Matter-Robotic Calibration for Bioshotcrete

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Construction techniques associated with traditional raw earth architecture are characterised by laborious manual tasks in which each clay mix is deposited in layers over a light formwork, such as with the wattle and daub technique. More sustainable solutions also exist for the use of concrete, including shotcrete or sprayed concrete over light formwork composed of fabrics, inflatables or metal meshes. This research explores robotic techniques for the digital fabrication of monolithic earthen shells, with the objective of reformulating the use of clay as a sustainable material to reduce laborious tasks, minimize the use of formwork, and to implement robotic fabrication processes. This unique technique is called “bioshotcrete” and is characterised by an innovative fabrication process of sequential robotic spraying deposition of different natural raw clay mixes over a temporary light formwork. Two case studies are described and analysed featuring two distinctive techniques: clay mixes sprayed with a robotic arm and with a drone. Details are highlighted, and key considerations are identified, in terms of subtle adjustments for the material formulation and application sequences, robotic tooling strategies, and customised robotic actions. This series of experiments was formulated as an ongoing experiment to address challenges related to limitations of reaching distances and lightness of machines to bring on site, and to explore newfound possibilities for aerial deposition techniques using drones. Variations related to Tool/Matter performance (spray velocity and surface adhesion) were explored at each clay mixture iteration. Additional improvements were identified by recent physical tests, such as using the drafts created by the drone helixes to help the drying process at each layer, and additional conclusions establish how this technique is not only shaping new design and digital fabrication processes but envisioning possible future applications and offering new scenarios for sustainable large-scale earthen envelopes.

1
INTRODUCTION

Clay has been used since ancient times as a construction material in vernacular and traditional building practices. Some techniques like wattle and daub feature intertwined flexible branches as lost formwork that is sequentially coated by hand with different clay mix layers applied on both sides (Guillaud, Houben 2015, 345-348), resulting in wall panels used for discrete based construction or for building monolithic domes and vaults. The potential to revisit some principles found in these traditional construction techniques is that when associated with recent design protocols and robotic fabrication methods, an unexpected degree of freedom can be unveiled, such as constructing diverse non-regular vaults working under compression only (Block et al. 2010, 4-13), allowing varying thicknesses and textures from generated optimized geometries to use minimum material to achieve maximum strength (Burry and Burry, 2010, 126-130).

Several experiments carried out mostly in academic environments in recent years propose to revisit clay as a traditional material and to study possible formulations and applications using robotic technology (Fig.1), featuring additive manufacturing with two types of clay deposition: extrusion and spraying techniques. Initial experiments revealed that extrusion requires high precision (1 mm tolerance) in terms of distance, velocity of deposition, nozzle size and shape, and on the other hand, spraying allows a higher level of imprecision (up to 20 cm tolerance) in terms of distance nozzle/surface (Bravo, Chaltiel 2017, 15-18). Several references in building construction include the shotcrete industry offering different degrees of automation for spraying, where the control of the deposition material includes matter thickness, flow and cracks, are exclusively monitored by professional builders on site. Recent experiments at TU Braunschweig Germany explore robotic 3D printing by spraying to deposit each layer, offering a 3D printed version of shotcrete without formwork (DBFL TU Braunschweig, 2018). In addition, drones have been used in construction over recent years mostly to 3D scan construction sites to give feedback information to the performing robot as seen with the recent Achim Menges weaved carbon fibres structures (Felbrich et al. 2018, 248-259). Customised drones were used in the *Paint By Drone* project for paint spraying by Carlo Ratti in 2017, and in the weaving drones from Gramazio Kohler Research together with roboticist Raffaello D'Andrea's group at ETH Zürich's Institute for Dynamic Systems and Control, who are researching technological aspects of preprogramed flights as part of experiments using drones to perform non-recording tasks. Research focused on the specific tool/matter interaction could lead to specific architectural forms as highlighted by their resulting non-regular walls in the installation *Remote Material Deposition* (Augugliaro et al. 2014, 46-64) with the robotic throwing of small clay lumps. Some of these recent advancements in digital fabrication technologies are opening a fruitful territory for experimenting with novel design processes and construction techniques, offering the ability to reproduce non-regular structures and to optimize shell thicknesses to minimize the amount of material used, as featured in Philippe Block's project in Africa (Block et al. 2010 4-13).

This research explores the implementation of mud spraying techniques on light formwork for constructing monolithic earthen shells by using a robotic arm or aerial deposition systems for the spraying strategy (such as drones), with an emphasis on Tool/Matter calibration for surface adhesion and consistent homogeneous crust forming.

