A Reconfigurable Modular Swarm Robotic System for ISRU(In-Situ Resource Utilisation) Autonomous 3D Printing in Extreme Environments

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Abstract. Implementation of Robotics and Automation has revolutionised the Manufacturing Industry, generating unprecedented levels of efficiency, boosted productivity and lower levels of risks. As automation begins to seamlessly integrate and embed in various home applications, uptake in the AEC (Architecture, Engineering, Construction) Industry has been slow, only limited to off site fabrication. With this in mind, the departure point of the research investigation then lies in the identification of opportunities for on-site applications of robotics in construction. The paper proposes a new method of construction based on concepts of reusability and reconfigurability, re-envisioning operational life cycles in conventional, industry practices. An evaluation of industry and academic precedents of robotic applications presented an opportunity to propose a new conceptual framework for a reconfigurable, modular robotic swarm system that is comprised of an interchangeable "toolkit of parts". Application of the framework was first developed for NASA's 3D Printing Habitat Centennial Challenge, which manifested as an ecosystem of robotic assemblies that dynamically adapts to complete a multitude of tasks in the construction of a 3D Printed Shell Structure. The case study application was selected due to the extreme operational requirements such as size and logistical challenges, multiple levels of redundancies and adoption of "In-Situ Resource utilisation"[1] principles.

Keywords: Swarm Robotics, Modular Construction Systems, 3D Printing, Martian Habitats, Regolith, Reconfigurability, ISRU(In-Situ Resource Utilisation)

1 Introduction

The rise of robotics has visibly revolutionised our factory based manufacturing capabilities since its conception in the 1950s. Engelberger conceived Unimate #001 Prototype, the "first mass produced robotic arm for factory automation"[2] for General Motors. Automation provided companies with a competitive edge, enabling them to achieve "production speed never before achieved….more than double the rate of any automotive plant in existence at the time!"[3] as well as improving safety within their facilities by allowing robots to “perform jobs that were unpleasant and dangerous for humans”[4].

Yet, if we start to compare the automotive and manufacturing industry with the construction industry, there is very little indication of a similar digital industrial revolution ever taking place. With a global market value of $10trn, the application of robotics within the construction industry would have immense economic and socio-economic returns. Despite the opportunities, an average of 90% of large construction projects categorised as “megaprojects” still would commonly have “cost overruns of 50 percent to 100%”[5]. Demand for infrastructure and built projects is also forecasted to increase, with 68% of the world's population projected to live in urban areas by 2050 [6]. Combined with increasing capital costs of the labour force, global inflation and a shortage of skilled construction workers, these pressures will eventually force the industry to uptake and implement new methodologies that involve automation.

Even with surmounting pressures, the AEC is notoriously known for being slow to adapt, almost resistant to change. Seventy percent of AEC companies surveyed by KPMG in 2016 identified that major construction companies do not use robotic or automated technologies within the various aspects of their operations....most with no plans to use it in the future[7].

2 History of Robotics within the Construction Industry

The majority of robotics within the construction industry only serves as an extension to its manufacturing counterparts, which is often limited to the prefabrication of discrete components within a factory setting. Applications range from the fabrication, production and assembly of concrete components, Robotic Assembly of Modular Blocks, Automated Brickwork Plants and Steel Component Productions[8]. Any outputs of the production process is also subjected to the size and logistical limitations of both the factory and transportation infrastructure of the final site destination.

To attain a larger scale of impact to decrease the issues surrounding construction inefficiencies, there needs to be a focus for investigation towards on-site robotics. A new set of challenges present itself when robotics are placed on site. Every system must have the capability to operate, adapt and be aware of the volatile nature of a construction site.

Existing applications of robotics in construction is classified into 2 major categories, those that are intended to be used for a specialised, single task versus an “Integrated Robotized Construction” strategy that comprises of multiple robots[9].

2.1 State of the Art - On-Site Robotics

Commercial applications of robotics can also be broken down further into subcategories, according to their main functional purpose. We have identified six major categories of on site robotics functionalities: Analytics, Fabrication, Component Assembly, 3D Printing, and Logistics.

