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Shell Design Considerations for 3D Printing with Drones

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Abstract

Many researchers (e.g. Baarsen et. al. [2], Bos et. al. [3] , Galiaard et. al. [5], Perkins & Skitmore [11]) have reported on the potential innovations available when additive manufacturing (3D printing) is applied to the building design process, be it at the scale of an individual building component (Galiaard et. al. [5]) or the building itself (Baarsen et. al. [2]). However, by the very fact that the printing takes place inside the volume of the 3D printer, the finished product, even if printed at 'architectural scale' (Yasui et. al. [13]), must be smaller than the machine used to create it. To overcome this limitation, the authors are involved in a project to develop autonomous flying drones capable of 3D printing in the classic sense, by extruding liquid through a nozzle which then sets solid (www.aerial-abm.com). The initial focus is on using a foaming two-part polycarbonate composite, which possesses excellent properties in terms of minimizing raw-material weight for a given print volume, but whose tensile strength is limited and very variable. However, the general principle of compression only shell design assumes that self-weight will be the dominant load-case, and therefore much of the shell will be in compression, even under asymmetric wind load. If a shell is printed in a lightweight composite, this assumption is no longer valid, and there are repercussions for design in terms of the shapes of shells that can printed. This paper assesses the challenges for shell design introduced by the use of a lightweight material with low tensile strength, and discusses potential approaches to overcome such limitations in the context of 3D printing with flying drones

Keywords: Lightweight, Shells, 3D Print, Drones, Polymer, Concrete

1. Introduction

There is currently great interest in the use of 3D printing in the building industry. And what started as a way to optimize components (joints, structural members) has increased in scale to a method of constructing whole buildings. Hardly a month goes by without a press-release from a team which has printed a house or bridge using a (very) large, but static, robot arm using Additive Building Manufacturing (ABM). However, such structures, by the nature of the way they are "printed", have significant restrictions in terms of their geometry. They are often, disappointingly, made from vertical walls, which fail to express the freedom of geometrical design ABM offers. And since they are printed from a static armature, they have to be smaller than the robot that made them.

The authors of this paper are involved in a multi-disciplinary research project to develop a swarm of autonomous flying drones, capable of 3D printing structures of arbitrary geometry and with no theoretical limit on their size. The project is known as Aerial-ABM (www.aerial-abm.com), and aims to develop the innovative hardware, software and materials necessary to allow full-scale structures to be constructed autonomously in remote areas, without the direct physical presence of human builders. This would allow bespoke emergency shelters to be provided after natural (or man-made) disasters, in potentially hazardous or inaccessible environments.

Whilst using drones has many advantages in this context, there are of course some limitations that the project will need to address (Latteur et. al. [8]), not least the need to minimize weight, increase positional accuracy, and to allow for refueling of drones, both in terms of their electrical power and their print material. The hardware design [6] and materials development [4] for this project are already well underway and the focus of this paper is on the structural engineering challenges associated with Aerial-ABM, and especially how to approach the design of the buildings being 3D printed.

Since 3D printing removes the economic benefits of planar or modular construction, shell-structures present obvious opportunities in terms of providing shelter over large spans whilst using a minimum amount of material. However, material is usually minimized by transferring load to the supports through in-plane forces to minimize the bending moment that such shells need to resist. To achieve this, their geometry is usually optimized for a given, dominant, load case – which is almost always self-weight. In addition it is difficult to achieve reliable tensile properties in 3D printed material and the lack of self-weight makes it difficult to use weight to pre-stress structures in compression as is traditionally done with masonry vaults.

Since the Aerial-ABM drones have limitations on the amount of construction material they can carry per flight, options currently being investigated are to print using either a lightweight composite polymer or a cementitious foam. Whilst such materials are beneficial in terms of their print-volume to weight ratios, it is exactly their lightweight nature which means that when formed into shell structures their dominant load case is likely to be wind, or perhaps snow, depending on where they are situated.

