Behavioural Production: A Swarm-Printed Architecture

Swarm-Printing imagines the convergence of autonomous flying robot multicopters with 3d printing technology as a means to design, construct and regulate buildings adaptively over time. For a research topic in the AA School's DRL program, the agenda is unusually technologically specific and involved. In order to engage productively with the subject, the studio collaborated with a number companies who specialise in; 3D printing, multicopter design and manufacture, algorithmic design, structural engineering, and computer science.

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AN OBJECT ORIENTED ARCHITECTURAL RESEARCH

Within architectural education, design research often remains self-referential, responding to the profession's own theoretical past despite academia's role in preparing architects for a future of practice that responds to the present. Perhaps this hesitation to engage in the real present stems from the influence of continental philosophy which encouraged a world-view that perpetuated its own existence and refused to recognise the importance of matter outside of human subjective perception[1]. Deleuze and Guattari's realist philosophy influenced a shift away from this world-view within architectural education, towards an ontological approach to design by focusing on the becoming of objects. [2] Architectural practices attempting to respond to an increasingly complex and dynamic world, developed generative processes in lieu of predetermined or explicit geometry that enabled complex spatial and formal negotiations to be incorporated within designs. Unfortunately these processes were not able to offer substantial answers to the needs of contemporary technological society which cannot be resolved through correlations to form alone [3].

The recent philosophical movement "Speculative Realism" seems to facilitate architectural practice seeing beyond this generative yet correlative discourse on form by offering more emphasis on objects themselves (in both their speculative and real capacities). One particular branch of the philosophy known as Object-Oriented Metaphysics promoted by Graham Harman recognizes agency in objects themselves; valuing objects as real beyond continental philosophy's insistence that objects be valued for relational potential and solely through human perception. Harman argues that objects are not reducible to their correlations alone [4]. This unbounded condition suggests that anthropocentric activities of thought and representation are insufficient design research activities

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Figure 1:AA.DRL Student group Quadrants: Doguscan Aladag, Juan Montiel, Tahel Shaar, Vincent Yeh. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis, *Multicopter with 3D-Printer hardware attachment*

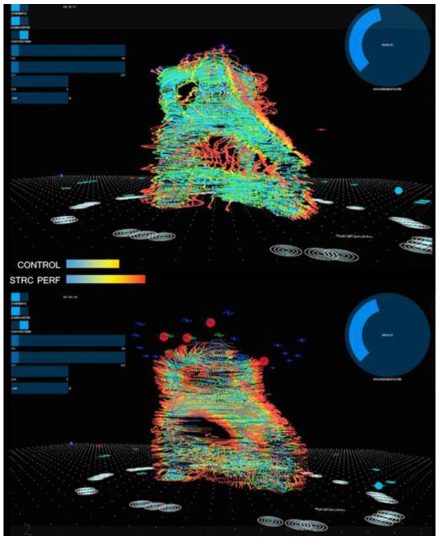


Figure 2:AA.DRL Student group Quadrants: Doguscan Aladag, Juan Montiel, Tahel Shaar, Vincent Yeh. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis, *Deviation analysis of Aerial Robot Swarm Simulation's ability to 3d print an explicit 3d model*

on their own as their disassociation from actual objects may constrain them to remain works of pure fiction forever confined to their 'established' meanings alone. This is not to imply that theoretical research should not be undertaken as it has immense value, or to suggest design research by engaging with real objects should be solely technical and pragmatic. A design research that recognizes the irreducible nature of objects is open to speculation. This paper presents one particular design research endeavour which has been undertaken as both "speculative" and "real".

