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Dry and Liquid clay mix drone spraying for Bioshotcrete

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Abstract

"Bioshotcrete" is a new technology being developed by a team of robotic experts, architects, engineers, and drones' specialists, aiming at using drones in the construction industry to spray natural materials over a temporary light formwork until a self-standing shell is completed. This technique consists in projecting paste-like matter composed of clay mixes following precise and customized deposition sequences over a temporary formwork, incorporating computational techniques in the design and fabrication stages, therefore proposing a more sustainable version of shotcrete. In particular, this paper features experiments using drones for spraying wet and dry ranges of clay mixes over a reusable inflatable formwork with the purpose to build monolithic earthen shells. The featured case studies propose specific protocols to control different deposition sequences, describing the proper formulation of clay mixes, the design and production of customized spraying devices, and fitting options in the drone allowing to vary pressure and other drone spraying parameters. The development of Bioshotcrete using robotic fabrication strategies could help expand and transform existing construction methods and processes to be applied at large scale, therefore incorporating innovative digital fabrication protocols towards a more sustainable building construction realm.

Keywords: Shotcrete, drones in construction, earth architecture, digital fabrication, on site fabrication, prefabrication.

1. Introduction

The use of robotics offers a valuable opportunity for experimentation in the construction industry, due to significant advancements in digital fabrication techniques, the fast progress in computation related to new design protocols and interfaces, and the appearance of novel material-tools calibration experiments. As a result, a new technology denominated "Bioshotcrete" is being developed since 2013 by a team of robotic experts, architects, engineers, and drones' specialists, aiming at easing the process of spraying natural materials over light or lost formwork. This process starts by formulating precise compositions of diverse clay mixes, defining specific deposition sequences, and calibrating robotic fabrication devices, culminating in the robotic deposition of diverse clay mixes sprayed on a temporary formwork, which prove to be crucial for the result of a successful self-supporting shell.

2. Origins of "bioshotcrete"

Spraying concrete on inflatable formwork has a long tradition in shotcrete, a construction method in existence since the 40s, where concrete is pulverized by workers holding a deposition apparatus positioned at different levels of a scaffolding. This technique was developed by Dante Bini with the Bini domes (Kromoser, 2016), and was widely expanded for different types of constructions, including civil works, buildings, swimming pools, etc. Since its inception, several improvements have been suggested to overcome some of its limitations, such as keeping constant pressure and spraying flow while the concrete mix is applied, and some authors have suggested that considerable improvements can be achieved by incorporating robotic actions to spray the material (Hennick, 1989). An alternative to spraying concrete mix was introduced by Concretecanvas, offering a prefabricated phase of readymade slices of textile and dry concrete that needs to be humidified by spraying water at a later stage. In parallel, a series traditional techniques have been developed over the last years, involving spraying liquid clay mixes over easily mounted very thick lost formwork of straw balls to generate domes under compression.

The use of temporary formwork has a long history in concrete construction in several modalities, such as fabrics, inflatables, and others. A series of experiments with temporary formwork were developed since 2013, which include self-standing arches supporting a stretched fabric to provide a shell defining surface serving as temporary support for the robotic spray a variety of clay mixes until the structure reaches a self-standing condition, at which point the temporary formwork is entirely removed (Chaltiel, Bravo, 2017). Further experimentations tested the suitability of using inflatable formwork based on advantages such as being recyclable, adjustable, affordable, and easily available off the shelf.

To inquire about the potential of using robotic fabrication in the construction industry based on shotcrete practices and temporary formwork deployment, a number of experiments have been conducted aiming to 3D print using additive fabrication techniques by spraying natural paste-like materials such as clay (Chaltiel, Bravo, 2017). This singular technique denominated Bioshotcrete, is based on a precise sequence starting by the material formulation, digital fabrication protocols, and robotic actions, which will be described below with more detail.

2.1. Material formulation

This research starts by carefully selecting biomaterials by revisiting traditional construction techniques (such as wattle and daub), studying mixes composed of clay, chalk, plaster, sand, fibers, stabilizers and water. The protocol for clay mixes deposition is heavily dependent on the formwork provided, the deposition apparatus and the robotic actions controlled by drones. Several prior experiments allowed the formulation of clay mixes suitable for the robotic spray deposition over a temporary formwork (Chaltiel, Bravo, 2017), establishing a strict protocol of materials to be applied sequentially in layers, as follow: Initial barbotine layer 1 Units (U) of clay + 2U of water, the middle layers containing on average 2U of clay 2 U water 3 U of fibers, and the upper layers contain 2 U clay + 2U water +3 U of stabilizers.