2
ORIGINS OF “BIOSHOTCRETE”

A new technique called “Bioshotcrete” is being developed by a pluri-disciplinary team of designers, engineers and robotic experts, aimed at formulating a more sustainable version of the current shotcrete industry by using non-toxic paste as the matter instead of concrete, smaller equipment, and a light and easy-to-erect formwork composed of natural fibres textiles such as jute (Chaltiel, Bravo, 2017 94-97). For its implementation, a precise process must be followed consisting in the careful formulation of different clay layers and in the correct deposition phasing (Chaltiel, Bravo, 2017 94-97), aimed at achieving matter/surface adhesion and added control in the resulting thicknesses used to construct large-scale monolithic earthen domes and shells in only a few days. The origin of Bioshotcrete is rooted in the formulation of a suitable material formulation and application sequence, robotic tooling strategy advancements, and the development of customised robotic actions.

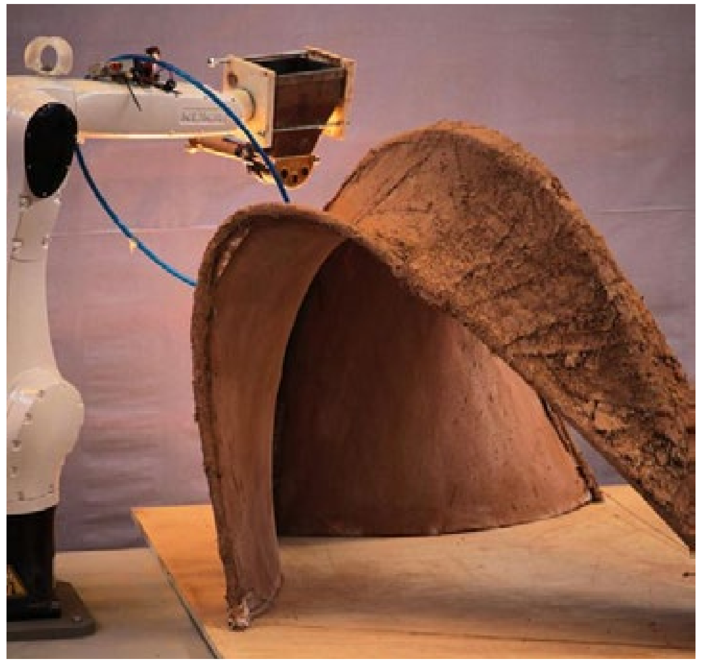


Fig. 1. Smart Geometry workshop Gothenburg featuring monolithic shells fabricated with robotic clay spraying. By the authors.

2.1 Paste-like material formulation for additive manufacturing

Clay matter shows clear advantages as a construction material exhibiting environmental benefits such as wide availability as a local natural resource, low entropy, and high inertia. This research proposes a protocol for the sequential robotic deposition of clay mixes by modifying the proportion of each ingredient in the mix, resulting in different consistencies, viscosity levels, elasticity and stickiness amongst other aspects. In addition, robotic fabrication using clay mixes requires the careful formulation of materials to achieve a desired performance in terms of solid crust adhering well to the previous layer or initial surface. Therefore, each deposition layer has a different composition in which grains, fibres, density, and the proportion of clay which acts as a binding agent and water can greatly differ (Fig. 2).

Three main types of clay mixtures have been formulated and tested:

1. The liquid layer for the initial spray called “barbotine” forms a homogeneous solid thin crust to replace the initial light formwork. This layer increases adhesion for the following layers, facilitating the removal of the temporary light formwork fabric at the end of the process.
2. Middle layers containing clay water and sands are high in fibres, helping to give thickness without overloading the delicate formwork, and helping to absorb excess moisture. These thick layers provide high inertia.
3. The upper coatings contain some natural stabilizing agents such as lime, combined while hot with animal fat mixed with clay and sands of larger grain diameter than in previous layers.

Various physical structures ranging from 1 to 3 m high and mud sprayed robotically on tense fabric were constructed following a precise material layer formulation (Fig.2) that includes a material composition described in terms of granulometry and proportion of ingredients, as follows:

a- Interface Layer or Barbotine: Composed of clay powder with a grain diameter of less than 1 mm. 1 Unit (U) of clay for 2 U of water;
b- Textile reinforcements that are porous with varying mesh densities (such as jute) of 1 cm. min. density that are applied by hand;
c- Layers 2, 3 and 4: 1 U clay + 1 U hard sand [2 mm diameter] + 1 U water;
d- Layers 5, 6 and 7: 1 U clay + 1 U hard sand [4 mm diameter] + 1 U water;
e- Textile reinforcement layer with a minimum mesh density of 0.5 cm. Applied by hand;
f- Layers 8, 9 and 10: 1 U clay + 1 U hard sand [5 mm diameter] + 1 U water. On the upper layers, different kinds of stabilizers can be added to the clay mix for waterproofing and to help prevent cracks.