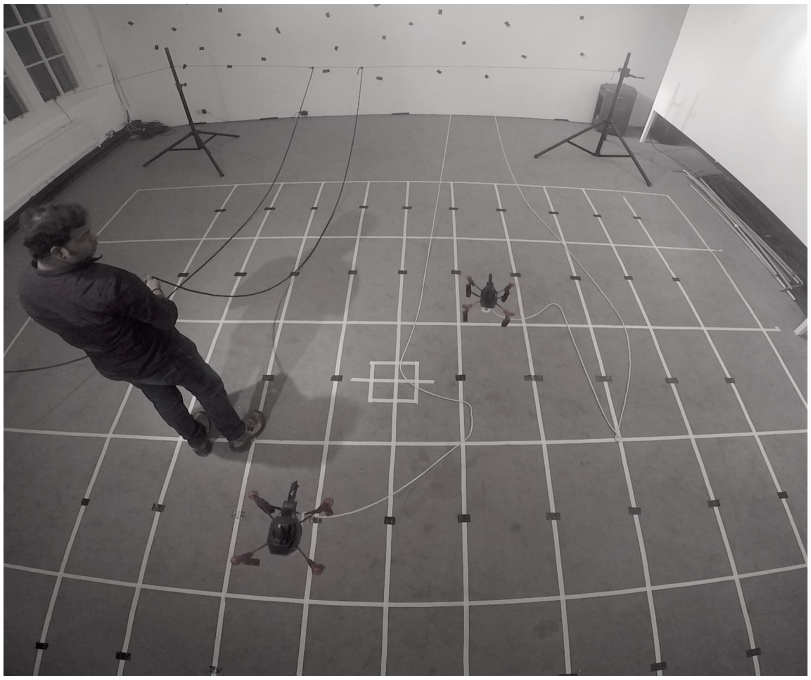
DESIGN RESEARCH IN THE AA.DRL

The Architectural Association School of Architecture's Design Research Laboratory (AA.DRL) [5] has a prerogative for integrating the practical making of technical prototypes with ambitious speculation. As a post-professional Master's program in Architecture and Urbanism, the AA.DRL is less constrained in syllabus than professional degree courses. The course assigns great importance to technological and prototypical research and its inter-connected co-dependence with speculative endeavours undertaken for design thesis. A design thesis emerges from, while also informing a technological development. Final project outcomes are practically worked on to a level considerably more detailed than one traditionally finds within an architectural program. While these technical developments offer no threat to the research of an engineering department, the work is done with intensity and credibility in so far as is productive to support and fuel the speculation of an ambitious architectural proposition. In this sense, research in the AA.DRL is both speculative and real.

Within the AA.DRL program, Studio Robert Stuart-Smith explores the architectural design and production of buildings through creative approaches to temporality within building life-cycles. The current research agenda "Behavioral Production" speculates on the architectural potentials of Swarm-Printing. Swarm-Printing imagines the convergence of autonomous flying robot multicopters with 3d printing technology as a means to design, construct and regulate buildings adaptively and flexibly over time. As a research topic the agenda is clearly technologically specific and involved. In order to engage productively with the topic, the studio formed a collaboration with a diverse group of industries involving companies specialised in; 3D printing, multicopter design and manufacture, algorithmic design, structural engineering, and computer science [6]. This geographically distributed collaboration required software code collaborations between parties and amongst the students themselves utilizing Github repositories [7] and regular video conference calls. The "real" was supported through engaging conversations and technological developments of software, hardware and firmware associated with the practical problems the research group faced in order to achieve mobile , flying 3D printers.

3D-PRINTING BUILDINGS WITH A SWARM OF FLYING ROBOTS

3D printing technology is entering into the construction industry due to its ability to offer significant reductions in transportation and overall building costs. As an additive manufacturing process it also enables a greater complexity of design to be achieved at practically no additional cost. The economics of 3D printing largely revolve around the quantity of material utilized and production time (which in comparison to industry standard practices is comparably fast). In 2014, Winsun Decorative Design Engineering Company in China 3d-Printed ten concrete houses of two hundred square meters each on one 3D printer within twenty-four hours.



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Each house cost less than five thousand US dollars to construct [8]. At one-fortieth the cost of alternative industry standard construction techniques the technology seems set to proliferate on the market with companies such as Contour Crafting in the US [9] and D-Shape in Italy [10] set to commence on-site 3D-Printed construction operations shortly. While these technologies offer benefits in speed and material efficiency, the engineering of these enormous 3D printers requires a large gantry-frame that positions the 3d-printer mechanism and moves it in three dimensions over time. This frame is of a fixed dimension and results in a limit to the size of the 3D Print achievable from the machine. This large, heavy infrastructure is inflexible and requires considerable time and effort to deploy on construction sites. Swarm-printing offers a viable alternative solution to construction oriented 3D-printing due to its exponential gains in speed and flexibility. By attaching 3D-Printers to flying multicopter robots, no fixed infrastructural frame is required to control the 3d Printer movements resulting in no size limitation to what can be achieved from a single 3D-print.