2.2. Digital Fabrication Deposition Technique

Existing automated mortar spraying equipment remotely controlled by the builder proved to be heavy, expensive, difficult to calibrate iteratively during the construction process, energy consuming, and difficult to bring to remote sites, such as the remotely controlled apparatus for shotcrete by Putzmeister (Ajaykumar R. Patel et. al, 2013). Alternative methods are proposed using aerial drone deposition based in two modalities: 1) Piped to a robotic arm, and 2) Aerial detached holding containers. A key aspect for the development and implementation of this technique is the use of drones ruled by precise deposition actions, which will be described next.

2.3. Robotic Actions

Spraying drones are widely used in several different domains, e.g. agriculture. For example, various automated solutions have been developed to bring precision and safety to farms and farmers (Sharma, 2016). In such applications, drones usually have to spray certain feature of the environment, e.g., spraying crops with pesticides. In both agricultural and construction robotics, an automated solution includes creating a map of the environment in which spraying drones operate. This may involve piloted flights in order to gather data for further process and create a 3D representation of the environment. This map can be enriched with various knowledge such as density, pressure, only to name a few. Given a map and an objective such as spraying the entire environment (shell), an automotive trajectory generator, called trajectory planner, computes a sequence of poses for an autonomous navigation of drones. The generated trajectory by the planner often must satisfy certain constraints that posed by the applications (Mansouri, 2017), e.g., temporal constraints on the order of places that have to be sprayed.

3. Case Studies

Two case studies (CS1 & CS2) were recently developed to explore robotic paste-like matter spraying deposition techniques over a light inflatable formwork. CS1 tested a large drone with spraying devices to deposit dry material separately from wet matter. CS2 tested the use of drone to apply different layers of clay mixes by calibrating Do It Yourself (DIY) spraying devices to deposit clay mixes over a 4 m dome.

The main parameters evaluated on each CS include:

1. Material mix described in mix composition, layers, sequence, and drying time;
2. Spraying tools of standard and customized devices;
3. Deposition technique parameters include Minimum Distance between Drone and Surface (MDDS); Velocity of Drone (VDS) which corresponds to the velocity of flight which vary according to the amount of weight being carried; Volume Deposited by Drone (VDDF) on each flight, and Volume of Matter Deposited per Second (VMDS), Energy used per Drone Trip (EDT) considering an average 10 min per drone trip.

3.1. Case study 1: Piloted drones spraying on inflatable formwork

Date: November - December 2017. Test by the authors with a drone specialist.
Equipment: Custom made drone RC Take Off; 2m wide; 8 kgs. weight; load capacity of 25 kgs.; 15 min. travel autonomy (depending on carried load).
This indoor experiment explored the potential of using a drone to spray wet and dry mixes from two separate tanks.

31.1. Phase 1 - Wet clay spraying

A Wagner Flexio heavy paint sprayer was connected underneath the drone with an on & off switch controlled by the Drone Pilot (DP). Successive custom-made air compressors were attached on top of the drone and connected to the sprayer. A 4L container with wet mix or Barbotine (2U of water for 1U of clay) with a spraying apparatus was attached underneath to fit in a 50-cm high bounding box defined to allow a safe drone landing. Some drone capabilities were tested, including the pilot ability to perform a stable flight while carrying a 2.5 kgs. spraying device, plus 22.5 kgs. of clay mix material, plus 8 kgs. of self-weight. While in the first set of experiments the air-compressor was actuated and linked to the spraying nozzle through a pipe of 4 cm diameter and 1m long rolled around the drone, the second set of experiments tested the air compressor device reduced to its minimum weight by removing the protection boxes and the pipe at 10 cm distance from the spraying nozzle. This was done after testing a fan aiming at reducing energy consumption which failed to spray enough material. The bear air compressor with a minimum distance to the spraying nozzle showed a greater success in terms of amount of material sprayed per second. This test showed that the pilot could spray with the drone a recognizable U Shape on the ground. The specific main parameters identified in the experiment are exposed in Table 1 for a surface of 2m by 1m.

3.1.2. Phase 2 - Dry Fibers and sand projection

In this phase, a DIY plastic container was fitted with a 5-cm diameter pipe pushed by the Wagner air compressor (used in the previous test), depositing on the wet lycra 3 cm length straw fibers mixed with 2 mm diameters feeding birds grains to add some weight. This stage explored adhesion, pressure adjustment and flow rate per minute.