Companies such as SkyCatch and DroneDeploy utilise Drones or UAV(Unmanned Aerial Vehicles) to conduct visual analysis and inspections of construction sites.[10], often capturing both 2D orthomosaics and 3D LIDAR Point cloud information. In the domain of Assembly, variations of robotic or telescoping arms are often deployed to aid or automatically place and fix a set of prefabricated blocks and/or components. SAM100[11] and Hadrian X[12]by Construction Robotics and Fastbrick Robotics respectively, are two different variations of bricklaying robots that are operating on-site. With the capacity of laying up to 3000 bricks per day[13], these robots have the capability to eliminate physical pressures on the daily labourer, whilst exceeding the physical performance limitations of an average builder by sixfolds.

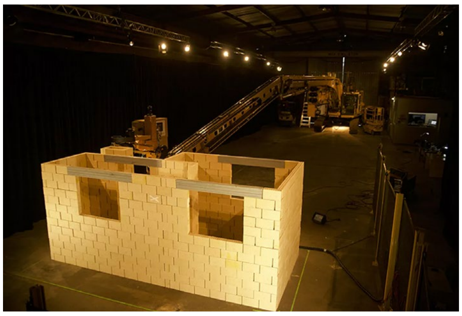


Fig. 1. Hadrian X by Fastbrick Robotics.. Image Source: https://cdn.vox-cdn.com/thumbor/6xhcMpxAxGX57bYvlk2ANYIN_Gw=/0x0:700x467/1200x800/filters:focal(294x178:406x290)/cdn.vox-cdn.com/uploads/chorus_image/image/62922632/hadrianx2.0.jpg

Fig. 2. US Armed Forces - 3D printed Barracks Image: Marine Corps Systems Command (MCSC)

More recently, with the commercialisation of 3D printing, companies are also starting to envision on-site 3D printing robots. Systems would often involve a large gantry system with a multi-axis printing nozzle. WASP’s green agenda uses a 12m tall 3D printer to print houses out of a combination of earth and husk fibers[14]; Chinese construction company Winsun, developed a large scale continuous 3D printer to be able to print “10 houses in 24 hours”[15]. Experimentation has even reached inside the processes of the US Armed Forces, exploring the potential of 3D printing technology to construct a “46-square-meter” concrete barracks in less than 2 days.[16].

When adopting an “integrated robotic construction” strategy, advancements have been focused on material handling, assembly and logistics, enabling human counterparts to be more efficient in accurately placing, transporting and installing large prefabricated components inside a building footprint. Robotic trolleys implemented as part of Shimizu Manufacturing’s SMART(Shimizu Manufacturing System by Advanced Robotics Technology) Roof System enabled them to have an “Automated Conveying System,...Automated Steel Assembly System,...Automated Welding System,....and an “Automated Transportation and Installation of Prefabricated Materials and Equipment.”[17].

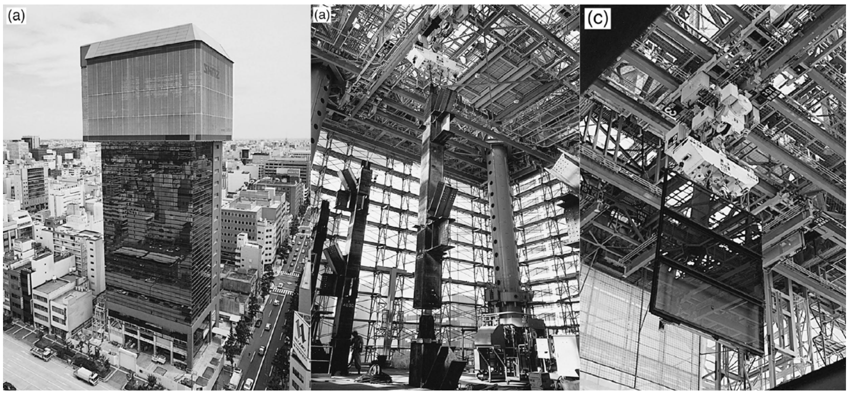


Fig. 3. Shimizu Manufacturing’s SMART Roof integrated robotic construction System Image: Shimizu Manufacturing

2.2 Discrepancy between Industry and Academia

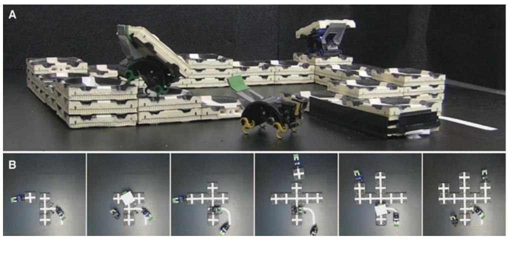
Despite existing commercial applications of robotics in Construction, there is an apparent gap between industry and academic experimentation. While it lacks scale in implementation, academic explorations tend to question the core methodologies, strategies or functionalities in various operational models.