As a modular system, a large group of multicopter 3d-printers are able to increase the speed of a print task by a factor related to the number of printers utilized. Considerable benefits in adaptation are available beyond this scalable time-frame through swarm logistics. A swarm describes a co-ordinated collective organization such as a flock of birds, school of fish or colony of termites. In a swarm individuals through their own local decision-making participate in larger actions and formations. Swarm systems are flexible, fast and adaptable; the non-hierarchical structure of a swarm makes all parts replaceable, enabling a swarm system to remain robust due to its generous in-built redundancy. Scientists such as Eric Bonabeau and Guy Theraulaz have been able to simulate the construction of termite mounds [11] through simple algorithmic principles whilst the experimental design practice Kokkugia has also undertaken extensive research into the use of swarm-algorithms for the generative design of buildings [12]. These have both demonstrated that not only do swarm behaviors offer practical and logistical efficiencies but they are also capable of producing emergent creative

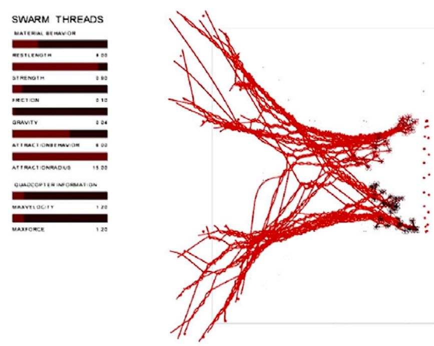

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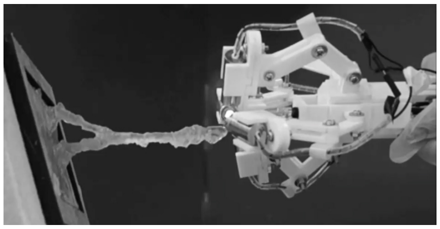
Figure 3: AA.DRL Student group Void: Karthikeyan Arunachalam, Maria García Mozota, Alejandra Rojas, Mel Sfeir. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis. *3 quadcopters collaborate to weave nylon ropes. Their movements are related to each other via communication through one laptop. The grid on the floor facilitates their perception of their local position which each quadcopter calculates individually*

Figure 4: AA.DRL Student group Void: Karthikeyan Arunachalam, Maria García Mozota, Alejandra Rojas, Mel Sfeir. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis. *Digital design simulation of quadcopters weaving theads together. The simulation is the same one utilised for real quadcopter movements*



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outcomes. As such, in addition to offering greater adaptation and efficiencies on-location when compared with existing methods of 3d Printing, a multicopter swarm-printing system is able to contribute creative input to construction.

While developing the technical capabilities to achieve multicopter swarm 3D-printing, the studio worked in-tandem on architectural design thesis proposals that explored the potential of Swarm-Printing to be utilized on demand in hard to reach places where the technology could offer a quick to build, adaptive construction model that is able to operate in real-time in relation to the activities and demands of people and "things".

