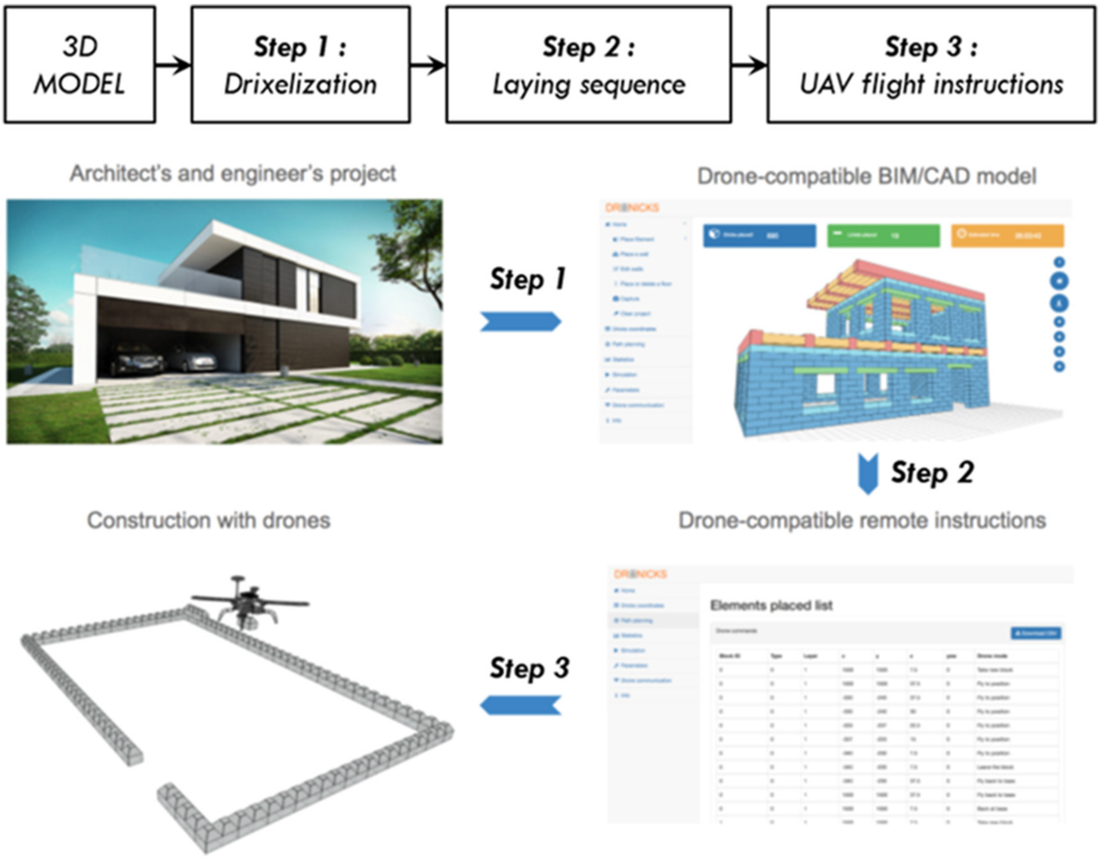

Fig. 19. From the 3D model to the flight instructions (Dricks).

4.2. Rectangular dricks

Fig. 8 shows a first family of rectangular dricks, with masses between 14 and 20 kg, which interlocking efficiency was successively tested in laboratory. These tests allowed to select the best angles (those who allow a good "sliding" of the drickxs on each other) and the shapes of the pyramidal parts that maximize the laying tolerance (in this case: 5 cm). The dimensions also result from the ease to place the blocks in diverse situation, for instance between two existing blocks (Fig. 9b). The reasons that guided the transition from one design to another are explained in Chapter 6.3. As shown in Fig. 10, the family of dricks presented in Fig. 8 needs eight different units to cover every possible straight wall configurations. Their sizes are similar to classical commercial concrete blocks. However, it is not excluded to enlarge dricks and use bigger UAVs with a payload up to 100 kg, which would then much more look like panels than masonry blocks. A supplementary design criterion is thus in this case the biggest possible size with a mass limited to 100 kg.

Fig. 11 illustrates the possible evolutions and the design process for other kinds of dricks that were compared and tested with small-scale 3D printed samples. The dricks of Figs. 9 and 11a only need one unit for walls and corners (except those needed for openings and the first layer) but show a bad "DC" performance when placed next to, or between other existing dricks. Dricks of Fig. 11b need four different units but are an improvement of Fig. 11a in the way that they can place themselves more reliably by naturally gliding between the dricks already placed. Dricks of Fig. 11b must however be placed with a given sequence (one out of two, then the others between the first ones placed). The drick of Fig. 11c (and all the followings ones) only needs three different units and can be placed according to any sequence (for a given layer). The dricks of Fig. 11d tempt to improve the previous ones with a less complicated shape. The dricks of Fig. 11e, f and g are hollowed and thus lighter. They can thus be enlarged, which makes possible a faster execution. They also allow different lengths, which brings flexibility in the possible length of the wall. The drick of Fig. 11g has a higher ratio height over length, which is favorable to the rotational stability of the UAV (this will be discussed in Section 6.3). Dricks of Fig. 11h are inspired from the droxels, with another way to assemble them together. Finally, for the dricks of Fig. 11i, the one direction slope of the faces doubles the tolerance, which is a great advantage. However the slope must be sufficient to compensate the friction between the faces.

4.3. The droxels

The word droxel is here defined as a portmanteau of drone and voxel, while the voxel designates a three-dimensional pixel. A droxel is thus an elementary 3D masonry unit that enables to shape an endless numbers of structural designs (Fig. 12), sometimes without using any scaffolding. This section presents the step-by-step design philosophy of the droxels geometry.

The problem was first considered in 2D with nature as a source of inspiration, in particular considering the bees' nest structure shape (Fig. 13a), that suggests a good laying tolerance thanks to the hexagonal shape, as well as the possibility of creating openings.

However, the impossibility of making perpendicular walls with this type of block limits its interest. This can be solved by shaping the extremities, as illustrated on Fig. 13b. With this configuration, the laying tolerance is only provided in the plane of the wall, but If a part of the block is removed at its bottom and added at its top, as shown in Fig. 13c, a block is able to lock itself with the others. Nevertheless, this transformation makes some angles too sharp. The solution is to slice the block at its top and its bottom (Fig. 13d). Besides, to get rid of the sharp edges, the droxel is also chamfered. In order to improve the interlocking features when a droxel is placed above another one, a cross on the top surface as added (Fig. 13e). Finally, to provide the possibility of building cantilever structures, four anchoring heads were added on top while four notches were hollowed at mid height (Fig. 13f).

With these features, droxels allow to create complex architectural forms without needing any formworks or support. Fig. 14 shows an arch made out of 3D printed droxels. In this case, the structure is first equilibrated by temporary droxels put at the right and left extremities of the structure, which are removed once the connection at the top is finished.

Each droxel is locked in position by its neighbours (a maximum of 10, as shown in Fig. 15). This means that besides providing an accurate self-alignment feature, the droxel also provides stability to the structure without any mortar (Fig. 16). Up to now, the droxel has always been presented with the same proportions, but it can take an infinite number of different shapes (Fig. 17).

As mentioned previously, droxels have in some configurations a lower laying tolerance. Fig. 18 shows the three possible laying configurations for a droxel and the associated tolerance. If a droxel is placed between two (in 2D) or more (in 3D) existing droxels, the laying tolerance is the best (Fig. 18a). If a droxel is put as a cantilever on another one (Fig. 18b), the laying tolerance is the one of Fig. 18a divided by two. Finally, if a droxel is put on another droxel, the laying tolerance is almost non-existent (Fig. 18c), but this case only occurs when creating a column. Fig. 18 also shows various sizes of droxels and gives their weight and laying tolerance for configuration (a) and (b).

5. Modeling and implementation of Uav compatible masonry

5.1. Methodology

In the introduction has been discussed the advantage of linking BIM models directly to robots, that could build structures with a completely automated process (Fig. 1). This needs an algorithm (Fig. 19) capable of:

- Step 1: Translating the structure (or its BIM model) into a combination of UAV-compatible elements like dricks or droxels. This process could be called the “Drickelization” or the “Droxelization”;
- Step 2: Finding an adequate laying sequence for the drickxs and the droxels, that guaranties the local and global stability of the structure at each step of the building process;
- Step 3: Creating a file that lists the UAV flight instructions.