A notable project with an ambitious agenda is the NEST[18] building in Dubendorf, led by ETH Zurich and NCCR(National Centre of Competence in Research) Digital Fabrication. The project aims to be “the first house in the world...designed, planned and built using predominant digital processes”[19], often embedding robotics within its core processes. As part of this project, they’ve developed sub-projects such as the

“In-situ Fabricator & Mesh Mould”[20], a “two-meter high construction robot” with the capacity to fabricate steel wire meshes serving as both formwork and reinforcement for in-situ concrete casting. Another application, the “Spatial Timber Assemblies” uses a “multi-robotic system to fabricate and assemble timber frame modules”[21]

Swarm Robotics || Modular Robotics is a sub-domain of research and development in robotics. Originally conceived to study and validate biological research [22], this approach utilises swarm intelligence principles to tackle complex tasks that require “unknown amount of resources” [23] to complete. The approach is highly scalable and flexible which is enabled through the miniaturization and cost reduction of simple robots. Execution of tasks is not restricted through a specific formula or sequence of sub-tasks but rather the emergent behaviour of the swarm as it adapts to its peers and its context. Such a strategy is usually deployed in projects that have a “high risk of losing robots...Loss of individual robots does not imply the failure of the whole swarm”[24].

Application and experimentation of swarm robotics within the architecture and construction industry have manifested in varying TRLs (Technology Readiness Levels). Conceived within the AADRL (Architectural Association Design Research Lab), Hypercell[25] is a reconfigurable architectural system that is comprised of small voxel units that adapts, self-organises and self assembles into structures that respond contextual changes within a city. Werfel’s Termite-Inspired Robot Construction System[26] deploys a decentralised multi-agent system that relies on “local sensing and coordination” between multiple robots, enabling them to adapt and react to situations they encounter through the construction process”. Unlike conventional agent systems, the approach does not try to predict the resulting structure based on simple rules but instead “automatically generates low-level rules” for a user specified structure.



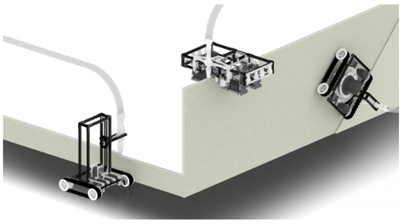


Fig. 4. Hardware demonstration of the Termite-Inspired Robot Construction System - Justin Werfel, Kirstin Petersen, Radhika Nagpal

Fig. 5. Minibuilders Robot Typologies - Base Robot, Grip Robot, Vacuum Robot, respectively Image: IAAC-Shihui Jin, Stuart Maggs, Dori Sadan, Cristina Nan

Another alternative approach to swarm robotics was conceived through IAAC's (Institute of Advanced Architecture of Catalonia) Minibuilders[27]Project. Tackling the size limitations of 3D printing machinery, researchers conceived a scalable system that deploys multi robot typologies with varying functionalities and roles within the collective system. The emergent behaviour serves to construct a structural element, a large cylindrical volume.

3 Case Study - Proposal

Fig. 6. Proposed Martian Habitat

Our proposal manifested as a solution to solve extreme construction limitations and challenges posed as part of NASA's 3D Printed Habitat Centennial Challenge. The brief calls for the construction of a habitat on Mars, capable of supporting and enabling four astronauts to live and work for one year. Conventional approaches for logistics and construction do not apply for this project. Systems must be autonomously operated as any direct telecommunication between Earth and Mars would, at most, have a 20 minute delay[28]. Design of construction systems must be optimised for mass, reusability and redundancy. As a strategy to minimise cost in transportation of materials to Mars, NASA imposed their agenda for "In Situ Resource Utilisation", implying that all competing teams must utilise ready-found resources on the martian surface. It implicitly specifies the combination and use of the abundance of martian dust (regolith) with 3D Printing Technologies and principles as the major construction methodology. The proposal also became the basis for the Group Design Project (GDP) for Cranfield University's MSc in Astronautics and Space Engineering Students, which became the preliminary high level feasibility analysis of the system.