A PRACTICAL APPROACH TO DESIGN RESEARCH

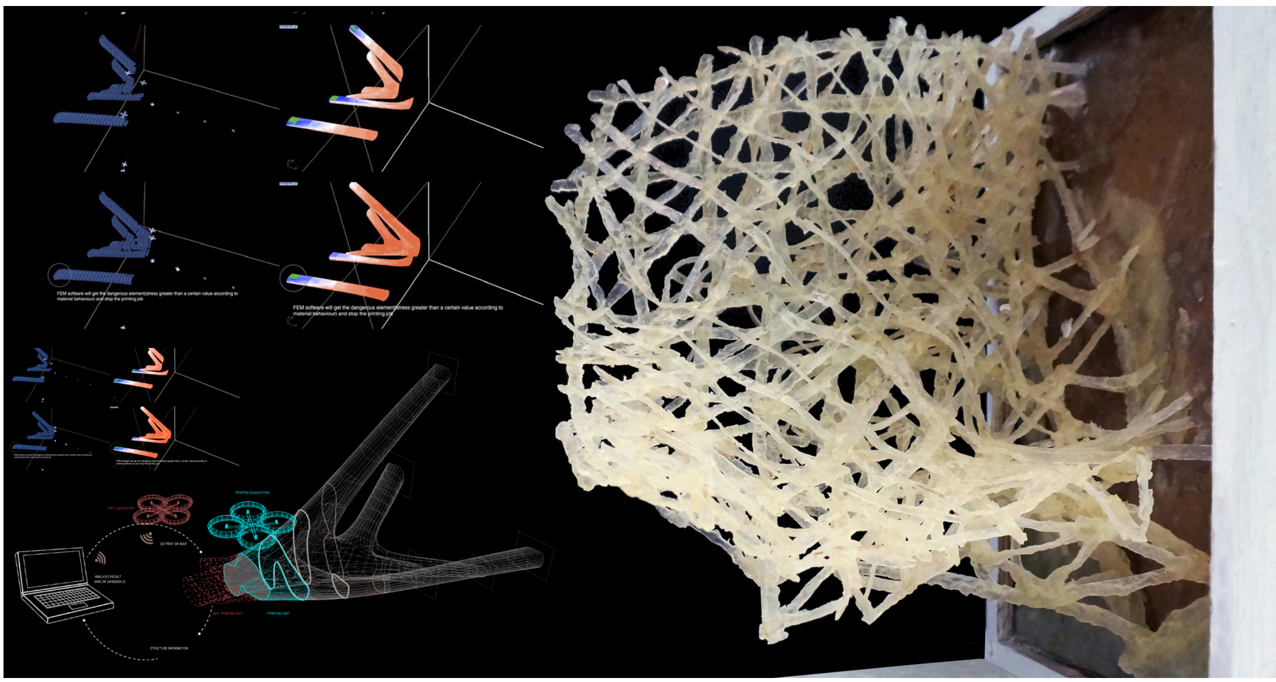
The three design thesis each explores opportunities for on-demand swarm-printed construction and speculates on different contextual and time-based scenarios where these can articulate an imagined architectural future. All three projects address the logistical and technical concerns of this time-based mode of construction in a manner that is intrinsically tied to the design possibilities that can be explored. In this sense the "real" is bonded to the "speculative". Separating the two impoverishes the design exploration and prevents further resolution and progress. All three teams experienced faster developments when the technical and design aspirations were at their most clear, yet the projects push far beyond attainable technical achievements (which to this date are a work in progress although the research is not yet complete) or immediate and obvious industry applications into unchartered speculative design territories.

The student team *Quadrant* [13] addresses the role of architecture within cold, hostile and fluctuating climatic conditions. *Quadrant's* thesis proposition arose from the observation that the dynamic time-based activities of visitors to remote northern winter environments would benefit from a more temporal and environmentally responsive architecture. Envisaging a swarm of mobile-flying multicopters are able to 3d-print ice structures the students speculated that they are able to provide a contextually responsive on-demand series of spaces that may be constructed from freely available snow, resulting in no material wastage, and minimal construction cost. The time-based construction logistics would enable each building's thermal performance to be monitored and wall thicknesses to be dynamically maintained by the on-site autonomous construction team to ensure continuous temperature control. Multicopters could continuously re-thicken walls as they melt, or demolish a structure to rebuild it somewhere else with minimal effort should the demand be there. Utilizing robotic production for such a purpose, an architecture can be proposed that is temporal, on-demand and facilitates the creation of pop-up architectural events. Although the inhabitants are not actively constructing the ice structures, they are able to participate by providing instructions and feedback of their needs and desires in order to curate different forms of winter gathering within a networked building typology. The design articulated a mico-urban indoor architecture in an environment where outdoor urban space is not practical.

Whilst *Quadrant's* project responds to a real climatic scenario, the student team *Void's* [14] departure point stemmed from the technology of the multicopter itself. Considering the constraints of the light-weight payloads the multicopters are able to carry, *Void* chose to avoid the use of a 3d printer and revisit the role of tensile construction within architecture due to the minimal material and weight required to create complex and large span structures. This led to the study of spider-webs

Figure 5: AA.DRL Student group SCL: Liu Xiao, Sasila Krishnasreni, Duo Chen, Yiqiang Chen. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis., *Custom designed resin 3d printing hardware*

which are efficient catenary structures that are constructed from a series of procedures, undertaken in relation to local contextual spatial constraints. Exciting and emergent structures are built from simple bottom-up rules that are locally executed without an overall geometry being enforced. These rules are sufficiently simple that they may be abstracted and applied to multicopter flight manoeuvres that the students are able to control. Depositing and wrapping threads, the multicopters are able to weave a structure when working cooperatively. By working directly with the flying multicopters, *Void* was also able to incorporate the principle of braiding to enable the multicopters to weave strands of variable thickness from a single consistent gage of thread ensuring greater flexibility in material placement and structural stability. Void's design progress was only possible due to their computer programming developments and their successful incorporation of demanding robotic tasks such as computer vision and positioning procedures.