5.2. Drixelization and laying sequence

A code that runs with the plug-in Dynamo from Autodesk [29] has been developed [31] in order to prove the feasibility of the drixelization process (Fig. 20). This code is able to translate a 3D Revit model into dricks. This process must respect specific rules that take into account the offset of the joints between the masonry layers and the fact that an automatic building process does not allow to cut the blocks on site, as a worker would do. Fig. 21 shows three possible ways of translating a wall into dricks:

- Imposing a wall's length to be a multiple of the dricks' length;
- Calculating the size of the reduced-size blocks that must be manufactured;
- Imposing the drick's size according to the total length of the wall.

After the drixelisation, the structure must be translated into UAV

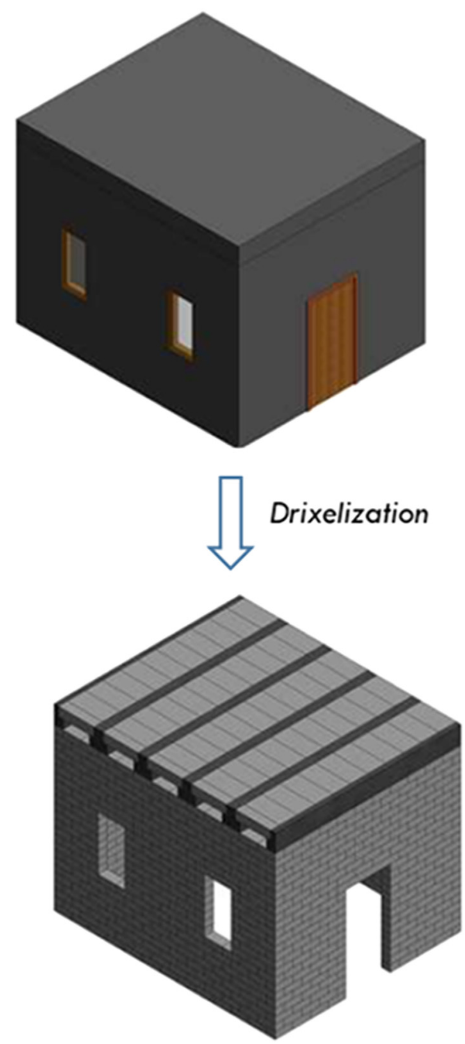

Fig. 20. The drixelization of a structure. Left: the 3D model of the structure. Right: the structure after drixelisation.

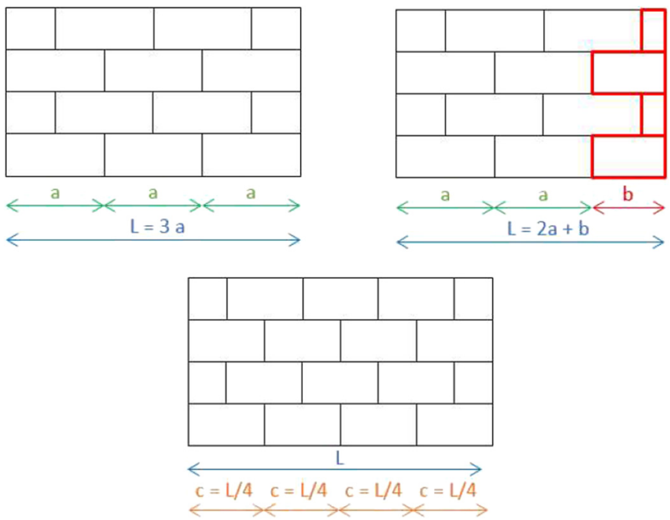

Fig. 21. Choosing the size of the wall regarding the size of the drickx.

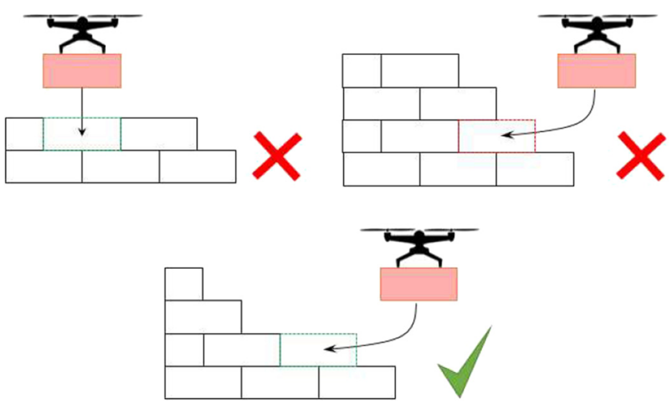

Fig. 22. Laying rules for basical drickx.

flight instructions, which can also be done with Dynamo software. This process must consider the type of drick, the stability at each step of the construction, and the existence of corners and openings [31]. Fig. 22 illustrates some examples of laying rules that have been implemented into the program.

5.3. Droxelization and laying sequence

Since droxels make it possible to build cantilevers and more complex architectural geometries, the process of droxelization and the laying sequence are more complex, as illustrated in Fig. 23. Fig. 24 shows an example of the "droxelization" of an arch, also tested via Dynamo software, according to the following process:

- The structure is drawn in a CAD software (Fig. 24a). In this case, a. STL file from Revit software has been produced;
- The model is imported into Dynamo, the space around the 3D model is virtually fulfilled with droxels, and their gravity centers are drawn (Fig. 24b);
- The code identifies and selects all the gravity centers related to droxels that intersect the structure (Fig. 24c);
- A droxel is kept on each of the selected gravity centers (Fig. 24d). Optimal mesh orientations (translation and rotation) can be found for any structure thanks to an iterative process, as illustrated in Fig. 25 that shows the droxelization of a straight wall. The optimal mesh orientation can be considered as the orientation which minimizes the number of intersections between the mesh and the structure. For instance, the solution of Fig. 25b is better than the solution of Fig. 25c since its number of droxels is smaller;
- Floating droxels (not supported by the ground or by another droxel) are identified and removed, as shown in Fig. 26;
- The "droxelized" structure is resent into the CAD software (Fig. 24e), where modifications of the structure, such as openings, can still be added, at the condition to make a new check concerning the floating droxels.

After the droxelization, it is necessary to define a laying sequence for the droxels, based on a succession of stability checks that can also be programmed into Dynamo software. Just as 3D printers do, a layer-by-layer construction is preferred in order to reduce the risk of collision between the UAV and the structure under construction. The global and local stability of the structure has to be checked each time a new droxel is added and, if a stability problem appears, a new laying sequence has to be found. As shown in Fig. 27, a structure, simply laid on the ground, is unstable when the position of the vertical projection of the center of gravity goes out of its support area.

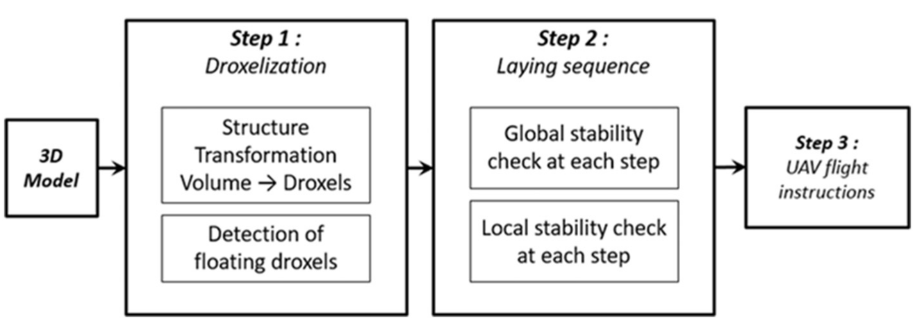

Fig. 23. From the 3D model to the flight instructions (Droxels).