A range of mixes were formulated and implemented in the featured case studies and will be compared in terms of parameters for matter deposition with good adhesion to the formwork surface. Also, aspects such as composition and sequencing will be further described, including application sequence in phases, as well as material composition in terms of ingredient types, granulometry, proportions of each material, drying times and the use of stabilizers.

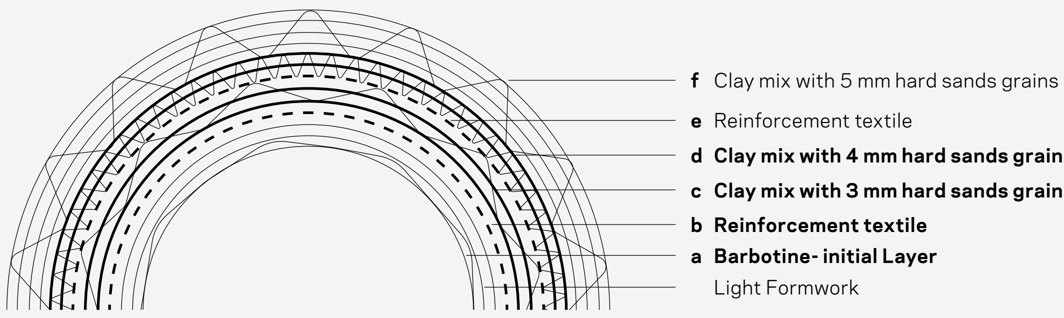


Fig. 2: Diagram showing the succession of clay layers to be applied on the temporary light formwork.

2.2 Robotic Tooling Strategies

Customised robotic tools to spray different types of clay mixtures over light formwork were identified as relevant because they eliminate the need for labour intensive scaffolding, but exposed certain limitations, such as the robotic arm's reaching capacity for large-scale structures, and alternatives such as aerial deposition are therefore explored. These early initiatives prove that robotically sprayed clay mixes remain vastly unexplored, and the aim of this research is to propose a phased robotic construction sequence for clay mixes using robotic arms and drones. The integration between matter and robotic actions must be carefully choreographed in a process defined by the sprayer device, the material container, and the process of continuously feeding the apparatus until a self-standing structure is completed.

1. Material container: The first part of the manufacturing process is initiated with the clay mixing with construction equipment (horizontal or “spinner” mixers). After the mixture is properly combined, it is placed in a container that must be continuously stirred as it had been observed in previous experiences that because clay is a granular material, it tends to adhere to the container walls, causing the mixture to leave a “mouthpiece” with irregular and non-homogeneous edges, creating disparities in the coating.
2. Material transport: For its deposition, suitable feeding mechanisms with several modalities were explored:
    1. Robotic arm fitted with a mortar hand sprayer able to carry up to 8 L of mix attached to a pipe connected to a ground air compressor.
    2. Matter deposition with drones in containers with a carrying capacity between 5 to 35 kg or connected to a ground container using a feeding line.
3. Sprayer output format: For the discharge, clay material must be in a hydric state compatible to pulverization (viscous). Therefore, as established in previous

tests, the machine must be capable of expelling matter with a specific granulometry with all grains not exceeding 1.5 millimetres in diameter, i.e. between clays, silts and fine sands. The type of outlet or "nozzle" could also be adapted in size (diameter) and shape. Therefore, a series of DYI "nozzles" were proposed with specific uses that can be changed according to the design and route of the robot, which could be improved and adapted depending on the different forms and structures.

4. The type of deposition apparatus is usually an attachment to a robotic arm composed of an end effector Wagner Flexio Spray or a mortar sprayer (machine a sablon), or in the case of drones, a DIY sprayer or a Wagner Flexio Sprayer.

Each case study features unique robotic tools suitable for robotic arm and aerial drone deposition, including robotic apparatus, material container, material transport, sprayer output format, and type of deposition apparatus, which will be detailed in the case studies.

2.3 Robotic actions for clay spraying

Robotic actions must be carefully calibrated to suit a precise application sequence. Initial tests helped shape the nature of the robotic spraying experiments by varying the type of trajectory the tool follows and associating a speed with a specific kind of trajectory. For example, horizontal circular lines need to be done at a speed of 0.5 m/s to achieve adhesion matter/support. In addition, the deposition apparatus must be linked to an ON-OFF switch controlled by the robotic arm code or triggered by the pilot and co-pilots for drone experiments.