Similar to the Minibuilders Project, we identified that a conventional 3D printing approach is not appropriate as the structural infrastructure needed would prove too large to be transported to Mars. Knowing that over 50% of all previous missions to Mars have failed, all aspects of the proposal must also include a triple redundancy system. To address the amalgamation of challenges and requirements of the brief, our proposal adopts a modular swarm strategy. The benefits identified in academic explorations outlined in swarm robotics will provide the most optimum and effective solution in the construction of a 3D printed structure.

3.1 Proposed Framework for Martian 3D Printing Swarm Robotic System

Extending the consolidated concepts explored, the proposal must first define the set of functionalities required to create a 3D Printed Habitat Structure. The perceived functionalities are as follows:

01. Understanding and scouting of existing site conditions to compose a map for optimum quantities of martian regolith.
02. Battery storage and power generation
03. Collection and Excavation of construction material
04. Screening and refinement of raw material into specific aggregate or particle sizes
05. Excretion and/or extrusion of processed raw material unto a set path
06. Self Organisation and Coordination with various robots on site.

The collective aim of the swarm will be to construct a compression-only shell structure that will protect a series of pressure retaining, prefabricated living pods.

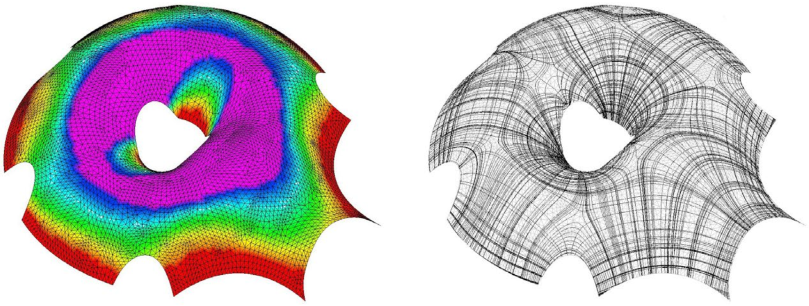


Fig. 7. Deflection and principal stress analysis of the proposed compression only shell structure. Image: Eckersley O'Callaghan Engineers.

Based on precedence explored, the majority of robotic swarm strategies emphasise morphological optimisation. The robots themselves are seen to become the discrete components that act as an all encompassing base unit for structure and spatial partitions. In contrast, we propose that the functionalities identified can develop into a set of "tool head" modules. Each module uses the same base geometrical shape to enable tessellation and the forming robotic assemblies, capable to reconfigure itself into interchangeable roles within the construction process. Every module will also be equipped with standard sensorial equipment that augments the coordination and self-organisation of other robot assemblies on site.

What results is an ecosystem of robot assemblies that are flexible to adapt according to any potential process delays or failures within the construction schedule. Our approach also incorporates multiple levels of redundancies as modules in a specific assembly typology can be easily replaced in the event of a failure.

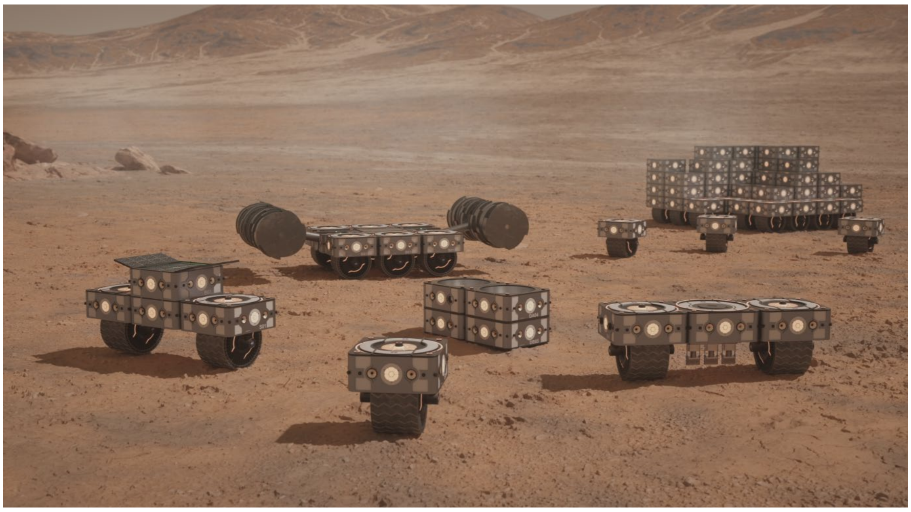


Fig. 8. Ecosystem of 3D Printing Robot Assemblies- Martian Habitat.

