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Will drones have a role in building construction?

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Abstract. This paper aims to explore the possibilities that robotic technologies, namely robotic arms and drones, bring to architecture and to the construction sector. The developed research was based in an extensive literature review, in the conceptualization of three experiments to be done with drones and in interviews with Fabio Gramazio, Tobias Bonwetsch (ETH Zurich) and José Pedro Sousa (FAUP). The paper starts by presenting a brief story of the introduction of robotic technologies in other industries and identifies the robotic technologies that are presently use, mainly in research, to assemble construction elements – drones and robotic arms. We then analyze the few case studies of construction performed with drones and robotic arms. Three experiments are idealized next in order to clarify the main difficulties of each action of construction performed by a robot. The advances in robotic construction are visible and growing every year. According to the experts robotic construction will be introduced in the construction industry in a hybrid way, where man and machine collaborate and not as total substitution of human labor.

Keywords. God, Creation, Adam, Eve, Architecture

Introduction

This paper intends to explore the hypothesis that robotic technology can bring to the construction industry. Taking into account the use of robotic elements in other industries such as naval, automotive and computer components, it is questioned here how these technologies could be used for the building construction industry and what would change in this industry by such an use.
Robotics technology has changed the method of production and the final products in several industries. In fact, industries like naval and automotive have embraced robotic construction and their operating modes and the final products have changed considerably. Our goal is to explore the possibilities of robotic technology considering the assembly part of construction, both with robotic arms and drones.
Robotic arms in architecture industry are used mainly to digitally fabricate by subtracting but there are some experiences worldwide using them for the assembly of construction elements, yet this use is rare and limited to experiments carried out at purely university level, which have been applied on few occasions in practice. The use of drones in the construction sector has increased considerably in recent years, mainly due to its use for 3D scanning and photogrammetry. In these cases drones serve to fly over the areas that will have an intervention and carry cameras, video cameras or sensors in order to collect data from the sites. The use of drones to assist the assembly of components of the construction has a much smaller advance than the similar one with robotic arms, and is limited to a few experiments carried out by universities, which seeks to explore how this technology can be used to build actual buildings. Experiments undertaken at ETH Zurich by the team of Gramazio Koehler Architects as "Flight Assembled Architecture" and "The Aerial Construction" with drones and with robotic arms, "The informed Wall" also by Gramazio Koehler and the "On the Bri-n-ck" by Ingeborg M. Rocker from Harvard University are very good examples of the use of such technologies. (ETHZ, 2017a; Bonwetsch *et al.,* 2017)
This paper is divided into five sections. We will start by analyzing the impact that robotic construction had in other industries, such as automotive, naval, and shoes making. In the second section we address the current state of the art of robotic construction in architecture by describing the technologies involved, the experiments undertaken and the opinion of the international experts. Section three describes the conceptual design of an experiment underdevelopment and in the last section we discuss the work and conclude.

1. New technologies in industry

The automotive industry has been the paradigm of the usage of brand new concepts, having Henry Ford applied, for the first time, the concept of assembly line in the production of his famous vehicles. This concept, developed by Frederick Taylor (1856-1915) decomposed complicated tasks into simple ones, by measuring the minimal amount of time required for each task. This process forced the workers to follow those tasks while leaving their own living conditions and needs on hold. In the beginning of the 60's, robotics were introduced in the industry and, ever since, this technique has been perfected so that robots execute specific functions such as welding, painting, fusing and assembling pieces allowing lower costs for the production (Ahlborn, 2016).

The *Lexus* factory is the current prime example of the use of robotic usage. In it, the robots, in the assembly line create and connect all of the pieces until its final product, being the quality check the only activity performed by man (Friedman, 2000). Subsequent to the utilization of technology and robots, the automotive industry is considered one of the most advanced (Jürgens et al., 1993), in fact, during 2013, 70.000 new robots were installed in many factories, increasing the worldwide production by 90 million units (Jürgens et al., 1993).
Just like the automotive industry, the naval industry has constantly been at the forefront in the use of technology for the construction of larger vessels. In this industry, robotics has been applied in four tasks: welding, painting, rivet and assembly of pieces of larger proportions during their construction (Rooks, 1997).
Contrarily to the automotive production, the naval industry, due to the size of some vessels, can't work on an assembly line, instead it works by collecting blocks produced in outsourcing and assembled them at the shipyard. In the industry of recreational crafts of smaller proportions, the process of construction only differs from the automotive due to the fact that the vessels must stay put at one site during the whole process, forcing the robotic arms and the workers to move sequentially in an assembly line parallel to the vessels. Some producers use robotic arms to reduce construction time and human imprecision. According to their sources, the total control of geometric robotic construction allows the creation of vessels with perfect aerodynamics ("BAVARIA YACHTS", 2017).
Also in the production industry of computers and their components, the replacement of the workers for smart machines have been taken place, through an assembly line in which the intervention of men in the manufacturing of the final product is not necessary.
In 2011, Foxconn, the biggest enterprise of manufacturing in electronic components and computers in the world with more than a million workers, installed 10000 robots (foxbots) capable of making simple tasks such as assembling, spraying and welding. Ever since these events, foxbots have been replacing workers and increasing the volume of production (Davidow and Malone, 2016).
Also in the shoemaking industry, smart robots are being developed for companies like ADIDAS, by using 3D technology, which will therefore allow a lesser need for human workers, thus surpassing the complex creation of shoes, increasing their production and customization (Patten, 2016).
It's nevertheless essential to mention that in the Premium sector, the tendency for robotization has not been as favourable. Many brands are betting on the hand-made as an added value to the product due to their exclusivity (Fionda and Moore, 2009). As an example, Mercedes-Benz has been developing new models exclusively hand-made, reversing the current phenomenon of robotization instead of humans in the assembly lines (Rico, 2016).