1. The optimum distance between surface and nozzle or drone end of pipe should be between 5 cm and 45 cm.
2. Matter Flow Rate should be between 2 Litres and 9 Litres per minute.
3. The Optimum Speed of the Robotic Arm or Drone should be between 0.5 cm per second and 1 cm per second.
4. Type of Trajectories Figures: Circular trajectories are suitable for initial spraying sequences starting from the bottom layers towards the top coats. Vertical depositions must always be done from bottom to top at a minimum speed of 0.5 cm per second, while horizontal motions must be done for thicker mixes that might contain fibres at a minimum speed of 1 cm per second.

These key parameters were formulated based on several tests and in careful iterative adjustments performed to match the robotic apparatus depositing capabilities, which will be detailed for each case study.

3
MONOLITHIC EARTHEN SHELLS ROBOTIC FABRICATION CASE STUDIES

The proposed methodology aims to describe suitable techniques for the robotic spraying of clay mixes in terms of material formulation, robotic tools and equipment, and deposition strategies.

Two case studies of monolithic earthen shells fabrication methods feature two distinctive robotic fabrication techniques to confirm the validity of the process and to calibrate the spraying instruments with different kinds of clay mixtures. The first case study uses a 6-axis Kuka robotic arm fitted with a heavy paint sprayer to apply different layers of clay mixes over a temporary textile formwork. The second case study takes advantage of the latest drone technology, piloted by a professional to carry a container and to deposit layers of different clay mixes over an inflatable formwork, as an intent to address the challenges highlighted in case study 1 in terms of the reaching capacity and the use of heavy apparatus that needs to be brought on site. Within each case study, the performance of tool/matter will be detailed in terms of correct matter adhesion to the support surface to reach consistent thickness and the matter flow deposition sequence.

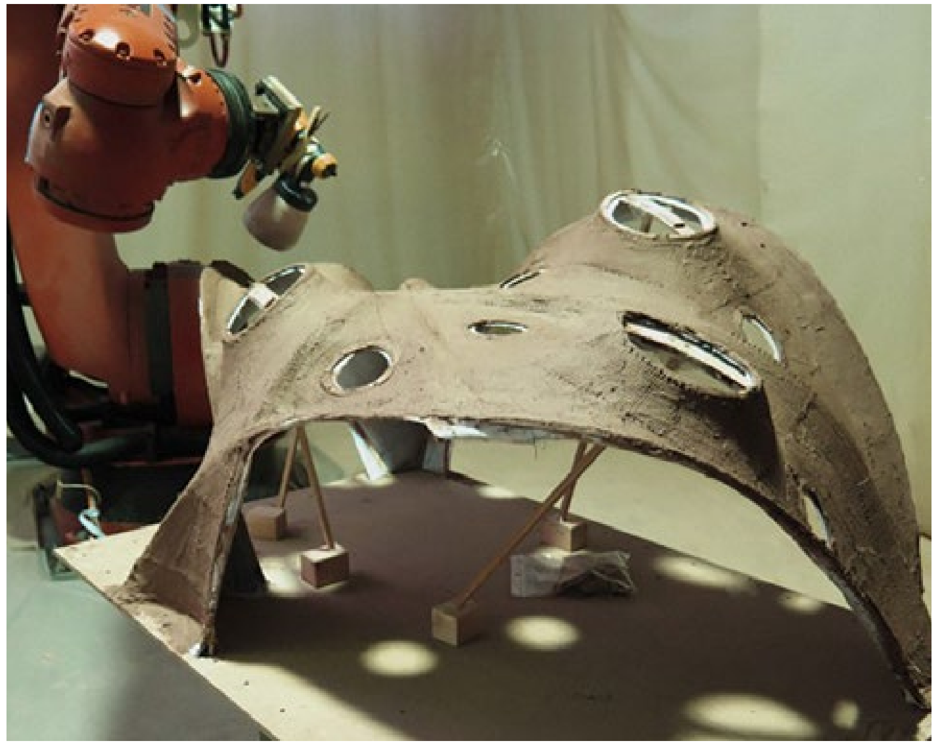
3.1 Case Study 1
CS1 Clay mixes spray with a robotic arm

Name: Clay mixes sprayed with a robotic arm.
Date: November - December 2017.
Participants: Authors, 25 Master Students Year 1 (five groups of 5 students each).
Location: Institute of Advanced Architecture of Catalonia (IAAC), Barcelona, Spain.
Equipment: Industrial Kuka Robotic arm; Wagner heavy paint sprayer; traditional mortar hand sprayer.
Objective: To build a monolithic earthen shell fitting in a 1-metre cube bounding box. A total of five structures were built in one week.