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The third project by the student group *SCL* [15] is concerned with the real problem of urban densification and its impact on high-rise urban metropolis' over the next fifty years. SCL proposed a series of habitable connective structures between buildings at high level that provided additional circulatory strata within dense urban cities currently too dependent on inefficient and over-capitalised ground level street circulation. These bridge-like structures would be difficult to build safely or quickly without a swarm of flying multicopter 3d-Printers. The project speculates on the potential for architecture to be rapidly built and adapted to a constantly changing urban condition. As a complex networked system, new building cannot be undertaken independently but must be dynamically adapted to the configuration of existing buildings. One example of this involves the addition of a habitable bridge that connects a building with a recently completed bridged space. The original bridge may not have the structural capacity to support the new bridge, requiring the mobile robotic construction team to add additional material to the existing bridge to sure up its structural capacity

Figure 6:AA.DRL Student group SCL: Liu Xiao, Sasila Krishnasreni, Duo Chen, Yiqiang Chen. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis., *3D printed cantilever structure fabricated without UAV utilizing custom designed resin 3d printing hardware. The simulations depicted to the left utilize real-time structural analysis to enable quadcopters to create cantilevered structures with printing behaviours that can adapt to both predicted and real-time structural concerns that arise from unpredictable scenarios caused by wind or material deposition inaccuracies on-site.*

ENDNOTES

1. Speculative Realism is a relatively new branch of philosophy that provides a counter argument to continental philosophy's anthropocentric views. A good overview is provided in the paper "Towards a Speculative Philosophy" [8]

2. In Deleuze and Guittari's "A Thousand Plateaus" they argue for a realism with ontological tendencies. A discourse on "matter-functions" describes the role of becoming within organizations of matter. Architects such as Greg Lynn and Ben Van Berkel have referred to this and Deleuze and Guittari's notion of the "Abstract Machine" in order to support design processes that delayed the "becoming" of form in order to avoid pre-conceived designs.[3]

3. Generative design enabled architects to incorporate practical criteria within a creative design process yet these operated within the design phase alone and could not actively engage with fabrication, construction or the occupation of buildings. Negotiations were virtual and frozen in time when implemented within the actual production of real architecture.

4. In the papers "Object Oriented Philosophy" [6] and "The Revival of Metaphysics in Continental Philosophy (2002)" [7] Graham Harman utilizes Heidegger's analogy of the tool to demonstrate his opposition to continental philosophical views that deny the independence and agency of objects outside of human perception that advocate objects can be only described by their relations. Harman sides partially with historical examples of metaphysics, discussing Aristotle yet positioning himself as not siding with Aristotle's concept of substances. Harman suggests objects are irreducible and both natural and artificial. He also suggests multiple objects can make up a larger object.

5. The AADRL is an abbreviation for the Design Research Laboratory. A post-professional Masters program in Architecture and Urbanism at the Architectural Association School of Architecture in London. The program runs for 1.5 academic years and the international body of students undertake their research project in teams within a design studio environment.

6. The companies involved included: Peachy Printer, CrazyFlie, Balmond Studio, AKT2 Engineering and others.

7. Github is a website and data structure that allows for a team of people to collaborate on computer programming projects. See [5]

8. It should be no surprise that robotically fabricated buildings would be cost competitive. More astonishing is the speed in which the houses were produced. For further information refer to [12]

9. Contour Crafting is a concrete 3D-Printing company formed by Behrokh Koshnevis, a Professor at USC in the US. See [11]

10. D-Shape is an Italian 3D-Printing company. Enrico Dini, the director developed a large-scale multi-head 3D-Printer large enough to make architectural scale 3D-Prints. See [12]

11. Eric Bonabeau and Guy Theraulaz have developed computer models of termite mound construction that operate through simple local behavioral rules including stigmergy. They are able to demonstrate that termites are able to construct quite an elaborate structure without the need for architectural blueprints. See [2]

12. Kokkugia is an experimental design research practice run by Roland Snooks and Robert Stuart-Smith. Kokkugia has developed a number of agent-based design methodologies that have been utilized with architectural projects within Kokkugia, Studio Roland Snooks and Robert Stuart-Smith Design.