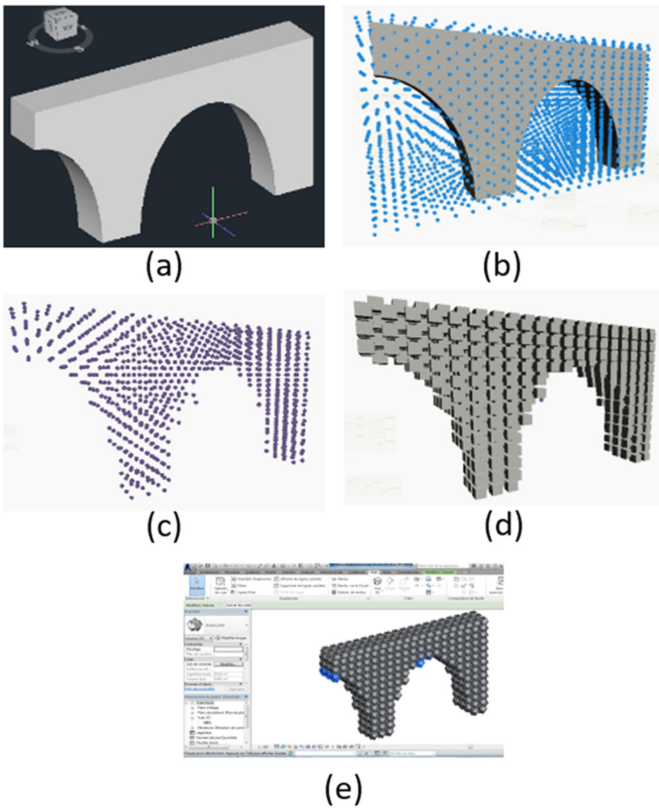

Fig. 24. The “droxelization” of a structure with Dynamo.

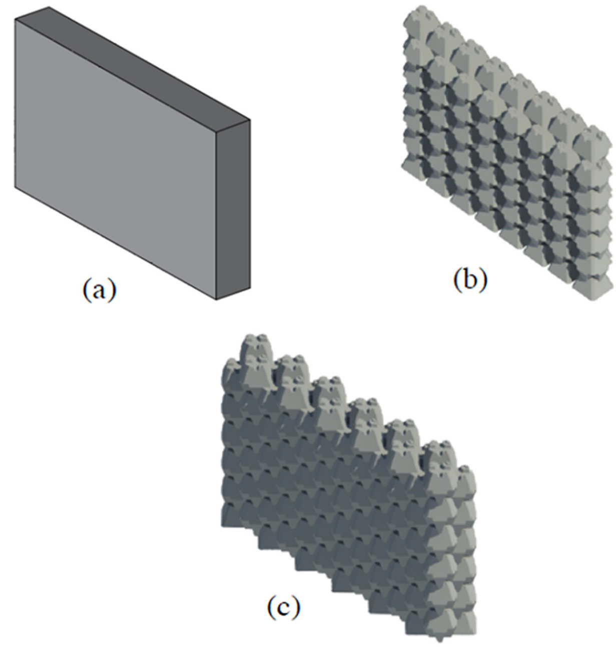

Fig. 25. Droxelisation of a wall: (a) model of the straight wall; (b) and (c) Droxelization according to two different mesh orientations.

During the construction phase, any droxel can be subjected at any time to a vertical load coming from the self-weight of the other droxels above him. This force can be centered or not on this droxel. A droxel is supposed to be “hooked” when it remains stable under this vertical force. On the left of Fig. 28, white droxels are hooked, while they are not hooked on the right of Fig. 28. Hence, a droxel can be clockwise hooked but counter clockwise not hooked (Fig. 28a.6), and reversely (Fig. 28a.7).

A “substructure” is defined as being a group of droxels, which is not hooked to the rest of the structure (Fig. 28b.5, b.6 and b.7). Hence, a substructure can also be itself composed of several smaller substructures (Fig. 29a).

A substructure is unstable if subjected to a vertical resulting force which axis that goes out of its own support area, as illustrated in Figs. 29b and 29c. These figures also show that the rotation point of an unstable substructure will always occur below the lowest droxel of the substructure. If this case occurs, the new added droxel is placed somewhere else and a new stability check is repeated until stability is reached. The algorithm illustrated in Fig. 30 has been programmed into Dynamo in order to identify the new substructures that can appear when a new droxel is placed, and to check their stability. The algorithm can easily be extended to 3D structures.

Once the stability check performed for the whole structure, the laying sequence is known and a file can be written, detailing the successive coordinates of the UAV between the material stock pile and the place of construction, the speed and flight paths to follow. Reducing the travel time can be achieved by optimizing the travel distances, using the shortest path between the stockpile and the final position of the droxel. One way to solve this problem consist in using the Dijkstra's algorithm which finds the shortest path between two coordinates while avoiding known obstacles [28].

Finally, structures made out of droxels could be designed according

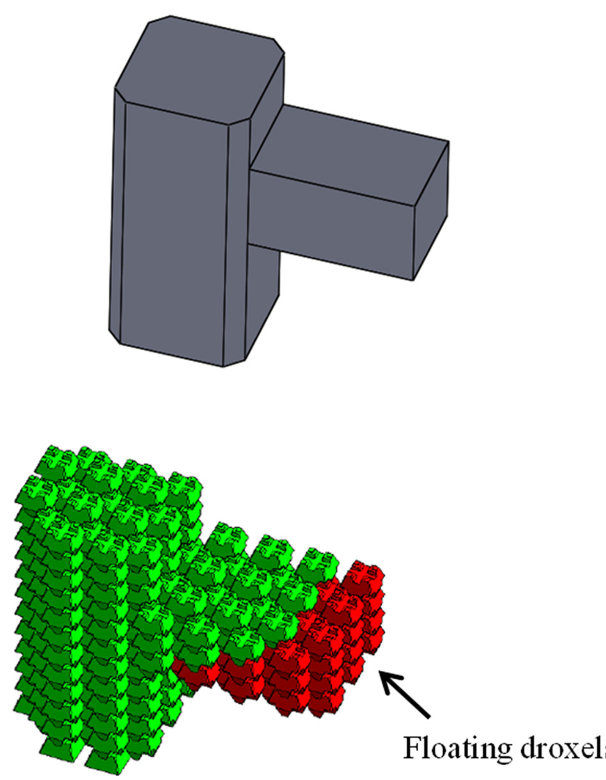

Fig. 26. Identification of floating droxels.

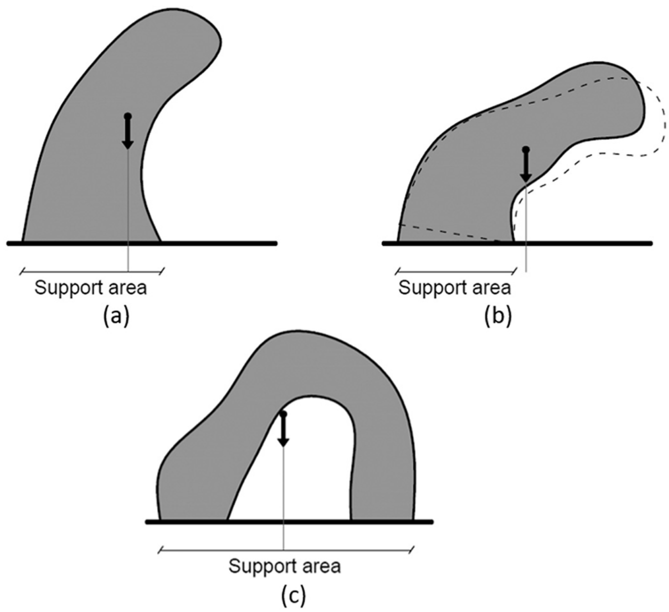

Fig. 27. The instability of a structure depends on the position of its center of gravity: (a) a single support stable structure; (b) a single support unstable structure; (c) a multi-support stable structure.

to a resource-efficient 3D-printed strategy such as the one proposed by Craveiro et al. [35]. In this work, concrete components are produced with a spatially variable composition, depending on the level of stress. This strategy applied to a structure composed of droxels could help reducing its weight.