This experiment features a robotic arm with 6 degrees of freedom using only the end effector's last articulation (Ar6) of the robot (Fig.4). The robotic arm is first fitted with an off-the-shelf Wagner Flexio sprayer then fitted with a traditional mortar hand sprayer to deposit the more viscous and high in fibre mixes (Fig.5). Other articulations are set by default to allow the Ar6 trajectories to avoid "singularities", defined as errors in the robotic code where actions cannot be performed, for instance if one part of the robotic arm would collide with another one of its parts. The code is set through Kuka Prc free software, and the robotic trajectories and actions can be set with Grasshopper for Rhino 3D definitions.

A succession of clay mixes was sprayed following a strict deposition sequence detailed in Table 1. Several stabilisers were tested, typically a highly viscous matter similar to gels or liquid soaps, including a cactus based traditional waterproofing solution that was sprayed successfully with a high matter flow and no detected sprayer blockage.

This case study proves that the technique allows good adhesion between matter and surface if the Tool/Mat-

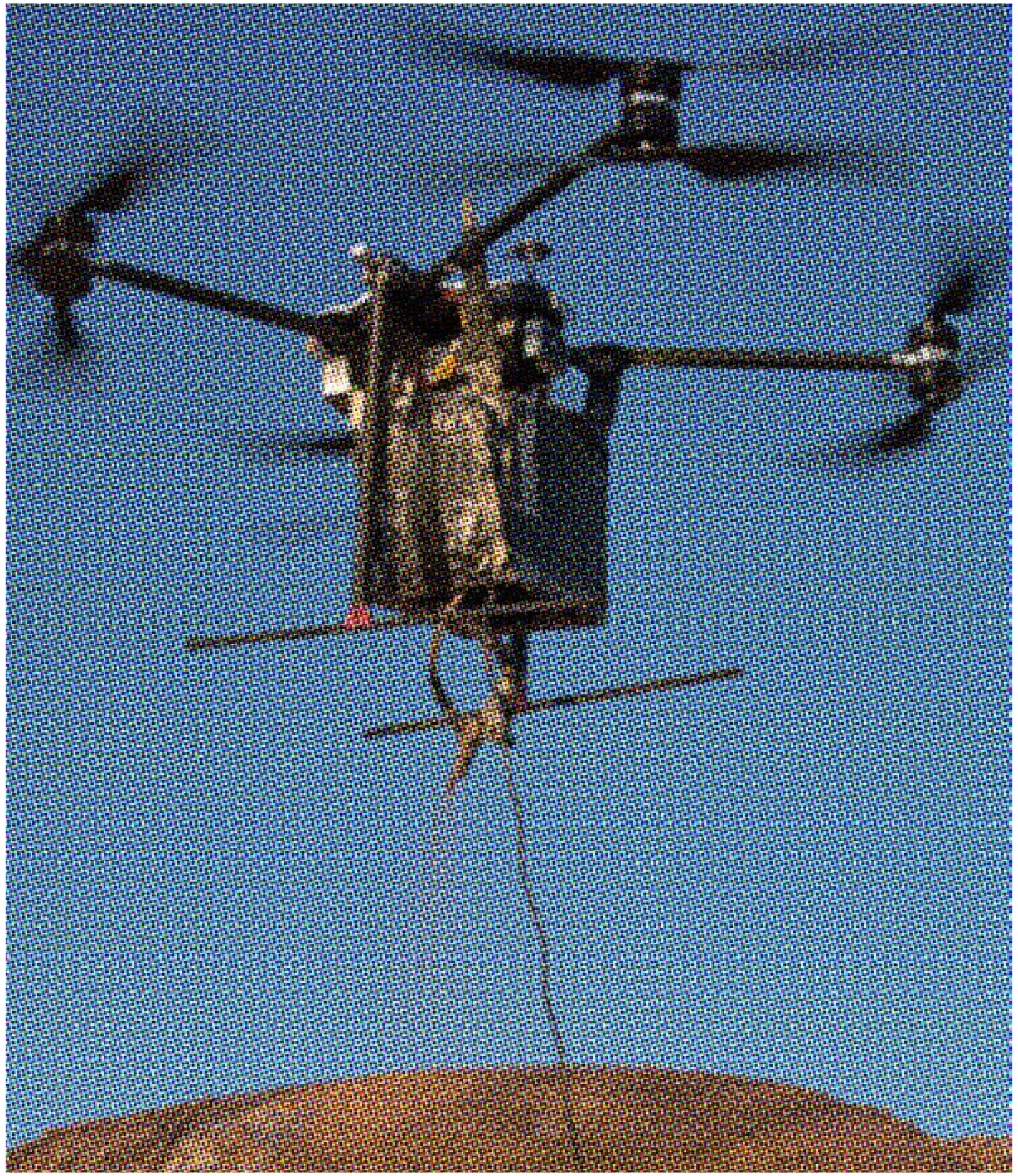


↑ **Fig. 4.** Traditional mortar hand sprayer fitted in the Kuka Robotic arm. Average angle to surface is set at 45 degrees.
← **Fig. 5.** Six degrees of freedom robotic arm Kuka 100 kgs payload applying the initial clay mix.