Another factor influencing the design of shells made from 3D printing drones, apart from the difficulties in providing tension-capacity through reinforcement, is the desire to avoid or limit the use of scaffolding or other falsework to provide temporary support during construction. Some researchers have generated structures with drones in the past using filaments wound around each other to produce a tensile net or surface (Mirjan et. al. [10]). And whilst the authors' project could potentially include tensile reinforcement placement using dedicated filament-drones alongside their foam-extruding colleagues, this would add significant complexity and is hoped to be avoided through careful design. Similarly, using some drones to print temporary scaffolding (perhaps from a different and easily removable material) to support the main shell structure is a real possibility, but as a starting point it is hoped that the geometry of the shells can be carefully chosen to avoid the need for support scaffold.

This paper discusses the authors' approach to tackling such problems, which is divided into two parts, the pre-calculated, idealized design of the building and the post-rationalized analysis of how to correct for manufacturing errors. It then goes on to discuss a short case study and outlines the future direction of the research and the many challenges that lie ahead.

2. Pre-emptive Design

Given a specific site (topography) and likely loading conditions (wind speeds and snow depths), traditional methods of structural analysis can be used to develop candidate building geometries. Architectural input is of course also needed to determine geometrical requirements based on the number of people likely to need shelter from each building and their specific needs in terms of spatial and thermal comfort. Given the unpredictable nature of likely sites, a parametric modelling approach suggests itself in terms of being able to generate numerous buildings across a site, each with slightly different constraints such as ground conditions and occupant needs. However, there are a number of issues specific to 3D printing with drones that require modification to the traditional approach.

2.1. Geometry

As discussed above, shell structures present many benefits in this context. But they are usually, quite rightly, designed on the assumption that self-weight will be the dominant load case. For drone manufacture the self-weight needs to be kept as low as possible, and so this assumption is no longer safe.

A shell which is to be 3D printed with drones therefore needs to be robust and more tolerant of bending moments. Stiff ribs might be introduced to attract load and to guard against buckling. Alternatively, (computational) time might be spent analyzing the likely loading on the structure through the application of Computational Fluid Dynamics (CFD) modelling of wind and snow, and the shell geometry adjusted to minimize such loading, rather than to minimize bending under self-weight.

All these aspects will necessarily lead to an iterative and computationally complex pre-emptive design phase. However, since this phase is only performed once, and is performed in the time between identifying a need for building and physically getting the manufacturing system to site, this computational burden is not an issue.

2.2. Stability During Construction

For many reasons, the design of buildings constructed by traditional means is almost always dominated by the need to be stable in a final configuration. Stability during the construction process itself is unfortunately often an after-thought and can lead to catastrophic failure when not taken seriously. Design codes exist to address such issues (ASCE [1]), but in the case of 3D printing a building many more issues come into play which require even more care and the consideration of situations outside the scope of such codes.

The main consideration when 3D printing a shell is that it will need to be able to support its own weight and resist moderate wind loads continuously whilst being printed. As discussed above, the self-weight load case is not as onerous as when printing with typical construction materials like solid (heavy) concrete, but nevertheless the shell must be stable at every stage of its construction. Similarly, the drones will have a maximum wind speed under which they can perform, and the shell will therefore not be expected to withstand storms during construction, but it must be able to cope with nominal wind loads and the down-draft from the rotors of the drones themselves.

Objects printed using conventional desktop 3D printers need to be carefully designed with the limitations of the printing process in mind (Ultimaker [12]). Since material is built up in layers, with subsequent layers placed on structure which has gone before, there is a limit to the amount of overhang that can be produced before scaffolding support material needs to be introduced. A shell structure does not gain all of its stiffness and stability until the whole shell is in place and able to take advantage of the stiffness that comes from arching action and double curvature. A shell structure has 3 membrane stress resultants and may be stable even before it is complete, unlike an arch which cannot stand until the keystone is in place. The shape of 3D printed shells needs to be optimized to minimize, if not completely remove, the need for support material solely used to stabilize the shell during construction.