It is neither a “single task construction robot” nor an “integrated robotized construction site” but something else entirely. This core functionality of the swarm will also ensure that the robotic modules will have prolonged usage beyond the initial build phase. Topological reconfiguration of modules is executed through a sequence of coupling and decoupling exchanges. Modules can be lifted and stacked to form specific assemblies.

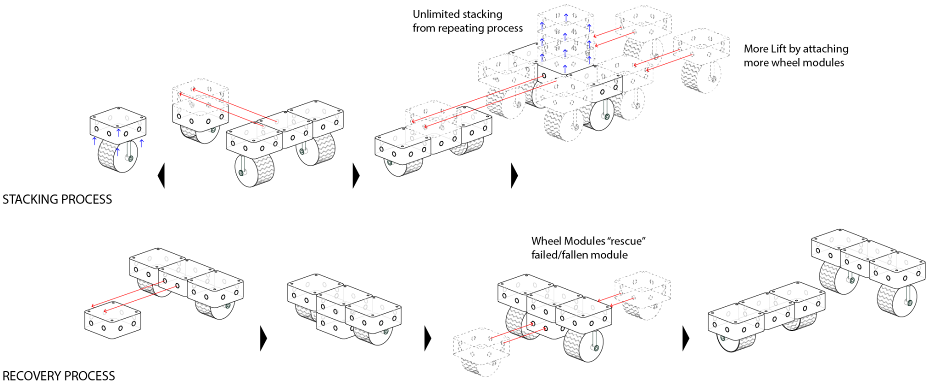


Fig. 9. Topological coupling and decoupling process for stacking and failure recovery.

Unique assembly typologies can be categorised into the main distinct functionalities identified within the construction process: Scouting, Excavation, Refinement and 3D Printing. The Scouting Assembly is a single module with an embedded wheel, gyroscope and motor. Its primary function is to detect optimum areas containing regolith within the construction site through ultrasonic testing and analysis. The

Scouting assembly is also the basis of mobility for all other assembly typologies, equipped with a housing mechanism that enables 180 degrees of wheel rotations to maximise maneuverability. Vertical actuation from the embedded telescopic framework also allows modules to place and stack other base modules in the reconfiguration process. The Excavation Assembly is comprised of four wheel modules, 3 battery/power modules and 2 excavation heads, digging into sources of optimum regolith identified by the Scouting Assembly. Design of this assembly has been derived from a previous Swamp Works prototype, The RASSOR[29], utilising rotating drums to scrape and dig surface level soil material. The excavated material must then be processed to ensure uniformity in the granular structure of the raw material. To complete this task, excavated material can be deposited into The Refinery Assembly, base modules equipped with conical spiral blades that can also be used as storage depots and intermediate pumps for the 3D Printing Nozzles. The Refinery Assembly has been conceived for continuous operation, ensuring a constant supply of processed raw material to the 3D printing Assembly. Once a refining module within the assembly has finished its processes, it can be transported onto the 3D printing Assembly via two wheel modules.

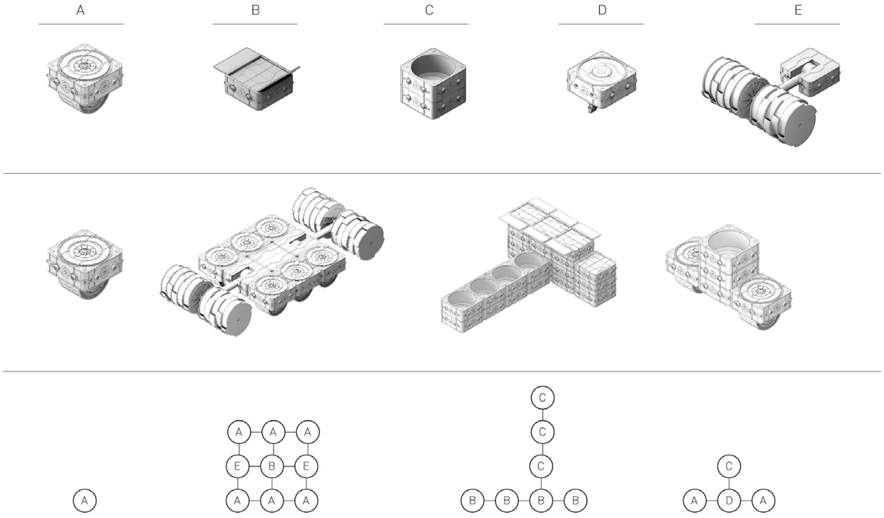


Fig. 10. Diagrammatic Representation of potential module connections and configurations for robotic assemblies

Martian soil simulants have been reproduced based on initial chemical and mechanical properties analysis, allowing various research bodies to conduct studies in relation to “dust mitigation, advanced life support systems and in-situ resource utilisation”[30]. In the domain of construction, several “analog” martian research facilities have tried to produce construction components with minimal processes.