	Layer 1 **Interface or Barbutine**	**Layer 2, 3 & 4**	**Layer 5, 6 & 7**	**Layer 8, 9 & 10**	**Stabilizers**
Material Composition (Type, Granulometry, proportion of ingredient)	1U clay + 2 U water	1U clay + 1 Water +1 U hard sand (3 mm)	1U clay + 1 Water +1 U hard sand (4 mm)	Tierra de granulometría homogénea (5 mm)	1U clay + 1 Water + 1 U hard sand (2mm) + 2 U stabilizers
Deposition Apparatus	Robotic Arm with End Effector (Wagner Flexio Spray)	Robotic Arm with End Effector Mortar sprayer (machine a sablon)	Robotic Arm with End Effector Mortar sprayer (machine a sablon)	Robotic Arm with End Effector Mortar sprayer (machine a sablon)	Robotic Arm with End Effector (Wagner Flexio Spray)
Optimum Distance between Surface and Nozzle	45 cm	35 cm	35 cm	35 cm	45 cm
Flow Rate Matter	50 L/min	70 L/min	70 L/min	70 L/min	50 L/min
Flow Rate Air	100 L/min	156 L/min	156 L/min	156 L/min	156 L/min
Optimum Speed of Robotic Arm	0.5 cm per sec	1 cm per sec	1 cm per sec	1 cm per sec	0.5 cm per sec
Type of Trajectories figures	From top to bottom	Horizontal circles	From top to bottom	Horizontal circles	From top to bottom
Energy used per layer deposition	7.35 KW	8 KW	8 KW	8 KW	7.35 KW
Energy estimated to complete the structure	73.5 KW (= 4000V)	80 KW	80 KW	80 KW	73.5 KW

↑ **Table 1.** CS1 Parameters for matter deposition.
← **Fig. 5.** Two kind of spraying apparatus are fitted underneath the drone. Left: projecting liquid clay mix. Right: Projecting sand and fibers dry mix.
→ **Fig. 6.** Drone depositing the clay mix containing a high percentage of plaster forming the second crust.

	Phase1: Liquid Matter	**Phase 2: Fibre Matter**	**Phase 3: Viscous matter**
Material Composition	2 U water + 1 U Clay	1 U fibres + 1 U grains	2 U clay + 2 U of 3 cm long fibres + 1U water
Deposition Apparatus	Wagner Flexio Sprayer	DIY machine (Fig. 7).	DIY sprayer (Fig.X)
Safe Distance between Surface and Drone (end of pipe)	10 cm	5 cm	10 cm
Matter Flow Rate	5 L/min.	9 L/min.	2 L/min.
Air Flow Rate Air (3 bars)	156 L/min	156 L/min	156 L/min
Drone Speed	25 km/h	30 km/h	Between 10 to 20 km/h
Type of Trajectories	from bottom to top	from the top	from bottom to top



↑ **Table 2.** CS2 Parameters for matter deposition by drone.
← **Fig. 8.** Application of the initial liquid clay layer by a DIY apparatus fitted underneath the drone.
→ **Fig. 7.** Diagram of the DIY apparatus where the air flow is connected to the matter pipe to be expulsed.

ter system is correctly calibrated. Future improvements include testing local stabilisers as potential ingredients and setting up an on-site protocol so they can be sprayed robotically into a homogeneous upper coating.

3.2 Case Study 2
CS2 Spraying clay mixes with a drone
CS2 phase 1
Name: Spraying clay mixes with a drone separating dry from wet matter.
Date: November - December 2017.
Participants: Anonymous, with RC Take Off company.
Location: Louvain, Belgium.
Equipment: Custom-made drone (by UCL Louvain & RC Take Off), 2 m wide, 8 kg In weight with load capacity of 25 kg with 15 min. travel autonomy.

CS2 phase 2
Name: Spraying clay mixes with a drone separating dry from wet matter.
Date: January 2018.
Authors: Authors, Raw Earth Architecture Specialist, Drone designer
Location: Barcelona Drone Center, Moia.
Equipment: DIY spraying and paste like matter deposition boxes.

These two sets of experiments explored the viability of using custom-made drones for spraying different clay mixes, with an emphasis on the separation of wet from dry matter (Fig.5) to avoid blockage and to minimise the weight the drone carries each trip. The temperature of the material in all membrane parts should be as homogeneous as possible, ranging from 10 to 20 degrees Celsius when wet. Previous experiments identified that each layer should warm up to a temperature of at least 45 degrees Celsius before applying the following coats of material. Future experiments will be designed so that sensors embedded in the drone will be able to provide readings of the temperatures in different shell areas.