A useful concept that can address these issues is pre-camber. If the likely movements of a shell during construction due to self-weight can at least be predicted, then the shape of the printed form of the shell can be adjusted to compensate, such that the shell deflects *into* its correct position as it is built.

2.3. Material

The materials suitable for 3D printing with drones are far from traditional. They need to be loaded onto a drone, transported to site, placed extremely accurately, and quickly gain strength such that they remain in place and can have further material placed on top of them. In order to allow a drone to place material accurately and get it to stay in place once deposited, liquids which quickly set solid are the obvious solution. The Aerial-ABM project is initially investigating the suitability of two-component polyurethane foams such as Reprocell® (Isothane [7]) as a precursor for later work on cementitious pastes with admixtures to modify the mechanical and rheological properties.

Any structural analysis therefore needs to be able to model and predict behavior of the material in both liquid and solid phases, and in order to deal with the time domain of automated construction, potentially also the setting process itself. For this reason, the authors are combining traditional structural analysis with mesh-free particle-based methods like Peridynamics, which in effect model the individual molecules of a material (or groups of them), and can therefore simulate liquid or solid phases in arbitrarily complex geometries. Miranda et. al. [9] have already demonstrated the suitability of Peridynamics to nonlinear modelling of concrete fracture, and this research is taking these ideas further by using it to model the liquid and setting phase of materials. It allows time- (and even temperature-) dependent results from detailed material characterization tests to be seamlessly incorporated into the structural analysis and simulation of building construction.

3. Reactive Correction

Another important requirement of the structural analysis is the ability to correct for inaccuracies during printing. There are many sources of construction defect, from the inherent inaccuracies of the drone's geolocation and 3D printing mechanism itself to the unpredictability of material deposition due to wind or material irregularities. Clearly the as-built structure will deviate from the pre-emptive design in some ways, and these deviations need to be identified and corrected for during printing.

Part of the Aerial-ABM team is dedicated to minimizing these inaccuracies, using innovative methods of drone control. However, it is acknowledged that they will never be removed completely, and so others are incorporating sophisticated 3D scanning capabilities onto the drones, be it the same drone as used for printing or a dedicated scanning drone which works alongside. Either way, it is envisaged that real-time information will be collected as to what exactly has been printed and how, if at all, this deviates from what was planned.

A bespoke bi-directional communications system is also being developed which will allow the control system to identify significant inaccuracies, and will query the structural analysis system to calculate whether the inaccuracies are of sufficient magnitude, or are in a particularly sensitive position, which means the structure will fail. If failure is identified, the structural system should be capable of devising a correction strategy, such as simply placing material where it should have been, thickening the existing shell locally, or adapting the geometry of the remaining yet-to-be-printed shell, to correct for the error. Exact heuristics for working out the best way to correct for a construction error are a topic of future research for the authors. But unlike the pre-emptive design calculations, whatever is developed must be extremely fast to compute since the drones will need to be told what to do quickly and cannot necessarily stop the entire construction sequence due to a localized problem in one area.

4. Case Study

In order to build experience of simulating the complex set of behaviors needed to pre-emptively design and reactively correct drone 3D printed structures, a series of simple studies have been carried out to prove the concepts.

4.1. Liquid Phase

Using a peridynamic solver, liquid material has been simulated falling from a 3D printing nozzle onto a rigid boundary surface. The actual material properties are unimportant for such benchmarking tests, since parameters like density, viscosity, stiffness and strength can all be adjusted at will once reliable material data has been determined and the materials themselves optimized for 3D printing. For the purpose of this paper it is assumed they represent concrete.

Each peridynamic “particle” represents a large number of actual concrete molecules and is simply there to model the overall effect of a liquid being deposited onto a surface and further liquid landing on top. Aspects such as spatter, clumping and slump can be identified and studied, as can the effect of nozzle movement on the resulting geometry. The particles interact with their environment (the boundary plane) and, when they come into close contact, with each other to form chemical-like “bonds”, which has the effect of simulating a solid mass of material.