Researchers at UCSD(University of California - San Diego) produced “Martian Bricks” by compressing “vacuum-dried martian soil simulants under sufficiently high pressure”[31]. The PISCES (Pacific International Space Center for Exploration Systems) in conjunction with NASA’s SwampWorks uses “planetary basalt material” as the main construction material for the ACME (Additive Construction with Mobile Emplacement) Project, with the aim to robotically construct “horizontal structures...such as foundations, pads and roads” out of “Basalt pavers...sintered at 2100 degrees F”. [32]

Fig. 11. PISCES and Swamp Works - ACME Project. Image: PISCES (Pacific International Space Center for Exploration Systems)

Lastly, the 3D Printing Assembly is comprised of two wheel modules and an interchangeable printing head. The module responsible for extrusion will be equipped with microwaving capabilities to heat the processed regolith into a viscous state, capable of printing onto a specific path and bonding to subsequent layers. Similar explorations have been explored, using a feedstock method. The benefit of having a disconnected refinery assembly is the ability to constantly provide pre-processed raw material stocks to the 3D printing assemblies, eliminating the need to deviate from the designated printing path.

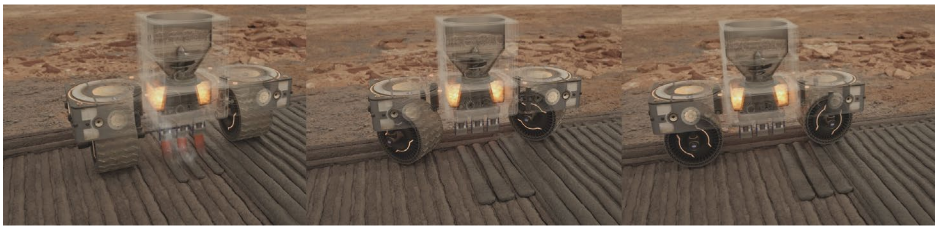


Fig. 12. 3D printing sequence and edge maneuvering

All of the assemblies will also be equipped with modules specifically for solar power generation and battery storage. These are also contained in a single module, and hence is completely scalable according to the power requirement of each unique assembly typology. For assemblies that have a static nature within the construction site, the power module can easily be swapped out when power storage has been depleted. With our strategy, reconfiguration can happen almost instantaneously, minimising disruptions due to logistics and intermediate processes within the construction sequence.

Structural Scaffolding. Scaffolding of the shell structure will also be executed with the digger robot. The envisioned construction sequence will adopt a similar strategy to the scaffolding strategy implemented for the Teshima Art Museum, where raw earth is used to support the weight of the cast shell as it cures[33]. The excess loose material is then excavated once the shell has set and attained its full structural capacity. Based on calculations made as part of the GDP, this process would only take a total of 3.96 years, which is acceptable given the abundance of time available.

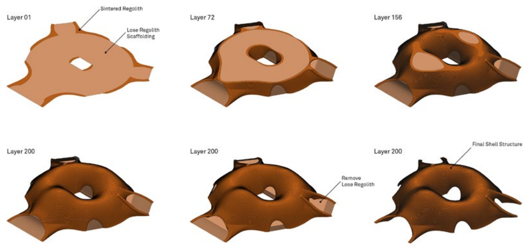
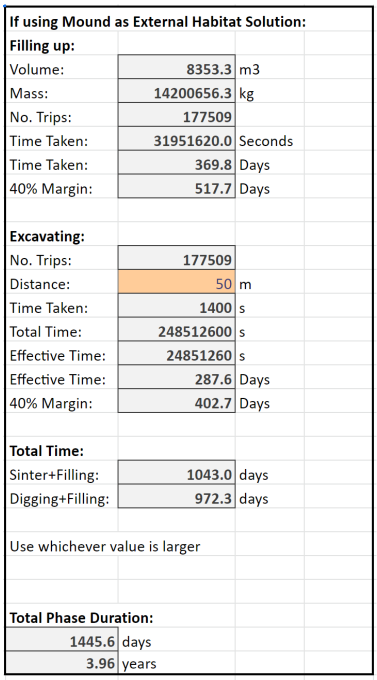