6. Results of the experimental tests

6.1. The custom built UAV

For this research, a custom built UAV has been made, which is a quadracopter equipped with four pairs of 2 kW motors powered by two batteries 6 s Lipo 22 V/22 Ah, with propellers of thirty inches (76,2 cm). Its mass is about 12 kg (with the batteries) for a payload of 25 kg (blocks + handling system). Its overall dimensions are given in Fig. 31. According to the lab tests, the UAV is able, with one set of batteries, to lift and assemble about 200 kg of materials, at a temperature of 20 °C (the autonomy of LiPo batteries strongly depends on temperature). During the tests, the drone did not show neither uncontrollable leap upwards while laying the blocks, nor any kind of instability.

Solutions exist to increase the payload such as the increase of the batteries voltage from 22 V to 26 V (6 s to 7 s), the use of more powerful motors, and the replacement of 2 blades propellers by 3 blades propellers. However, these changes could have an influence on the autonomy.

6.2. Results of the tests with concrete conical dricks

The very first tests concerned the construction of a column composed of conical dricks. The aim was to evaluate the global relevance of the drone-based construction, and in particular to study the behavior of the drone while lifting, transporting and laying heavy loads. The lifting system consists in a 3D printed cone with an electromagnet that drops the load when a spring equipped with a switch detects that the drick as touched the one just below (Fig. 32). The system needs a steel plate, which is embedded into the upper surface of the concrete block.

The tests with the UAV were carried out inside the UCLouvain DroneZone with the help of a pilot using a remote control (Fig. 33). During the tests, the pilot was able to easily and repetitively take the dricks with the UAV and stack them on top of each other. The tests confirmed that the lateral tolerance of 6.5 cm (Fig. 7) is sufficient to allow an easy stacking. A greater accuracy is however expected from an automatic guiding system (discussed in Section 6.5). For these dricks, several concrete compositions were used (between compositions 2 and 4, see Table 1) and all of them gave satisfaction, even if some of these compositions provide a bad surface rendering.

The tests highlighted that the rigidity of the connection between the UAV and the drick influences the flight behavior and the laying

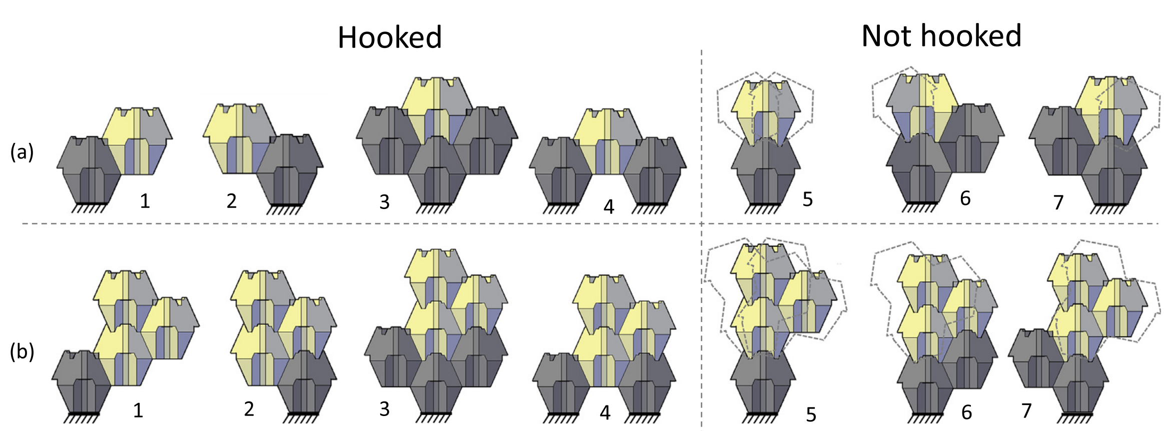

Fig. 28. (a) 7 possible cases when a new droxel is dropped; (b) 7 possible support condition for substructures.

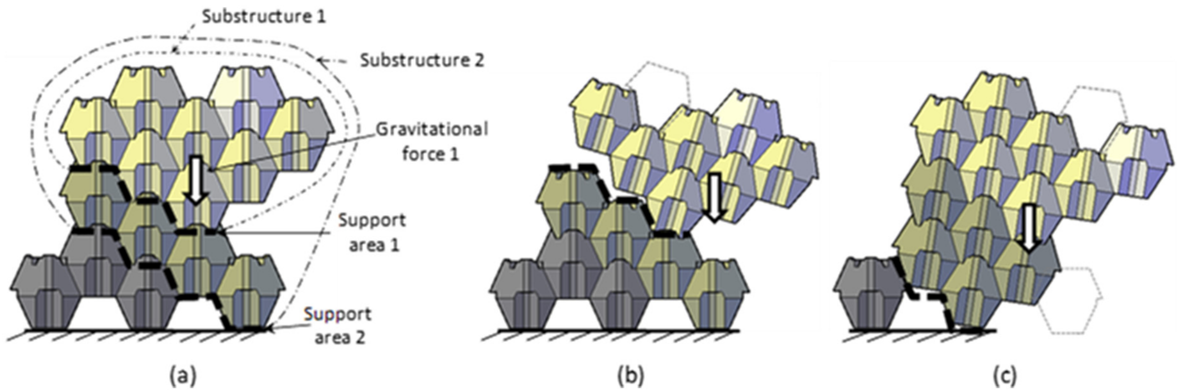

Fig. 29. (a) substructures 1 and 2 stable. (b) substructure 1 unstable. (c) substructure 2 unstable.

accuracy. As shown in Fig. 34, a too rigid connection not only prevents the UAV to incline itself (and thus to move horizontally), but also obliges some motors to give more power. At the contrary, a too flexible connection makes the block oscillating, destabilizes the UAV and increases the tolerance needed for the laying. An adequate compromise between both solutions is thus necessary. An

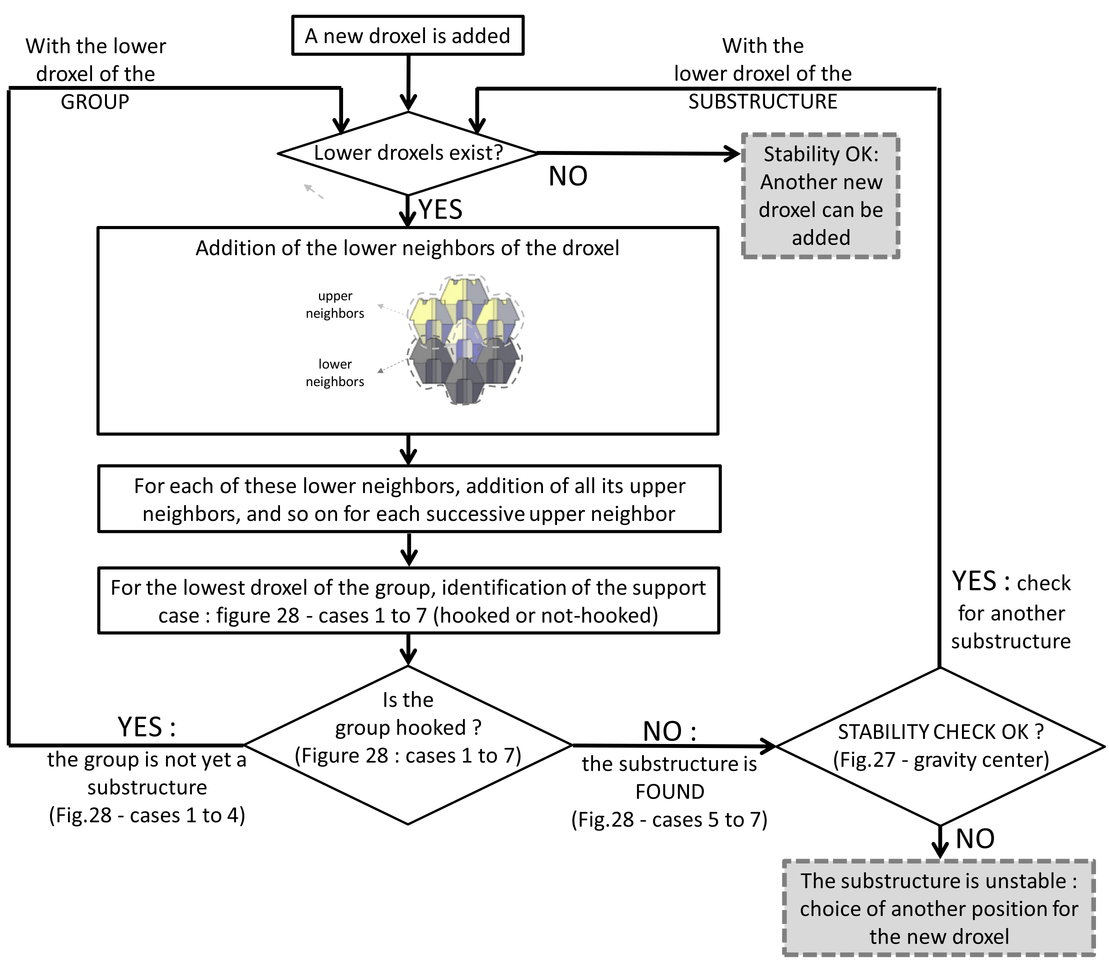

Fig. 30. Search for the substructures and stability check when a new droxel is added.