The simulation shown in Figure 1 shows a coarse model of foam solidifying after printing onto a hemisphere, which could represent inflated formwork or part of a previously printed shell structure. The authors’ numerical experiments show that using the computer’s graphics card (GPU) instead of all the cores of the CPU results in an increase in speed by a factor of up to 50, depending on the computer.

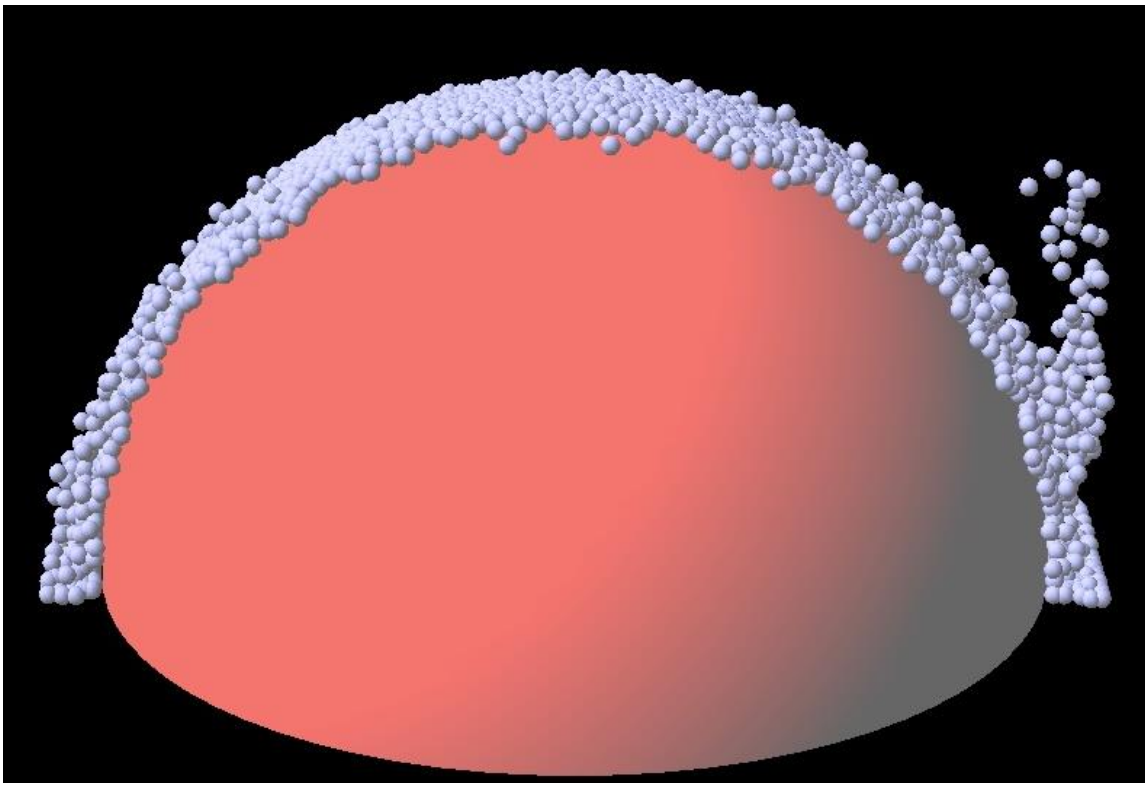

Figure 1: Peridynamic model of liquid concrete being printed through a nozzle onto an inflated hemisphere

4.2. Solid Phase

Peridynamic analysis was then carried out on a realistic geometry based around a potential drone path taken form a recent physical experiment. Particles were generated around the 3D printer nozzle location of a drone flight trajectory simulating printing a dome structure. Figure 2 shows how peridynamic particles were generated around the nozzle path, and where the nozzle passed over previous paths, the peridynamic particles were connected to each other, as a liquid concrete would bond to previously laid, solidified concrete.