The details of each clay mix with its associated relevant parameters is described in Table 2. In both case studies, the succession of clay mixes results in upper layers containing grains higher in diameter than those found in bottom layers.

During live flights it was observed that spraying light matter (such as fibres and grains) allows the pilot to come much closer to the structure with a limited collision risk as the stability is higher than when transporting heavier liquid or viscous mixes (Fig. 9).

During this experiment it was confirmed that the initial layer of clay mix should contain a high percentage of plaster to aid in rapidly obtaining a solid thin crust, so that the inflatable formwork is no longer the main agent holding the construction, thus making it possible to stop blowing air inside (Fig.6). While the system doesn't require high precision in terms of distance and angle to the surface, timing appears to be key for the different materials to merge into a common shell. For example, dry matter needed to be projected with the right pressure and at the correct speed (0.5 cm/s) on a wet and viscous layer, so that it could adhere to the surface without bouncing back (Fig. 9).

4
FUTURE CALIBRATION FOR BIOSHOTCRETE

Traditional construction materials such as clay represent an emerging field that brings opportunities to engage with culture and construction traditions where old and new are combined, highlighting robotic actions to allow new construction processes to emerge. The use of robotic fabrication

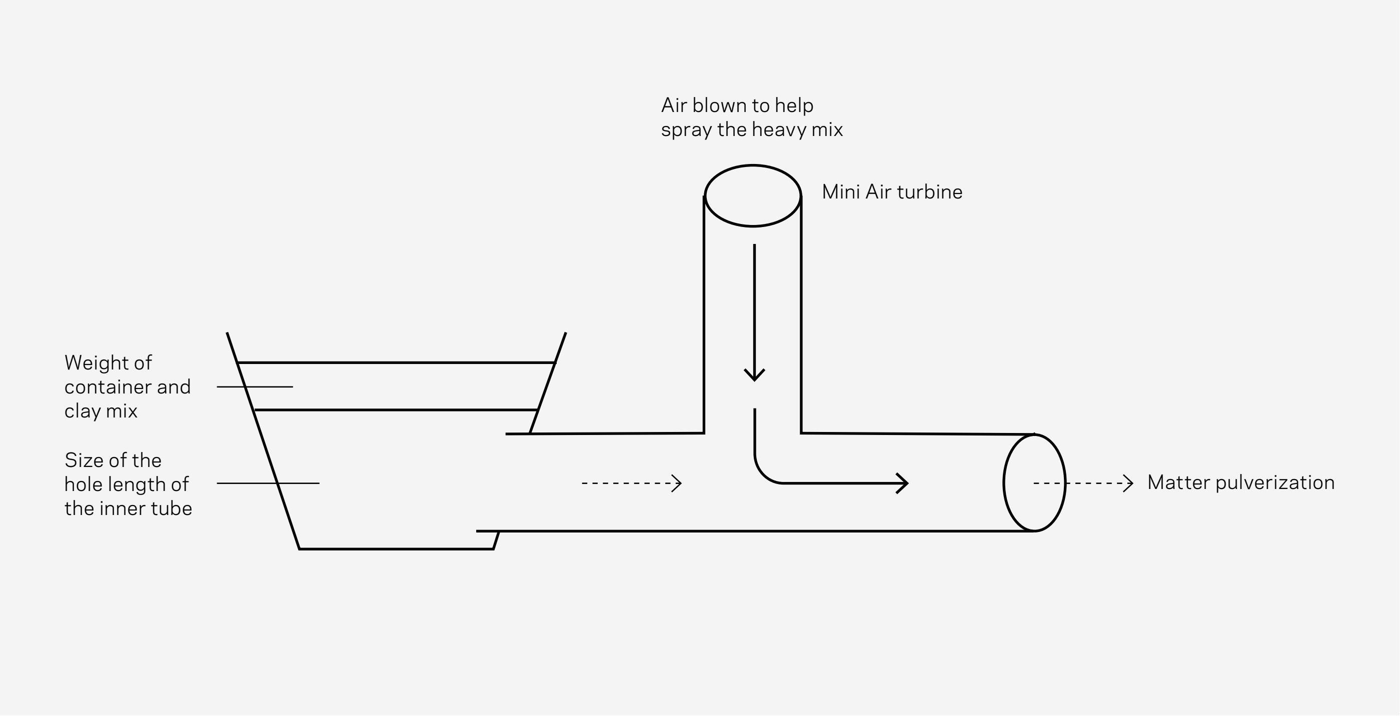


Fig. 9. Close-up of the viscous middle layers projected by drone on the surface

methods using clay spraying on light formworks opens a vast range of possibilities and opportunities for the building construction industry. Robotic actions can effectively ease the most laborious manual tasks (such as reaching high areas or building scaffolding), resulting in a more efficient use of materials and the possibility to embed customisation features into the construction sequence.