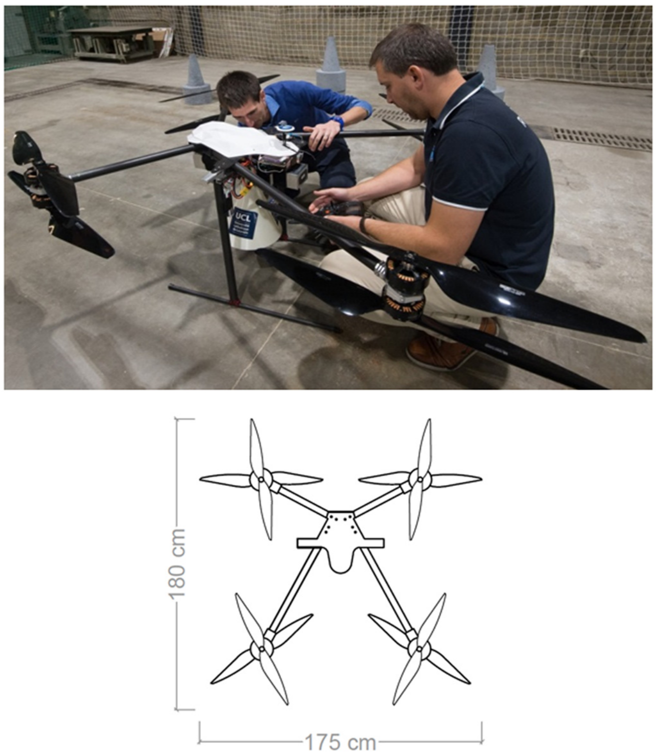

Fig. 31. The custom built UAV has a payload of 25 kg.

improvement of this system consists in adding propellers with horizontal axis on the UAV, which is under development and explained in Section 6.4.

6.3. Results of the tests with concrete rectangular dricks

The second series of tests concerned the construction of a straight wall composed of the rectangular dricks presented in Section 4.2. The tests, showed in Fig. 35, were also made indoor with a pilot using a remote control.

Several drick geometries with a laying tolerance of 5 cm were successively tested with several concrete compositions between composition 2 and composition 4 (Table 1). The tests highlighted the influence of surface rendering on the correct laying of the dricks. Regardless the composition used, blocks with 45° slopes did not allow a proper and repetitive laying. The design was thus adapted with an angle of 60° (Fig. 36), leading to the dricks of Fig. 8. With this value of 60°, concrete compositions similar to composition 2 had a sufficiently smooth surface rendering to allow a proper and repetitive laying.

The dricks in Fig. 8a have the inconvenient of having very fine and fragile edges and led to the improvement shown in Fig. 8b. However, this solution has the inconvenient to show a slight local imprecision while laying, with a cumulating effect that was not acceptable. This led to the third design shown in Fig. 8c. This last solution allows a proper and repetitive laying. As shown in Fig. 37 the lifting device is equipped with two electromagnets and a 3D printed system, and that requires two steel plates embedded into the upper surface of the concrete block.

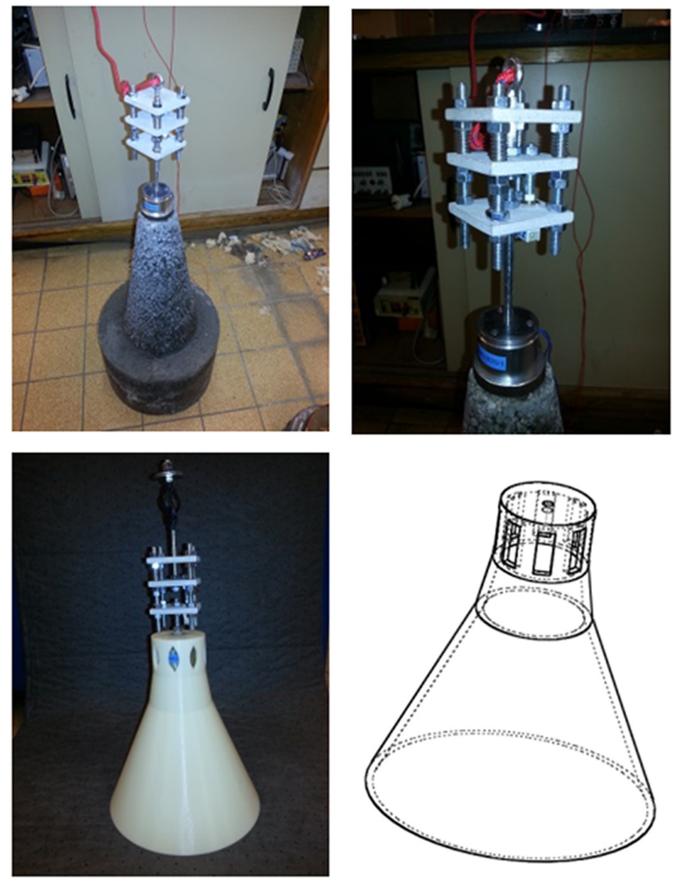

Fig. 32. The lifting system composed of a 3D printed cone, an electromagnet inside the cone, and a spring device that allows the automatic laying of the drick.

6.4. Results of the tests with a concrete beam

Tests have been made with a reinforced concrete beam with a mass of 20 kg lifted by a system also equipped with electromagnets. The extremities of the beam were shaped in order to fit the conical dricks, as shown in Fig. 38. The laying of the beam at the right spot has been uneasy for a reason linked to the UAV inability to counter the rotational torque due to the rotational inertia of the concrete beam. Indeed, to modify the angle yaw, the UAV has to adapt the power of a pair of motors, as shown in Fig. 39 (middle), but the resulting torque is not sufficient to counter the tendency of the concrete beam to keep on rotating, with the UAV. The consequence is the difficulty to regulate the yaw angle of the UAV. This experiment suggests that, for the transportation of long elements, UAVs should be equipped with propellers with horizontal axis that give a sufficient torque capacity. Such a UAV must have a flight controller that uses, one the one hand, the propellers with vertical axis only for the vertical displacements, and, on the other hand, the propellers with