13. AA.DRL Student group Quadrants: Doguscan Aladag, Juan Montiel, Tahel Shaar, Vincent Yeh. Supervisor: Robert

while also building the new bridge simultaneously. A similar time-based process is also required for the construction of a single new bridge where the aerial construction team constructs the bridge structure from two ends simultaneously. As the two ends must operate as cantilevered structures until they are connected in the middle of their span, the structural stress conditions of the bridge dramatically shift at the moment of this connection. The construction sequence takes this into account and material is strategically deposited within a timed sequence to allow for such a dynamic transition to occur. The design proposal is highly dependent on an understanding of these logistics.

This extremely dynamic and adaptive construction model demonstrated autonomous robot decision-making based on real-time structural analysis. It suggested a flexible building system, responsive to fluctuating demand within the city that is sufficiently self-aware to consider the networked implications of new decisions. Whilst the project is highly speculative, as with the other thesis projects in the studio, the technical logistics of the speculative scenario are practically accomplished to a high level and are intrinsic to the design resolution the students are able to develop. The logistics of autonomous aerial construction and bridge building that respond to real-time structural analysis become a platform for the design investigations which pursue ambitious mid-construction cantilevers and provide detailed sequencing of construction deposition that is coordinated amongst a large number of multicopters. These logistics translate into local algorithmic rule-sets that are incorporated into the design process, enabling the design process to become a virtual simulation of an imagined actual construction.

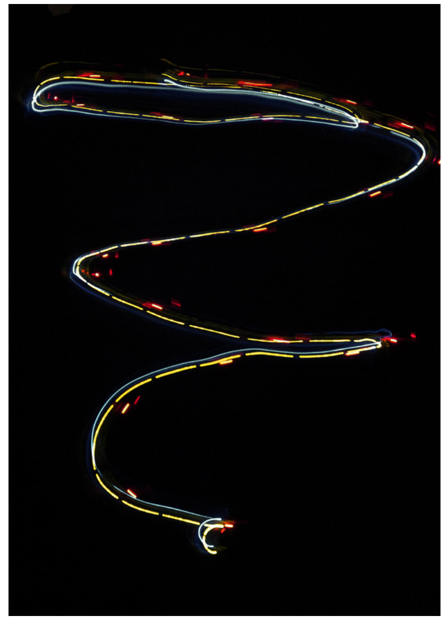
The three projects developed multicopter flight control, material deposition strategies and software simulation logistics in tandem. Material experiments were critical to each team's workflow providing immediate feedback on a range of issues difficult to foreshadow or work through by other means. Quadrant frequently arranged for a mobile freezer-room unit to be rented and installed on the school premises in order for 1:1 ice wall building to be tested at sufficiently cold temperatures. Similarly, SCL undertook many iterations of hardware development to achieve effective resin deposition with a sufficiently simple yet high-speed curing procedure. Whilst this technology is a work in progress and not fully operational it is already sufficiently developed to enable material studies that can provide logistical constraints and aesthetic observations to be constantly incorporated within the digital simulation software. The digital simulation software was developed as a collective effort between all three teams and teaching staff and incorporated a wide array of construction logistics that became intrinsic to any digitally simulated design solution. This same simulation software was utilised to control actual flight movements of multicopters. The two-fold utility of this bespoke computer program suggested a curiously unique fusion between the speculative and real scenarios (perhaps prompting the speculative investigations to become even more speculative).

SPECULATIVE YET REAL

While the core ethical value of these architectural endeavours rests on social, human and environmental concerns, the architectural research is not anthropocentric. Without ignoring cultural and historical precedence, the work is driven primarily from scientific and technological opportunity and action. It is immediately positioned in relation to real-time interactions between objects:

objects to objects, objects to people and people to people. For all practical and theoretical purposes, a person within this scenario is also participating as an object engaged in the dynamics of architectural construction via swarm-printing.

Whilst buildings are often perceived as singular iconic objects, Graham Harman has described how buildings in object-oriented philosophy may be described as composed of a large number of small objects (such as screws, nuts, bolts) that exist beyond a user's perception and operate together in an irreducible way as a building. Swarm-printed construction is a dynamic and real-time process that directly engages with object-oriented metaphysics [16] in its conception and operation. It is a logistical flurry of object-to-object interactions taking place over time whereby neither the building,the built material, semi-autonomous constructors or inhabitants are reducible or sufficiently describable as a simple network of relations. All in fact may be considered part of "a building" while each one holds agency and autonomy beyond their respective affiliations. The whole is beyond a single point of understanding and may only be engaged with directly. Therefore speculating requires dialogue with the real world of objects.