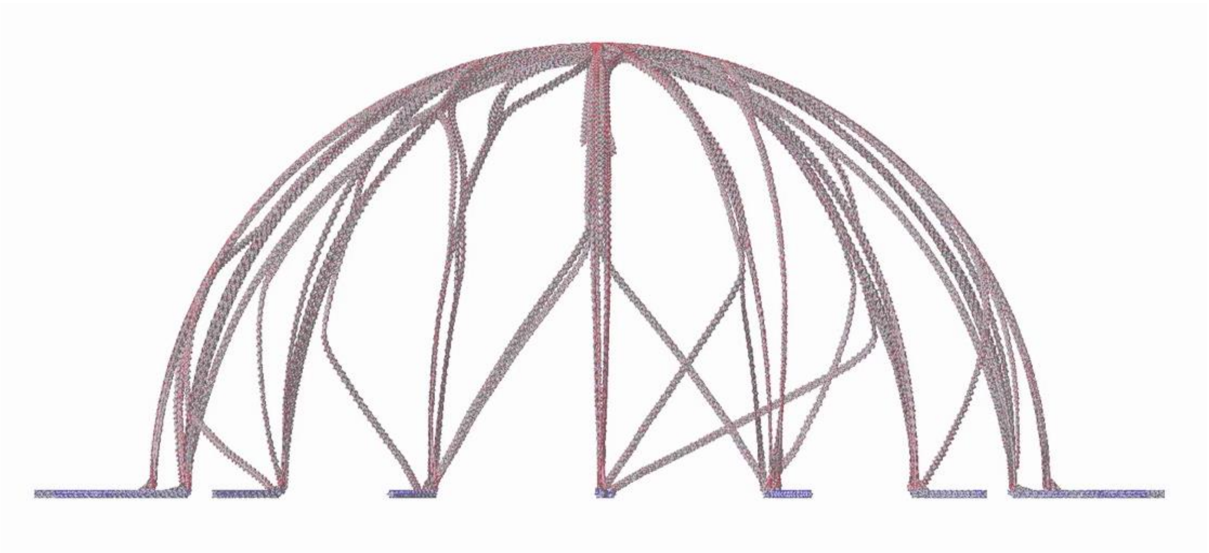

Figure 2: Peridynamic model of concrete laid down by drone

4.3. Shell Stability

In order to demonstrate the stability analysis of a shell throughout the printing process, a dome with double-curvature was modelled using Peridynamics in various stages of completion, based on a ground-up printing schedule (see Figure 3). At each stage the ability of the shell to support its own weight was checked and the movement at the top of the currently-printed geometry was monitored. The full model contained 64 million particles and was still easily analyzable on a single laptop (using the GPU).

4.4. Reinforcement

One possible technique for overcoming the poor tensile strength of printed material is to deposit short wires (or “needles”) as shown in Figure 4. Here the drones would have to deposit both the needles and a matrix to connect the needles to form a composite structure. The image in Figure 4 shows the computer simulation of a dome made from such needles, deposited sequentially from the ground up in a random but interlocking formation. Needles are prohibited from being laid down if they would pass through areas where voids are undesirable, either for architectural reasons or where structural analysis suggests reinforcement is not needed. The dome is partially complete in Figure 4 to show the geometry of the needles on the exposed upper layer, with the full dome consisting of one million needles. Its structural stability can be demonstrated via standard finite element analysis or a modified Peridynamic formulation where particles representing the ends of the needles interact with each other in response to contact between needles.

4.4. Swarm

An advantage of the Aerial ABM approach over ground-based 3D printed building systems is the flexibility that the open sky offers to print with several drones simultaneously without the danger of overcrowding or drone-drone collision. Drones can work autonomously but can specialize in different tasks or work collaboratively as a “swarm”. There are parallels in nature of where many individual insects collaborate to build huge structures (compared to their own body size), such as the termite mound shown in the left of Figure 5.