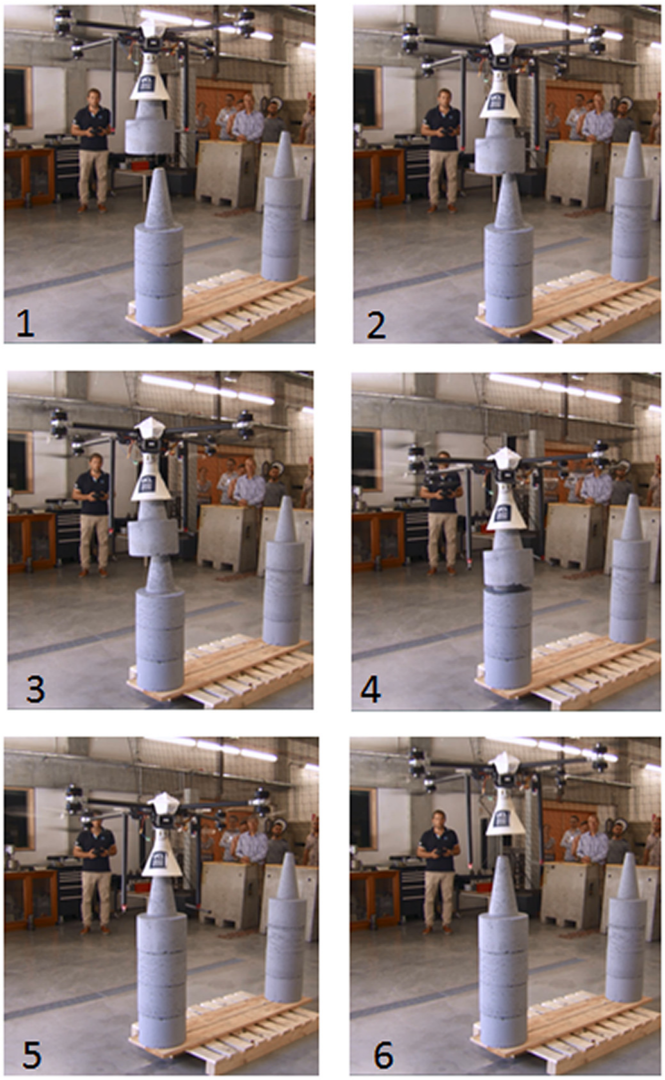

Fig. 33. Assembling conical dricks into a column (UCL DroneZone).

horizontal axis for the horizontal displacements and the yaw control. This is illustrated in Fig. 39 (right).

6.5. Drone positioning and guiding systems

The positioning of the UAV at the right spot and its displacements between the lifting spot and the laying spot are a fundamental aspect of the UAV-based construction. Up to now, the experiments have been conducted with a pilot and a remote control, but this solution is of course not compatible with an automated construction process such as the one presented in Fig. 1. Fig. 40 summarizes a few possible systems, although the current technology still does not provide any ideal system.

A first system shown in Fig. 40a is based on 3 pairs of on-board laser sensors, directed towards 2 perpendicular screens and towards the ground or the ceiling. A trigonometric algorithm allows to calculate the (x,y,z,yaw, pitch,roll) position of the UAV. This has been successfully developed by the authors and described in details in [30]. It has the advantage of being very cheap, simple, and accurate (a few centimeters). However the system has the inconvenient of needing screens around the construction site, whose flatness must be sufficiently stable and controlled. Practically, The system is thus only useful for lab tests, but very difficult to use on construction sites.

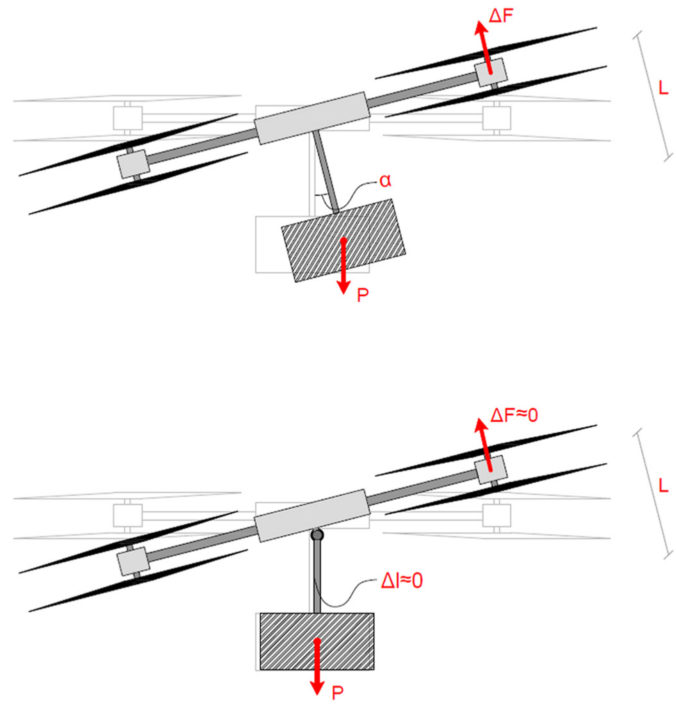

Fig. 34. On the left, a too rigid connection. On the right: a too flexible connection.

The second system (Fig. 40b) is based on a combination of global GPS and local GPS (RTK, Real Time Kinematic). The RTK system improves the precision of the GPS signal thanks to an information coming from one or several ground stations. The system was tested outside and, although in the best conditions it can theoretically reach a precision of the order of 1 cm, it can be strongly disturbed by trees or neighbor buildings. Moreover, this system works only outside. The precision and reliability of this system is thus not compatible with the drone-based construction, although this conclusion could change in the future with the improvement of GPS systems.

A third system used by some researchers [15, 17] is an optical tracking system (like Vicon), which is based on image analysis using several cameras placed around the experiment site (Fig. 40c). Such systems are very accurate in laboratory conditions but require the installation of several very expensive cameras with a precise calibration and they are thus mainly used indoor and in a stationary setup. Therefore, the solution is not adequate for an outdoor on-site use.

A fourth system shown in Fig. 40d uses a total station, which is a frequently used for topographic surveys at construction sites. It

Fig. 35. Construction of a wall composed of rectangular dricks.

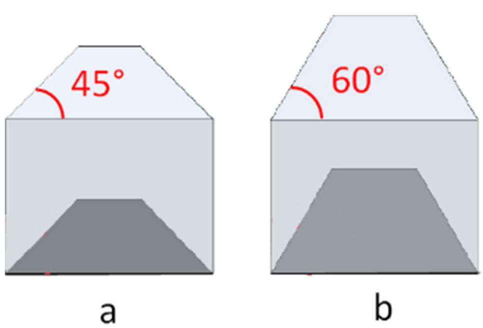

Fig. 36. Modification of the angle to ensure a proper and repetitive laying.

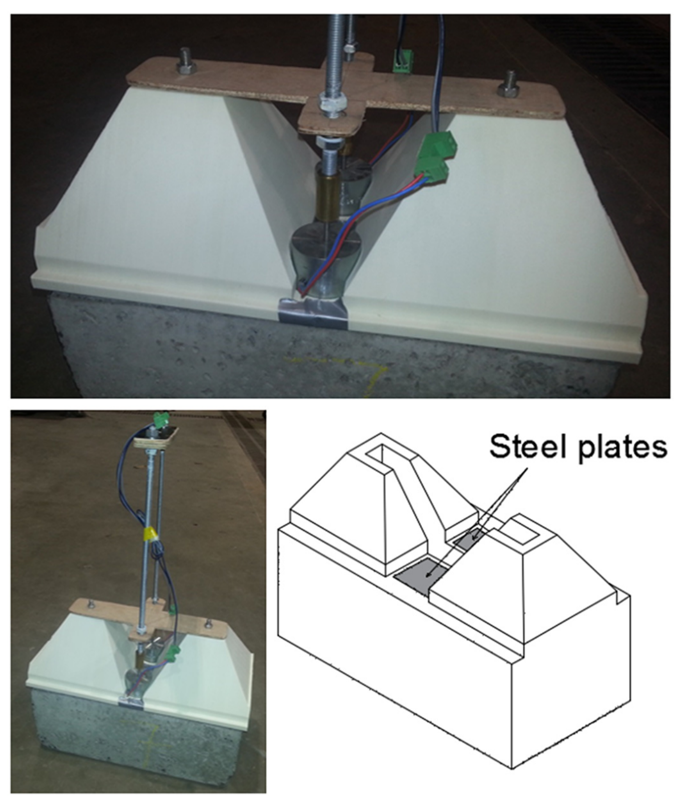

Fig. 37. Lifting system for the rectangular drick.

measures the horizontal and vertical angles between two targets, as well as the distance of these targets. The distances are measured using a range finder infrared or laser, which allows measurements in inaccessible places. The measurement is done using a reflective prism used as a target. In our case, the prism is placed on the drone. The feasibility of this system combined with a drone has been proved by a team of researchers from Stuttgart [33]. This system has the advantage of being very accurate (precision of a few mm) and uses very common equipment used on construction sites. However the system has also disadvantages: first, one total station can only guide one drone. Secondly, the system sometimes loses the target, which is likely to create a drone crash. The coupling of this system with