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Architects engaging in this research are not only dealing with the design of architectural objects, but are developing fundamental agent-actor capabilities that require investigations into the time-based nature of the construction and occupation of buildings. Rather than a concern for explicit architectural outcomes this work inevitably focuses more on designing spatial and material contingencies that can cope with unplanned change. As design engages with the indirect, non-linear control of events, far less guess-work is possible unless a pre-construction simulation is undertaken. Through simulations robotic behaviors and quantities such as time, material and cost can be evaluated. Real-time decision making can be aided by such processes also. These analytical yet generative processes offer a new creative approach to construction that can be termed Behavioral Production.

BEHAVIORAL PRODUCTION: A GENERATIVE APPROACH TO DESIGN & PRODUCTION

Behavioral Production aims to offer an alternative to inefficient and unimaginative practices within the building industry that result from the formal separation of design and production. Production-naive design agendas often necessitate costly post-rationalization initiatives whilst design-and-construct solutions that attempt to marry these two processes have typically compromised design for the sake of production profits. Behavioral Production argues for the fusing of design and production as a generative process that provides for more efficient and creative potentials than exist within standard industry practice.

Algorithms are able to directly control production-machine operations whilst also engaging in design through computer programming. Uniting design and production within a computer program enables something profound to occur: a simulation of an actual production process can also operate as a design algorithm. A design is generated through a simulation that also defines the instructions for how the design is to be constructed, or more directly, the design may be generated in real-time through the production process. In this scenario, the boundary between the real and speculative is dissolved. Simulation and production are interchangeable and both are capable of generating design solutions.

Figure 7: AA.DRL Student group Void: Karthikeyan Arunachalam, Maria García Mozota, Alejandra Rojas, Mel Sfeir. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis. *Time lapse photo-graph of algorithmically controlled Multicopter flight path*

Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis.

14. AA.DRL Student group Void: Karthikeyan Arunachalam, Maria García Mozota, Alejandra Rojas, Mel Sfeir. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis.

15. AA.DRL Student group SCL: Liu Xiao, Sasila Krishnasreni, Duo Chen, Yiqiang Chen. Supervisor: Robert Stuart-Smith. Studio technical consultants: Tyson Hosmer, Manos Matsis.

16. Refer to note 4 for more information on Graham Harman [7]

17. Edward Lorenz utilizes the term 'sensitive dependence' to describe that non-linear systems can produce extremely different results from infinitesimally small variations in a processes starting conditions. Lorenz has proven this by mathematical proof and through scientific observations on climate. See [9]

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While it is possible to orchestrate this process in a linear fashion where a sequence of fabrication operations are pre-described and executed sequentially the advantages are more significant if the process is event-driven in real-time and therefor non-linear and complex in nature. A non-linear process enables simultaneous negotiations to take place in real-time building a design intelligence into production beyond automation alone.

The designer is free to engage with this process as much or as little as desired. At its simplest level, a designer could work with a predefined geometry yet allow specific design concerns to be resolved in real-time through algorithmic production processes (for example, an interior space's form could be designed explicitly yet the actual form of the exterior and wall section cavity profiling are determined in real-time through a negotiative construction process in order to minimise material waste and production times). Alternatively a designer might work in a less-predetermined way by establishing a set of local event-driven rules in which a design solution is able to emerge autonomously without their active involvement. In this scenario the chaotic principle Edward Lorenz described as "*sensitive-dependence*" [17] would give rise to radically different design results due to contextually diverse starting conditions.

Behavioral Production aligns design speculations with real world actualization in a manner more accurate and creative than can be achieved by pre-determined design and automation alone. Whilst there are quantitative benefits from such an approach it is also the qualitative affects such integrated processes can develop that motivates our ongoing design investigations.

The AA.DRL Studio Robert Stuart-Smith's research into swarm-printing aims to capitalise on this generative approach to design and production by providing solutions to practical problems that are currently unresolved within 3D printing construction systems whilst speculating on the architectural opportunities that this affords. By engaging with the real world of objects we are better able to make informed speculations. Whilst the designs push beyond our capabilities today, they are grounded in the practical work we have developed and achieved over the course of this research. The qualitative characteristics evident within the designs are also intrinsic to the operational logistics developed. This design research is therefore positioned as both speculative and real.

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FROM TECTONIC TO TECHNIQUE-
ADVENTURES IN ARCHITECTURE"S ONTOLOGIES