2. New technologies in the construction industry

2.1 Drones and Robots

The Robotic Arm (RA) is a robot that functions much like a human arm, being able to function autonomously, or as a part of a more complete robot. The RA is a programmable manipulator, composed of rotational or linear segments that control the precision of their movements (Harris, "How robots Work"). On the extreme end of the RA, usually there is a tool which is able to move, position and manipulate objects, this could potentially be a milling, to cut, or a tube to deposit material. In the Naval industry, the RB can execute tasks in ship hulls such as electronic components in a faster and more versatile fashion rather than the human hand. Also in the automobile industry, the RA is used in the assembly line, improving the managing of time consumption and precision (Anona 2017; Harris,"How robots Work").
The drones are unmanned aerial vehicles. They are manually commanded through remote control, travelling under real-time human control, or programmed by using integrated systems of digital control, such as sensors, radars and GPS (Margaret Rouse, 2017).
The military drones, were primarily used in aerial platforms, reason why they were designated as UAV (Unnamed Aerial Vehicles). The first UAV, Havilland DH82B from 1935, was piloted by "servo-operated controls", being regularly used as a target. Nowadays, UAVs have been slowly substituting manned aircrafts (Pereira da Silva, 2014). In Afghanistan, the UAVs have been used for acknowledgement and recognition of terrorist targets (Pereira da Silva, 2014). In land, the drones have been used in Syria to replace the tanks in the defence of Russian bases, and are expected to replace other armed systems thus bearing less casualties, even though many ethical and deontological problems arise. (Joyner 2014)
Civilly, drones are used in research during rescue missions, mapping, photographing, and even in the movie making industry. They also serve purposes like material deliveries in hard access zones; and in commercial aviation, monitoring of traffic, meteorology and even riving of cars. Drones have in three usual dimensions: miniatures, medium sized and large; the first ones are used as indoor amusement

(hobby), the seconds (c.15x15cm) are used outdoors mostly to film and photograph, and the last ones (c.30 a 40 cm) can fly outdoors without pre-required conditions, as seen in the Amazon project, which grants the delivery of packages up to two kilos (Amazon, 2017). The manually commanded drones reach up to a distance of 1.5 kilometres, while the Export System can reach up to 50 kilometres and 200 meters high, and 50 mph of speed, being able to fly between 5 to 40 minutes, depending on their batteries, tasks to execute, speed of wind and weight of the shipment, which can vary from 1 kg to20 kgs (Dronelli, 2017).

2.2 Case Studies

In this section two examples of robotic construction developed by the team of Gramazio Koehler Architects at ETH Zurich, the project *Flight Assembled Architecture* (ETHZ, 2017) and the project "The Aerial Construction" (Mirjan et al, 2016) will be analyzed.
During the year of 2012, Gramazio Koehler and the robotic engineer Raffaello D'Andrea programmed drones capable of lifting and assembling thousands of bricks, in the center FRAC in Orleans. The project "Flight Assembled Architecture" was a pioneer in the assembling of pieces by drones. A structure with 6 meters high by 3 meters in diameter was built, with 1500 polystyrene's parallelepipeds (weighting around 100 grams and measuring 10x30x15 cm (ETHZ, 2017a)). The project intended to verify the feasibility of the construction of buildings by drones (Hobson, 2015). Four drones were necessary, each one of them possessing servo-powered pins that cut a hole through the brick and hold it during the flight, a blueprint, a foreman, and a construction team. It was verified that the faster the flight occurred, the less external disturbances, such as turbulence and collisions, happened and smaller error margin. In the case of an inferior speed and a softer landing, the error margin was higher (Mirjan, 2014).