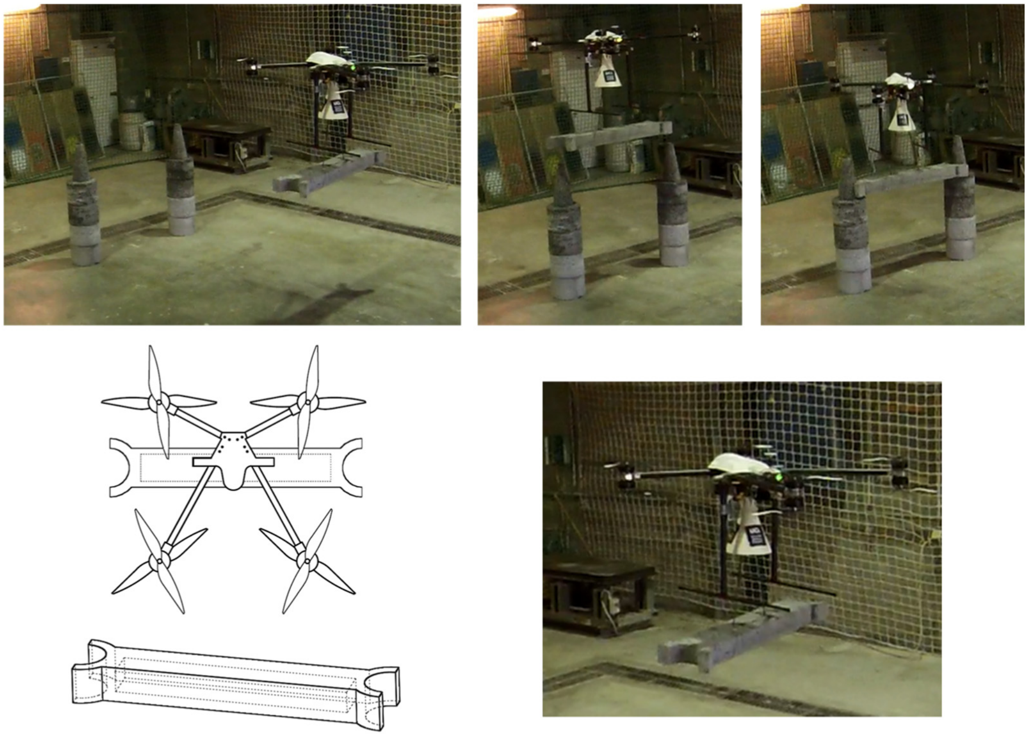

Fig. 38. Lab tests with the concrete beam of 20 kg.

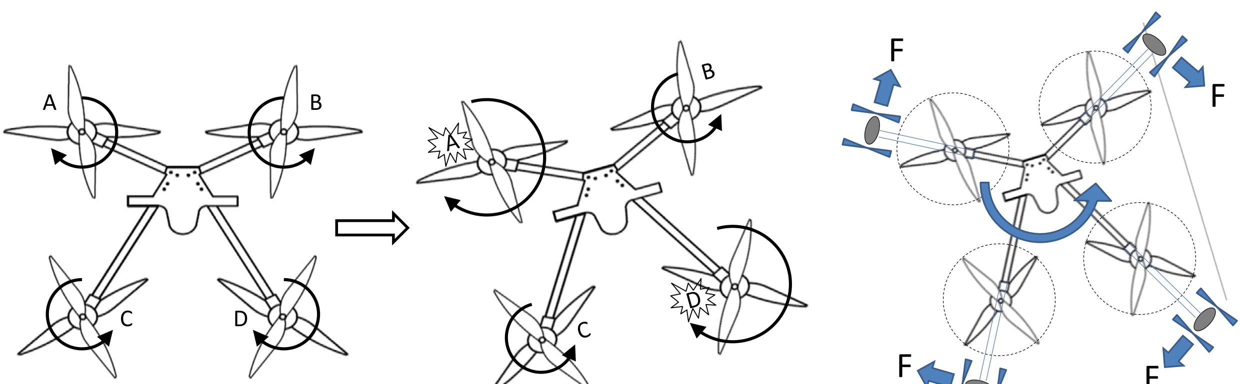

Fig. 39. UAV rotation. Left and middle: yaw control of a UAV. Right: Schematic view of UAV equipped with propellers with horizontal axis, allowing the UAV to better regulate the yaw angle while lifting long construction elements.

another positioning system such as the UWB seems relevant (UWB = ultra wide band, which can guaranty a precision of the order of a few tens of centimeters both indoor and outdoor). With such a system, the UWB could be used to guide several drones at the same time, while the total station would guide each drone successively and more precisely when they arrive on the laying spot. The UWB system can also be used as a backup when the total station loses the target. A last disadvantage of the system is that the compass of the drone remains essential, while its precision can be badly affected by metallic structures, for instance while indoor tests. Fig. 41 illustrates the system, under development by the authors, based on a total station combined with the UWB.

7. Discussion, conclusion and futures developments

About the drones, the experimental tests showed that a 12 kg drone could lift and lay concrete blocks above 20 kg without showing neither uncontrollable leap upwards while laying the blocks, nor any

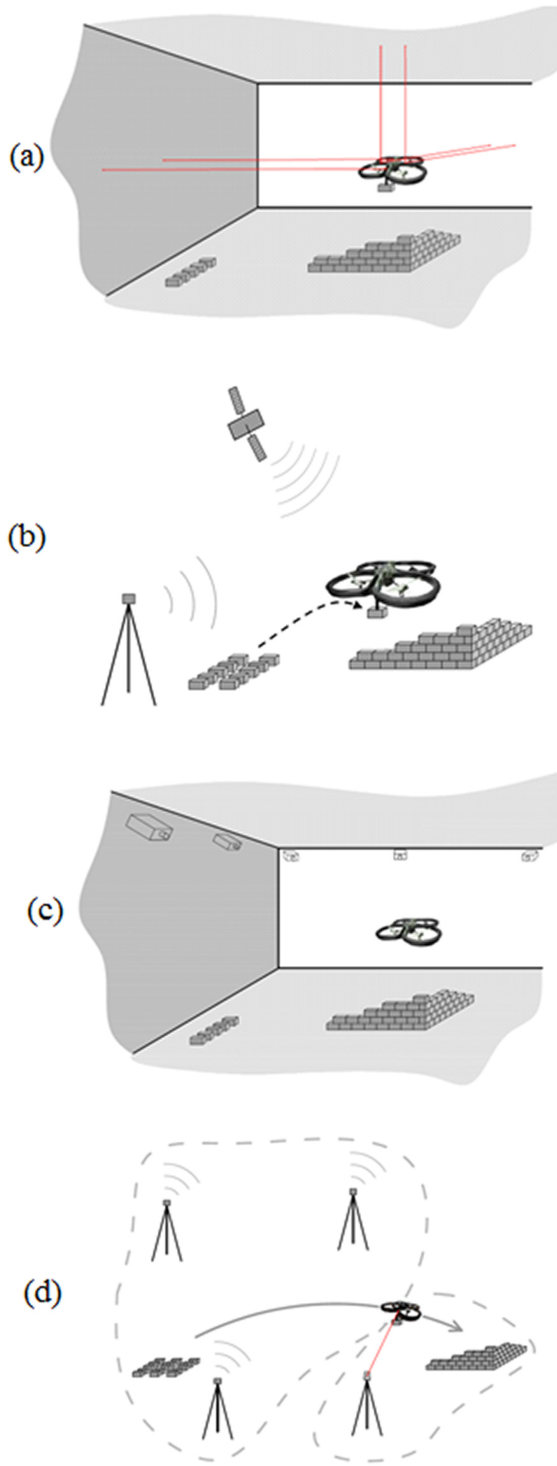

Fig. 40. Several global positioning systems for UAVs: (a) the laser-based positioning system; (b) the GPS-RTK system; (c) the Vicon system (or equivalent); (d) the total station system eventually coupled with an UWB system.

instability or oscillation. The experiments were led with an experimented pilot and a remote control and proved that the geometry of the blocks had to allow a laying tolerance of 5 cm. However, developments have to be done, both for the flight controllers and for the propulsion systems, in order to improve their stabilization when transporting longer and heavier elements. Several systems were developed in order to allow an easy "plug and lay" of the concrete blocks, all of them equipped with electromagnets combined with embedded steel plates into the blocks. Although very efficient and low power consuming, this is however a limitation for a future industrialization process: steel plates will have to disappear and the lifting system probably adapted. Concerning the global guiding system, the solution that combines the total station with another one like UWB seems to be the one with the minimum disadvantages and worth developing. The research also shows the necessity to combine a global guiding system and a local one, such as image analysis, that allows the UAV to lay the load at the right place despite his movements around the theoretical position. In this field, creative solutions are necessary to get rid of – or reduce at its minimum - the necessity to develop construction systems with too particular (and thus costly) geometry. Outdoor or wind tunnel tests should be performed to re-evaluate the range of the "drone compatible" character. Finally, depending on the construction system, developing ways to allow the UAV to cling to the existing structure before placing a new element seems to be another relevant field of investigation.