Figure. 1. Left: Drone spraying the clay + water mix. Right: Drone spraying a clay mix containing plaster.

Table 1**.** CS1 Parameters for drone deposition in Phases 1 and 2.

Parameter	Phase 1: Wet Clay	Phase 2: Dry Fibers & Sand
Min. Distance between Drone (end of pipe) and Surface (MDDS)	5 cm	2 cm
Velocity of Spray (VDS)	Between 10 to 20 Km/H	Between 15 to 25 Km/H
Volume of material Deposited by Drone on each Flight (VDDF)	4L	2 m3
Volume of Matter Deposited per Minute (VMDM)	0.5L per min.	0.2 m3 per min.
Energy used per Drone Trip (EDT)	18 Ah 4 cell batteries of 10 V each = 40 V in total	18 Ah, 4 cells batteries of 10 V each = 40 V in total
Number of Drone Flights Trips (DFT)	7 DFT	3 DFT

Improvements detected from CS1 include: a larger amount of material is required to be sprayed with no interruption, necessity of achieving minimum distance between the nozzle to air compressor, fabricating a lighter air compressor device, considering a double tethered system feeding the drone with electricity and material from the ground, and using the air draft produced by the drone helixes to help spray the mix and help dry each layer.

3.2. Case study 2: Large scale test drone spray over inflatable formwork

Date: January 2018. Experiment by the authors with a drone and an earth architecture specialist.
Location: Drone Center Barcelona, Moía.
This outdoor experiment features the deposition of clay mixes over a light support by using the same drone than CS1. An affordable prefabricated 4 m inflatable dome was used as formwork as it offers compression only resulting forms. The objective was to verify the theoretical calculations related to the number of Drones Trips (DT) necessary to cover the spherical surface, and to continue testing the separation of dry from wet matter to prevent spraying devices blockage and to reduce the weight of the material being deposited by the drones. In addition, on site calibration of two devices fitted in the drone aimed at spraying thicker clay mixes than in CS1, depositing large amounts of clay and plaster mixes to form the initial shell crust than in previous tests.
Phase 1 - Liquid clay mix spray. A wet mix composed of 2U of water for 1U of clay was applied with a simplified spraying system that allows a thicker than in CS1 clay mix deposition. The calibration of the spraying tool was set in function of the viscosity of the mix at the time of being projected by the drone, amongst other key matter related parameters that was measured, and helped with the tools calibration for next physical experiments.
Phase 2 - Second layers containing plaster. A mix of 1U of clay for 3 U of plaster +2 U was placed inside a box and an Off and On command, was controlled by the drone pilot to allow the passing of the flow of paste like material on the surface.

Table 2. CS2 Parameters for drone deposition in Phases 1 and 2.

Parameter	Phase 1: Wet Matter	Phase 2: Dry & Fibers Matter
Min. Distance between Drone (end of pipe) and Surface (MDDS)	20 cm. MDDS (increased compared to previous experiments).	5 cm
Velocity of Spray (VDS)	Between 10 to 20 Km/H	Between 10 to 15 Km/H
Volume of material Deposited by Drone on each Flight (VDDF)	0.5L per min.	0.3L per min
Volume of Matter Deposited per Minute (VMDM)	10L per min (measured by counting the number of minutes to empty a 1L container fitted in the drone).	10L per min (measured by counting the number of minutes to empty a 1L container fitted in the drone).
Energy used per Drone Trip (EDT)	18 A/h batteries. 3 or 4 cells batteries of 10 Volts each	18 A/h batteries. 3 or 4 cells batteries of 10 Volts each.
Number of Drone Flights Trips (DFT)	15	15

Although in CS1 and CS2 the batteries and the material were carried directly on the drone, future tests will include connecting the drone with supply pipes to energy and matter. Industries such as firefighting and roof cleaning know a number of those tethered drones' strategies. (Gomez, 2014). As a next step, a traditional industrial mortar sprayer will be adapted for the pulverization pipe to be fitted within the drone. Articulated additional nozzles could be developed and engineered to help spray at different angles, and particularly improve the deposition at the bottom of the domes, where matter needs to be sprayed almost at a 90-degree angle. Further experiments have started on the prefabrication of the thick slices of textiles containing clay, plaster dusts and fibers, where each mix could be calibrated according to its shell position (Fig. 3), which engenders tests of different drones spraying speeds and kind of trajectories depending on which zone is being sprayed.