In 2006, in ETH Zurich, the *Informed Wall Project* was developed, led by professors Gramazio and Kohler with the collaboration of post-grad students. Each student conceived a project, pursuing the goal of building distinct brick walls by using robotic arms to test their architectonic potential. In this experiment students had to use a robot with 6 axes, with an intervention area of 3x3x8m, capable of building architectonical components at a real scale. The robot needed to be able to construct a space using different materials, processes and construction shapes, with no exogenous interferences, reaching any point in the tri-dimensional space, and executing all the tasks as predicted by the Edeffector programme (Bonwetsch et al., 2017). In the experiment traditional bricks were used. A claw was attached to the robotic arm in order to grab, lift and place each brick in its correct place. It was also necessary the development of a computer script capable of translating the CAD data in coordinates by using the MAYA software. With the combining of the software and the chosen material, many wall prototypes were produced, concluding that the robotic arms can be used in a simple way in repetitive tasks with simple geometries by quickly placing bricks with a minimal error margin. The team concluded that in order to execute more complex geometric shapes, a bigger investment in software and hardware is essential (Bonwetsch et al., 2017).

2.3 The opinion of the experts

To help the discussion of the future of robotic assembly, direct testimonies from some of the most relevant protagonists worldwide in this area were obtained: the architects Fabio Gramazio, pioneer in robotic construction and responsible for the creation of a robotic Lab for architecture research "Laboratory for Architecture and Digital Fabrication", in ETH Zurich; Tobias Bonwetsch researcher in the ETH Zurich Robotic Lab and co-founder of the ROB Technologies company; and José Pedro Sousa co-promoter of the OPO'Lab project, co-founder of the architecture practice ReD, Research+Design and professor in Universidade do Porto.
Many questions were posed to these specialists with the goal of obtaining their opinion on the future of robots in architecture. Gramazio opinion is that the current robotic technology can already be applied in construction. In his developed experiments it was established as a pre-condition the necessity for the existence of a system of sensors and a system of independent controls, for the usage of drones in construction. Regarding the processes of conceiving architecture, Gramazio referred that, due to the proximity of the robots emergence, we can only speculate on the impact of robotics in architecture, even though we do acknowledge, through history, that the new technologies have consistently transformed the form of thinking and acting. To Gramazio this technology is disruptive and will only slowly enter the construction industry due to the massive cost difference. Gramazio predicts that its utilization will only happened in zones with difficult accesses, e.g.nderwater. Gramazio also referred that a hybrid system, in which the human and the robot work together, will be the most likely attainable. He also believes that the intensive use of this technology in the future is nothing but pure speculation and a 50 year advanced prediction is very difficult to do. Bonwetsch shares the same opinion, adding that this technology may

reduce the work related accidents and its introduction will also affect businesses economically, socially and aesthetically on the expected final result. Pedro Sousa is also of this opinion, further adding that robotics may already be applied on the construction of pre-made elements in controlled environments.

3. An experience with drones

In order to understand on the one hand the advantages and on the other, the complexity involved in the construction process with drones, three conceptual experiments were developed that will be put in practice in the following months. Each one of the three experiments holds a higher grade of complexity and intends to demonstrate different investigation hypothesis. The first of the three described experiments constitutes the theoretical basis of the two following. The first experiment consists on the construction of a brick tower, the second is the composition of a flat vertical brick wall, and the third consists on the assembly of a geometrically complex brick wall. All of the described experiments consist on the construction of objects through the piling of elements, using drones. With this goal in sight, we chose a simple construction where patronized elements, such as clay bricks, are assembled.

The experiences were to be done in a controlled environment, preferably indoors through technologies that can provide a complete mapping. In order to do so it is essential to provide a space covered by sensors much like a tridimensional grid, in which any point in its space corresponds to specific coordinates.

To the practice of the previously explained experiments, the following equipment is essential:

- Two professional drones, with claws attached capable of carrying up to 1 kg bricks, or adapted commercial drones: DJI, 3D Robotics or Parrot.
- A tablet with an Android system
- Digital and tridimensional drawing software (e.g. Rhincoeros, Maya, 3D Studio max, Revit);
- Drone control software
- Coordinate control sensors for indoor action (beacons, a proper location with a source of wi-fi with resource to triangulation, on-board systems with autonomous navigation, collaborative systems, with many drones, data fusion in the many software, drone sensors and the localization systems as previously mentioned)
- Brick dispenser
- Bricks

The first experiment [Image1] envisage a construction using two drones of a vertical wall with overlapping bricks, only secured by gravity. A circular route, defined in a specific software, allows that a drone is directed towards the brick dispenser, while the other is placing a brick in the predetermined coordinates. The dispenser, found at a specific location, places a brick in the exact same coordinates every time. The drones are placed on a table, from where they departure and land to rest, alternately flying towards the dispenser. While the first drone displaces towards the dispenser, grabs the brick, carries it to the construction coordinates, lands and let go the brick, the second starts flying towards the dispenser, and do the same route as the first one. At the end of the sequential placing of the six bricks, the drones return to the starting table. The full process is controlled by a software, in a controlling computer, showing in real time the construction process and the drones' routes. The trajectories of the drones must be previously planned and constantly corrected in order to minimize possible brick placement errors, as exemplified in the experiment *Interactive learning project*, at ETH Zurich by Raffaello D'Andrea, who corrected several errors post identifying them.