About the masonry blocks, two solutions emerged from the research: the drick presented in Fig. 8c has a geometry that shows an excellent behavior for the construction of "simple" walls, while the droxel has a much more complex geometry with some configurations showing a poorer "DC behavior". However, droxels have the great advantage of making it possible to build complex architectural shapes and covers, without the use of scaffolding.

About the construction processes and the link with BIM models, paragraphs 5.2 and 5.3 showed that special rules for the drixelization/droxelization and the stability check at each step of the construction can easily be listed and programmed with the use of software like Dynamo, combined with Revit. The next probable revolution in the field of construction is the link between BIM models and clouds of UAVs combined with other types of robots that will build structures in a fully automated process. This revolution will avoid the need for execution paper plans that have to be translated on site by the workers, with all the problems of profitability and quality that this creates.

To end this conclusion, the possibility of designing UAVs capable of transporting building elements of several tens of kilograms and assembling them with a sufficient accuracy was appearing uncertain and even wacky at the beginning of this research project, but seems now obvious. Although the limitation on the transported mass has an impact on the possible spans and the multiplication of the number of connections between construction elements, the developments about the dricks and droxels show however that solutions exist to build large structures composed of many small elements. Timber construction also opens an interesting investigation field, given the good ratio resistance over self-weight of wood. Fig. 42 shows some experiments about UAV timber construction, more described in [32].

Concerning the cost and the CO2 balance, a field that is not detailed in this paper, a first approach [20] tends to show that the UAV based construction is competitive. However, there are few doubts that in the future, the cost and CO2 balance optimization will require the adequate combination of different kinds of flying and non-flying robots.

This research opens up infinity of development perspectives, both in

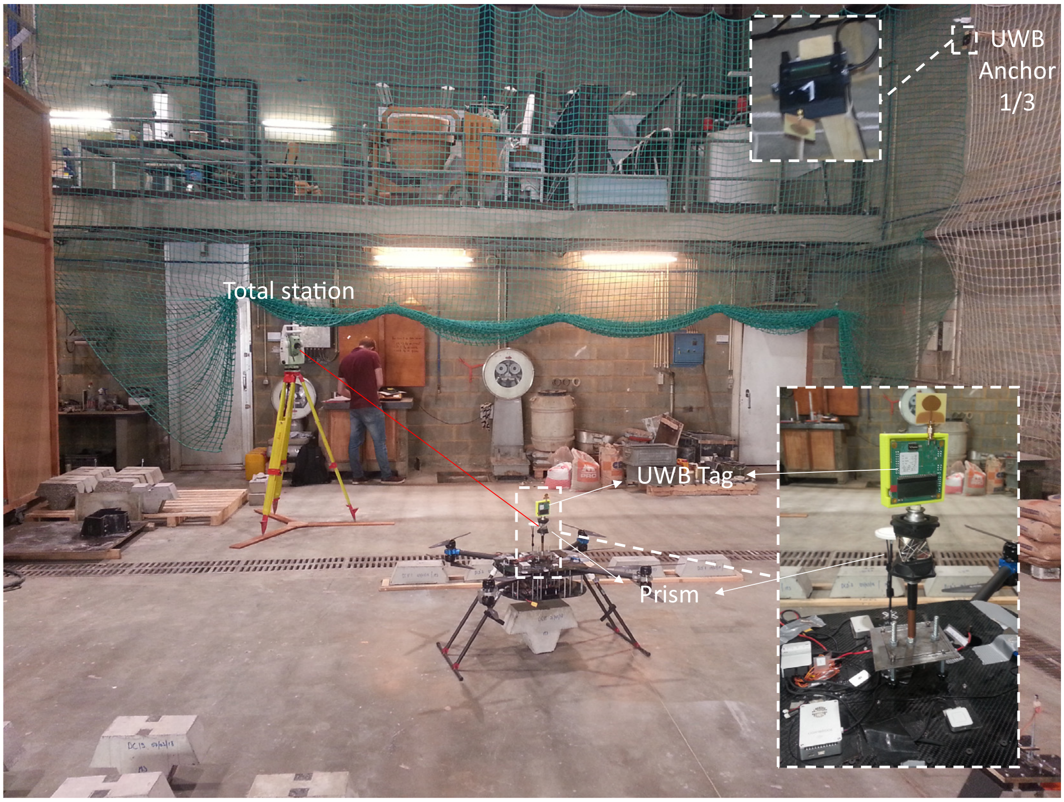

Fig. 41. The total station combined with the UWB system.

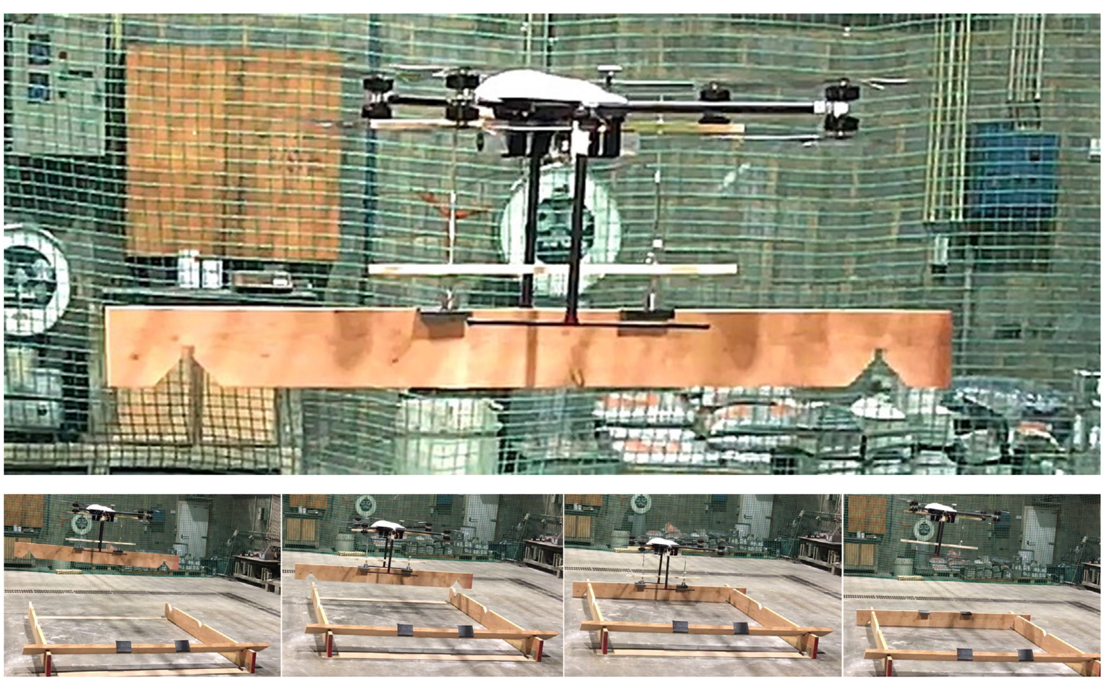

Fig. 42. A lab test with the drone assembling timber beams.

the UAVs themselves and in the “UAV compatible” construction systems. Authors are convinced that all kinds of robots will spread in the construction sector in the next decades.

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