Fig. 13. Diagram for scaffolding system - Sequencing - Regolith Infill



If using Mound as External Habitat Solution:		
Filling up:		
Volume:	8353.3	m3
Mass:	14200656.3	kg
No. Trips:	177509	
Time Taken:	31951620.0	Seconds
Time Taken:	369.8	Days
40% Margin:	517.7	Days
Excavating:		
No. Trips:	177509	
Distance:	50	m
Time Taken:	1400	s
Total Time:	248512600	s
Effective Time:	24851260	s
Effective Time:	287.6	Days
40% Margin:	402.7	Days
Total Time:		
Sinter+Filling:	1043.0	days
Digging+Filling:	972.3	days
Use whichever value is larger		
Total Phase Duration:		
1445.6	days	
3.96	years	

Printing Path and Movement Behaviour Simulations. Initial exploration into the behaviour of the swarm was explored through agent based modeling. The material scouting process adopts stigmergic principles normally found in the behaviour of termites or ants as they explore for resources and food[34]. The trail can then be established as an optimum route for the Excavation Assembly to collect the raw materials.

For the 3D Printing construction process itself, the final geometric form of the shell structure can be sliced into layers, similar to the processing of virtual geometries for commercial 3D Printers today. While this is normally completed using a single multi-axis print head, the same task can be distributed amongst a series of printing robots, dividing the printing path into smaller sections for different individual robots to execute simultaneously.

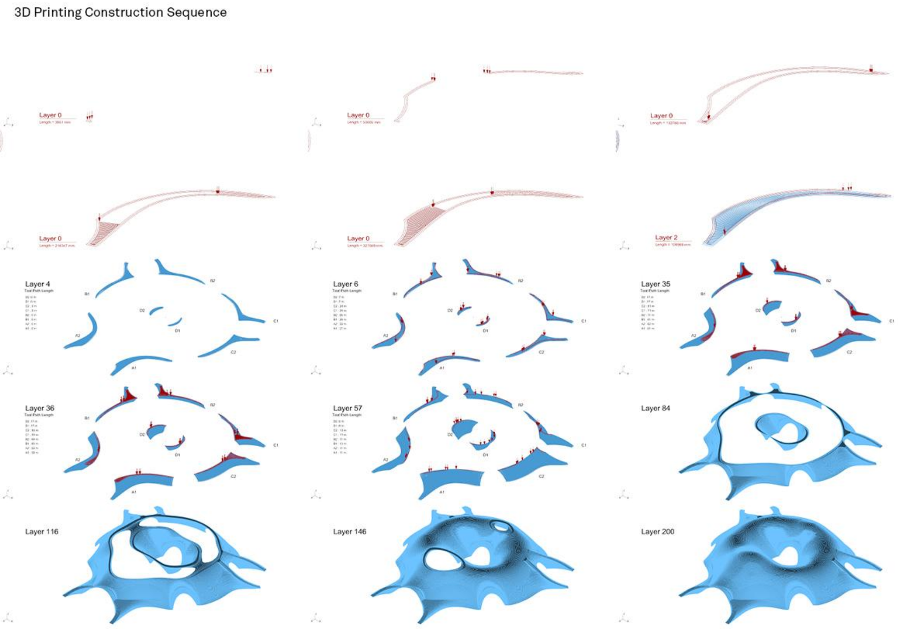


Fig. 14. 3D Printing Path Simulations

4 Conclusion

The framework aims to encourage the uptake of on-site robotics in construction by proposing an Intermediate application of swarm robotics as a construction system rather than a holistic architectural system. An Interchangeable tool “kit of parts” allows robots to reconfigure themselves based on perceived needs of the construction site, enabling flexibility and dynamic adaptation throughout the progress.

Further research can be conducted into the physical prototyping, mechanics and programming of the proposal. Full autonomy will require modules to have embedded artificial intelligence to understand and assess conditions that they operate in.

Applications of the proposed framework on earth can also bring about change within operational models within the construction industry. Implementation of such robotic systems on site will inherently change the flow and management of information, which augments the role of designers, architects and engineering professionals to keep up with ever-increasing demands of infrastructure.

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