Figure. 2: From Left to Right Close ups on the matter surface adhesion and the drone spraying 2 kinds of clay mix over the formwork. January 2018. Test at the Barcelona drone center by the authors.

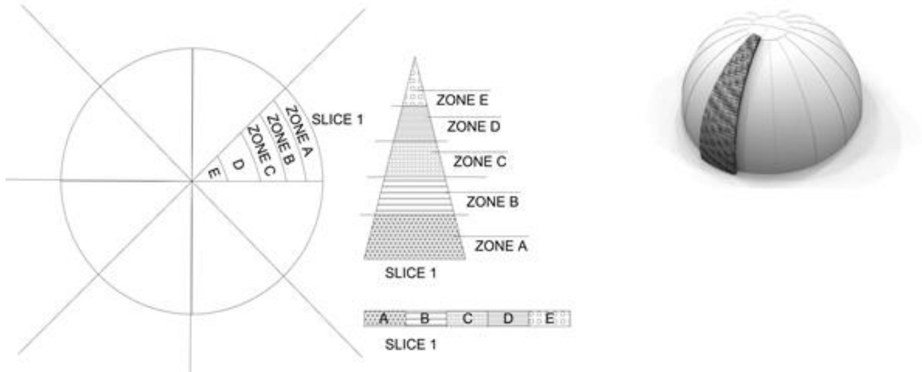

Figure 3: Diagram illustrating Zoning of the a thick (10 cm) Textile + Dry Matter Slice (DMS).

The 4 m diameter dome presented in Case Study 02 allowed to identify that gaining sufficient thickness in a limited amount of days is part of the current techniques ‘challenges which contributes to shape future real scale demonstrators.

4. Conclusion

The experiments carried out allowed to refine a formulation for Bioshotcrete by testing solutions suitable for monolithic earthen shell construction. The robotic fabrication strategy consisting in the aerial matter deposition is linked to critical parameters related to: matter separation and sequencing, formwork strategy, and drone flight.
These series of experiments helped verifying than separating dry from wet matter could improve the technique by avoiding blockage of the deposition apparatus, while decreasing the weight carried by the drone at each trip resulting in higher deposition speeds shown in Table 1 and 2. The tests featured the use of inflatable temporary formwork highlighting its advantages, such as being easily mounted and lightweight, allowing possible customization of shapes and patterns, while permitting multiple uses. Other potential solutions can incorporate removable or DMS lost formwork, where fabric is combined with dry material to become an active contributor of a range of carefully calibrated dry mediums, allowing the technology to focus on drone spraying liquid mixes or even water to solidify the shell. Further tests will involve a prefabricated phase of customized DMS to be paired with a singular drone spraying sequences (including speed, type of trajectory) to gain sufficient thickness and stability in a only a few days. Drone flight proved critical in the process, because of the reach it offers and the possibility of iteratively calibrate its characteristics according to the structure evolution along the construction helping to avoid errors in correcting planned and unexpected results of tool-matter-light formwork in place. Furthermore, current tests consider fluctuating thickness and material composition of the DMS lost formwork and require increased flight complexity of the drone with integration of an automated strategy. Basic spraying parameters proved critical during the tests, such as pressure angle and distance to the surface required to achieve precise control of the spraying apparatus, which needs further customization and the possible integration of an adapted system to redirect helices’ draught to help project matter and improve the drying times. New applications were discovered during the tests, where further automation of the drones spraying actions and flight sequences could grant a higher degree of repeatability and homogeneity on each layer, opening the possibility of execution by non-highly qualified builders, therefore facilitating its immersion in the construction realm. Immediately available technology related to automatization of multiple drones working collectively must be adapted for collision avoidance and repositioning trajectories due to external agents such as wind,

detection of empty material tanks, automated emergency landing if sudden system´s failure occurs, are some of unexpected considerations to be resolved. The robotic assessment could also benefit from added artificial intelligence, to enable the drone to scan and detect cracks, or to monitor the construction remotely in real time, for instance.
Bioshotcrete is still under development for the robotic fabrication of monolithic shells. Ongoing experiments are currently being conducted to include structures of up to 3 m high, that could enable the incorporation of alternate bio materials, advanced digital fabrication techniques, and drone automated flights within the construction industry in the upcoming years.

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