Figure 3: Peridynamic model of a concrete shell during printing

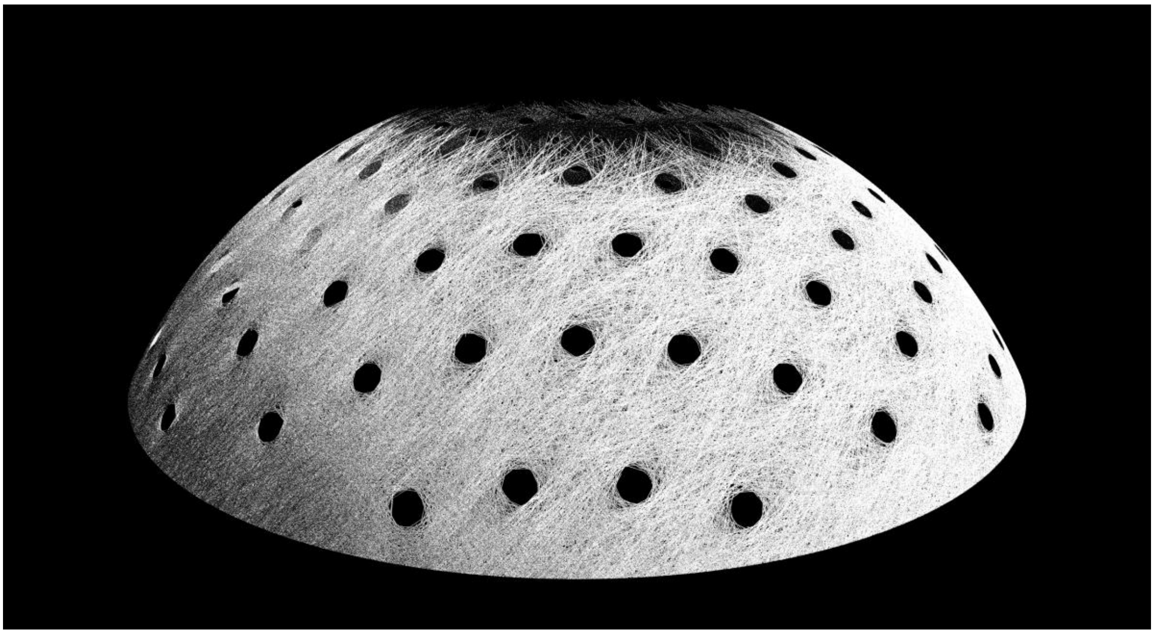

Figure 4: Printing with needles

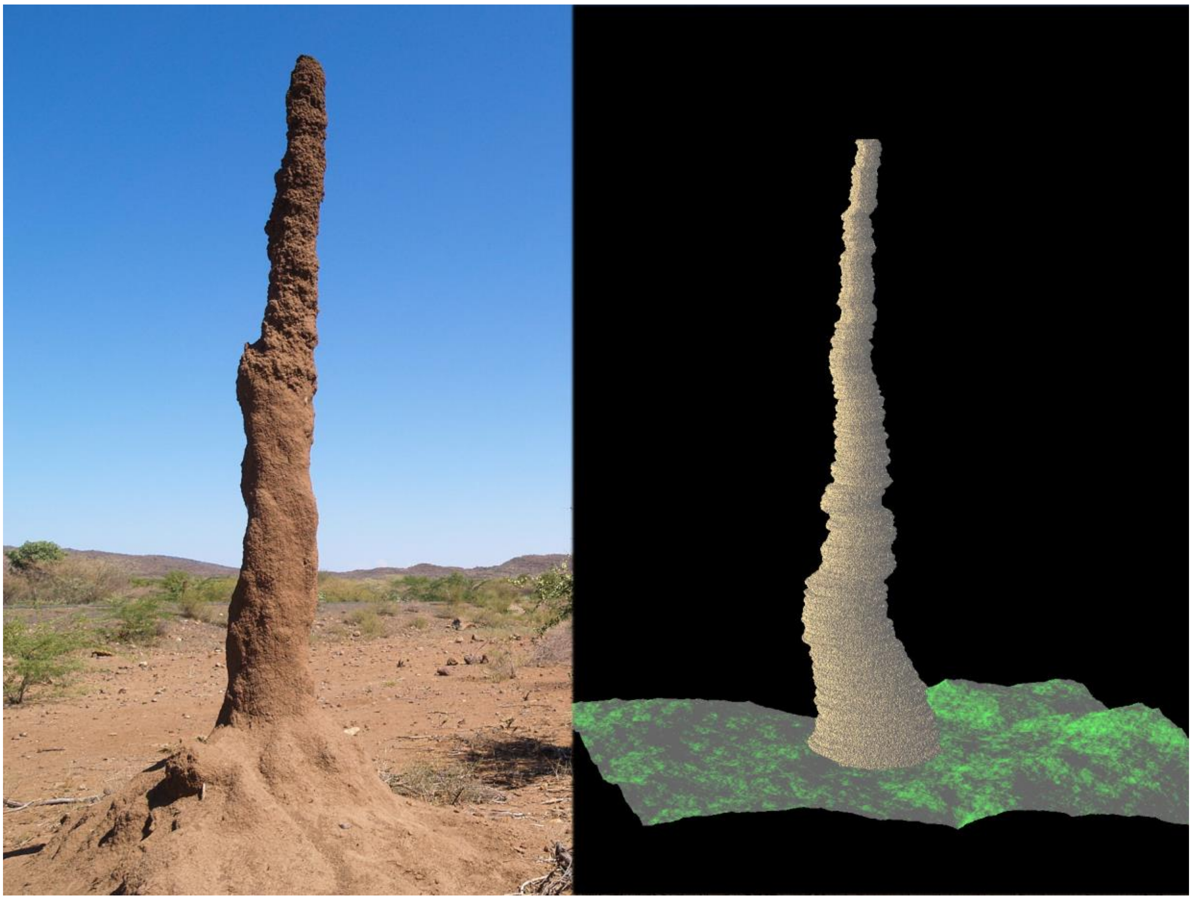

Figure 5: Photo of a Termite Mound (Kreuzschnabel/Wikimedia Commons, CC-BY-SA-3.0) and Computational Simulation of a Drone-Printed Column

The image on the right of Figure 5 shows the Peridynamic simulation of a structural column constructed by a swarm of aerial drones, with randomly generated “noise” (error) in the placement of successive layers of material. The future challenge of this research is to develop stigmergic heuristics which would help individual drones correct for such errors on-the-fly, and to optimize the print-recharge-refill strategies and task-allocation amongst large numbers of drones, such that the structure can be printed in the shortest time without mid-air collisions.

5. Conclusions

Many and varied constraints have been identified that 3D printing with drones introduces, which are very far from those traditionally seen in structural engineering. As such, a new framework for their design and construction needs to be developed, at the interface between robotics, design visualization, materials science and civil engineering.

The Peridynamic framework is very flexible and highly suited to modelling the 3D printing of buildings using flying drones. It can simulate foamed materials like polymers and concrete in both liquid and solid phases, in a wide variety of complex geometries.

However, a vast amount of research remains to be done. Pre-emptive design strategies need to be developed which derive geometries that minimize the need for support material solely for the construction phase. The construction process itself needs to be modelled and pre-camber-like adjustments made to the printing sequence such that the desired final geometry is realized. More detailed material characterization needs to be done to determine the way materials flow, harden and bond with each other, as well as improving their mechanical properties to make them suitable for reinforcement-free shells.

Perhaps the biggest challenge will be in developing extremely fast heuristic methods of correcting for a wide range of possible manufacturing defects *on-the-fly*, and the authors look forward to exploring the exciting research directions this will inevitably lead to.

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