Although this work is still in early stages, the iterative calibration between robotic spraying parameters and the sequence of deposition for homogeneous coating fabrication present in the two distinctive techniques help to focus, speculate and reflect on future building practices.

The goal of the paper makes it possible to identify existing and ongoing challenges in robotic and drone-based construction related to suitable material formulation and application sequence, advancements in robotic tooling strategies, and in the development of customised robotic actions.

The precision and repeated actions introduced by robotics in bioshotcrete allow new biomaterials to be introduced that can provide enhanced structural performance and high inertia amongst other qualities. For example, certain kinds of local stabilisers can help waterproof the structure, and resins can be integrated if they are poured in a liquid state at the right temperature. Material formulation and application sequences proved feasible using a robotic arm with three phases: Phase 1 - Viscous matter; Phases 2-10 - Clay with sand (from 3 to 5 mm); and the final Layer - Stabilisers. The sequence was the same with drone application but needed to be adjusted according to wind conditions (natural wind and wind created by the drone's helixes) and offered the possibility of applying highly viscous and fast-hardening matter such as plaster mortar. In future large-scale physical tests, the maximum size of grains to be used for upper layers should be assessed so the structure gains strength without losing its auto stability if too much weight is applied on certain areas. In addition, traditional raw earth architecture shows invisible ingredients present in clay mixes that include different sulphate gases and minerals (such as mica, quartz and feldspar), which are must be further analysed, stirred adequately in the mix, and adjusted to fit the technique in future tests.

In terms of robotic tooling and customised robotic actions, using a robotic arm in CS1 proved effective in terms of the linearity and ease of the process, the precision of spray depositions and opening the possibility of performing subtractive manufacturing, but showed limitations such as the arm's reaching capacity, the cost and size of the equipment and the difficulty of transporting these heavy apparatuses to remote sites. In addition, while robotic actions need to be set with a precise trajectory in CAD software such as Rhino 3D, an initial 3D scan of the temporary formwork is required. In contrast, the piloted drone spraying in CS2 does not require this 3D scanning step. Therefore, future tests will aim at improving the drone spraying strategy, emphasizing a further degree of automation that could allow the drone pilot to vary pressure and remotely control the angle of deposition, leading some manual tasks to be performed robotically amongst other aspects. When the drone is connected to a mortar spraying machine pipe (Fig.10), it allows a constant feed of the material and is expected to increase matter flow rate and matter/surface adhesion in future earthen shell fabrication.

CS2 highlighted that while this project currently focuses on using drones to deposit the matter, further laborious on-site actions such as excavating, sieving, mixing or transporting could be eased by the introduction of small robotics specially assigned for such tasks.

Several challenges were detected in relation to precision requirements and drying time required in between layers. In the near future, this could also be embedded in the artificial intelligence present by using monitoring drones passing the information to drones performing actions. Initial piloted flights allowing an automated setup appears crucial in the integration of this technique in the construction chain. As the process is based on the fact that each layer needs to be dry enough before applying the next layer, hot and dry climate locations allow fast construction, but bioshotcrete can also be implemented in cold and humid wet regions if the drying time is accelerated by directing the wind produced by the drones and by developing adjusted engineering systems to help each layer reach the right temperature.

In addition to the two case studies presented in this paper, some preliminary tests run at the Institute of Making in London indicated that trajectories for drone spraying can be coded, and key parameters can be defined and refined, such as the optimum distance to the surface, spraying angles and, in particular, the speed, which can be integrated in the code so that artificial intelligence could improve the technique on each flight sequence. For example, the system can detect a crack and transmit information to the drone sprayer to stop or to fill up cracks when they are detected. Increased matter deposition freedom could allow the use of technology to monitor the structure in progress, which could lead to controlling and varying thickness in subsequent tests.

Although the feasibility, relevance and precision of spray deposition results for clay-based structures using drone material delivery remain exploratory in this research, further experiments must be carried out regarding suitable tool matter calibration and drone capabilities for the future construction of a complete, full-scale earthen shell. Robotic spraying on temporary light formwork is just the first step towards a much larger revolution currently underway in the construction industry, prompted by the combined use of robotics with natural materials that could help transform future large-shell structures towards more sustainable realms.

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Fig. 10. Thick mortar sprayer pipe connected to the drone for constant materiel feed.