The second experiment [Image2] consists on the built a flat vertical wall made entirely out of bricks, assembled in a traditional way and also fixed only by gravity.

The goal of this experiment is to compare the construction process of a traditional brick wall by a bricklayer man, with another built by drones, comparing bot time spent and final quality. On the first model, the construction coordinates X and Y were always the same, only changing the coordinate Z. In this second model the bricks would be placed in changing Y and Z coordinates, keeping the axe X.

The third experiment [Image3] consists on the creation of a curved wall, created by several rows of brick spaced between them. The experience allows to compare the precision obtained by the drone assemblage in a complex geometry design. In this model, each brick has a specific coordinate in order to create the wall's curvature, leaving a two quarter space between them ensuing for the upper rows to have a sitting area on top of two bricks. Each one of the brick is placed according to its coordinates in Y, X and Z. For the construction of a wall, with this sort of complexity, it's essential to perfect and calculate the trajectory of each drone, in order to place the bricks with minimal error in their exact position.

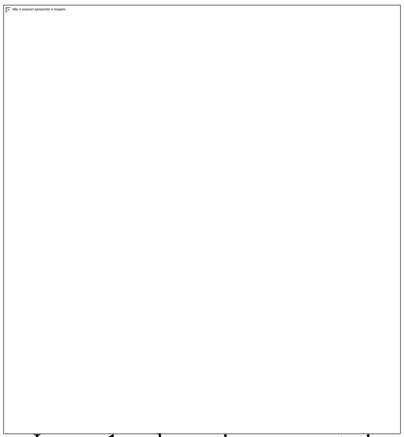

Image 1- schematic representation of the tower using 6 bricks, experiment 1, elevation and plant, by the author.

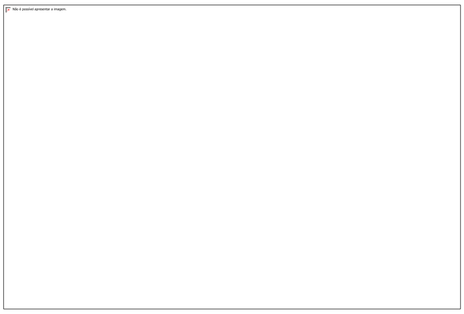

Image 2- schematic representation of a traditional linear wall, experiment 2, by the author.author.

Image 3- schematic representation of the pattern of the wall created, experiment 3, by the author.

4. Discussion and Conclusions

After analysing the pioneer industries on the implementation of robotics in production, we can identify that the construction industry has resisted the introduction of robotization. The construction process is still slow, imperfect and highly expensive, depending, almost entirely, on human work. This situation may be altered with the introduction of construction processes that include robotization, mainly with the aid of drones and robotic arms. The use of this technology may, in similarity to what happened to other industries, come to alter the construction industry, allowing to e.g. execute low standardize cost houses. The possibilities that these technologies bring may allow to: i) build complex shapes nimbly and with little to no errors, ii) promote the usage of new materials by the new acquired assembly flexibility; iii) idealize architecture in a new way, enabling the use of free shapes. The robotic arms and the drones may be used simultaneously, with different tasks, in order to assemblage a building as a whole, and reducing the human error and speeding the building process.
The two experiments with drones introduced in chapter 2.2 were successful, namely in the construction of tensile structures (through tessellating) and the construction of a brick wall (through deposit). Nowadays, this technology is available but more financial investment and will is necessary to make this process grow and be applied in practice. Both drones and robotic arms allow a faster construction, with less cost, that enables to explore new shapes and materials, and introduces a new way of thinking that may re-project architecture.
The interview to three architects that work in the areas in analysis revealed that, proved to be very relevant. Even though the technologic evolution is developing quite fast, the experts' opinion is that it will be difficult to apply in a near future to the construction industry. They referred that this slow introduction is the result of the high cost of the drone application that may only be justified in extreme cases as submarine construction or in dangerous situations. To these architects, the introduction of these technologies will only begin with the application of a hybrid system, man-machine, due to the fact that the technology is currently midst development, and not capable enough to respond to the *in situ* situations. Nevertheless, for Pedro Sousa, says that during the pre-fabrication in controlled environments, this technology can already be applied. It was unanimous that whatever prediction with drones is pure speculation.

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