What Holds, What Yields

Material Behaviour and Adaptive On-Site Fabrication

Anton Tetov Johansson

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Abstract

This research investigates adaptive on-site robotic construction using dynamic, locally sourced materials. It examines how robotic fabrication can respond to material behaviour, environmental variation, and construction constraints through feedback between sensing, modelling, and making. Rather than treating earth as a uniform material, the work explores how its variability can inform both design methods and fabrication processes. Through the development of an integrated platform, iterative prototypes, and a full-scale demonstrator, the project studies the knowledge, tools, and workflows required for adaptive construction in practice. The research contributes to emerging approaches in digital fabrication by proposing a design methodology for building with responsive systems and heterogeneous natural materials.

1 Introduction

In times where the sustainability challenges are pressing, influencing all parts of society, the need for new construction of housing and workplaces clash with environmental concerns. Transformation and reuse, process digitalisation and construction automation could provide answers, while at the same time also challenges current paradigms of industrial construction. The architecture, engineering, and construction (AEC) industry plays a crucial role in addressing the sustainability challenges brought forth by climate change due to its large impact on global emissions. This responsibility involves a critical rethinking of material utilisation, and manufacturing processes. The industry must innovate and adapt to more sustainable practices, reshaping how we approach building design and construction.

This project is an exploration of on-site digital fabrication, with a focus on computational design with dynamic alternative materials fabrication feedback loops. The research involves topics from architecture, robotics, material research, and computation, and addresses environmental sustainability through rethinking material choice and sourcing, where construction elements are built using resources available on-site.

The project's goal is to explore novel ways to design and construct building elements with local and low-processed materials through large scale 3D printing of earthen materials. It encompasses on-site digital fabrication of earth, clay and aggregates, typically excavated and transported away from the construction site. Taking inspiration from vernacular construction, where necessity dictates material sourcing and (lack of) processing, creating a system that incorporates material behaviour in a digital fabrication process, using industrial robotics and machine perception to manage non-linear materials and dynamic environments.

This text is a kappa written for my midway seminar in March 2026. It details my work within the research project "Interactive Construction robotics: 3D-printing, adaptation and sensor feedback", fundedby Svenska byggbranschens utvecklingsfond (SBUF), project number 14187. The kappa details the research context, its theoretical framework, method, experiments undertaken and planned, and a discussion based on the experiments and their findings. It includes one paper, *Shaping design and fabrication processes for sustainable materials through adaptivity*, submitted to the conference RobArch 2026but not accepted, and one abstract, *Adaptive Volumetric Modeling for On-Site Robotic Fabrication of Hybrid Stone-Clay Structures*, submitted to Design Modelling Symposium (DMS) 2026but not accepted. Both will be further developed based on reviewer feedback with plans and submitted to other venues.

The research is exploratory, following a research-by-designmethod [36], where design is part of the experimental work. I have prepared a prototype outdoor construction robotics setup, with a mobile robotic platform [24] outfitted with a clay/earth 3D printing system and extruder and sensors. This setup is and will be the basis for the experimental work. The topic will be studied through the design and construction of foundations from earth and stone, stacked and extruded on raw, uneven surfaces. This involves adjusting to on site geometries, heterogeneous material assemblies (earth and larger stones), and sets the scale of exploration to that of building components.

1.1 Background

The AEC industry faces a dual challenge: reducing its environmental impact while increasing production. The construction industry accounted for 32 % of global energy demand, and were the source of 34% of carbon emissions in 2023 [44, pp. 26-30], while the global building floor area is expected to grow by 45% by 2050 [21, pp. 43-48]. We need to both build more and build more sustainably, and any approach to construction that addresses one at the expense of the other is insufficient.

Innovations and changes to address this must be able to scale to make an impact, the shortage is too large and the crisis too urgent for solutions that only work on individual projects [11]. The industrial approach achieves scale through standardisation and uniformity. Material producers guarantee known properties, provide product sheets and building information modelling (BIM) objects, and decouple material sourcing from construction through defined interfaces and contracts. This enables optimisations through economies of scale, simplifies code compliance, and makes structural design predictable. However, this model depends on supply chains involving heavy transport, materials with high extraction and processing costs, and extensive site preparation including excavation. New construction projects typically take a *tabula rasa* approach, excavating a site to create a concrete foundations on top of gravel transported for this purpose.

The alternative – local, low-processed materials, such as earth, stone, and reused components – has deep historical precedents. Today, there is a renewed interest in local and sustainable materials as well as transformational approaches, in order to lessen the environmental impact. Earth, mud, and stone is already on site and available to be used, instead of getting removed from site [8]. Sustainable earth construction is in use today and new methods are being developed, and there are ample examples of historical practices that might be useful today [32]. The main hindrance usually stems from lack of standards and material suppliers [39].

For any alternative to gain traction, it must provide scalability and efficiency at least approaching that of current practices [11]. This is where the difficulty lies. When local materials or reused building elements are used, the complexity of a construction project increases dramatically. There is no construction material producer guaranteeing properties, no product sheet, and applicable regulations (if available) are open-ended. Yet there is a theoretical point where the benefits of accepting this complexity outweighs its costs, and given the urgency of the planetary crisis we might be approaching it, especially as computation design tools reduce the cost of managing that complexity.

Digital fabrication offers a way through this, not as a technological optimisation within the existing paradigm, but as a fundamentally different approach to construction. Through data-driven design and fabrication processes, building elements can be customised to local conditions and materials rather than requiring standardised inputs. Digital fabrication includes fabrication methods such as additive and subtractive manufacturing, as well as robotic construction. Design goals are encoded into machine instructions and carried out more or less without human intervention. Yet, realising this potential is not straightforward. Non-industrial materials behave unpredictably – they deform, settle, and interact with their environment in ways that industrial materials are engineered to avoid. Using them in an automated fabrication process requires ways to perceive and respond to this behaviour in real time, and ways to express design intent that leave room for that response.

I use the term *fabrication behaviour* to describe these designed rules and responses – the counterpart to material behaviour, which is what the material does on its own. This means shifting from defining a wall segment by its geometry (height, thickness, length) to defining regions in space where material must or must not be placed, and gradients between where placement is more or less acceptable. This has applications in recycling and reuse of materials as well, where adaptivity is required to handle indeterminate geometries. This behaviour needs to be driven by feedback, some mechanism of sensing. The study of feedback-driven systems is the core of the research field cybernetics [45]. The cybernetics research field is not only the progenitor of the artificial intelligence field, it has also been adapted into psychology, sociology as well as design [12] and architecture [40]. This concept's relevance to digital fabrication is less explored.

1.2 Hypothesis

On-site digital fabrication with non-industrial materials such as earth can be made compatible with scalable construction if the design space is formulated as constraints on fabrication process and outcomes rather than as predefined geometry. The fabrication process process adapts to material behaviour by operating within spatial and process-based boundaries and drawing on real-time sensing of material and site. This could bridge earth construction, digital fabrication and industrial construction, and would shift architectural authorship from specifying form to specifying the rules governing how form emerges.

1.3 Research questions

The following research questions guide the research:

1. How does material behaviour during and after fabrication (deformation, settling, material interaction) constrain and inform an adaptive earth 3D printing process?
2. What sensing and computational methods can provide the information needed to inform an adaptive earth 3D printing process in real-time?
3. How does an architectural designer engage with an adaptive, feedback-driven robotic fabrication process, what is required and what opportunities does it offer for design?
4. How can a research environment be constructed to enable the systematic investigation of adaptive, feedback-driven on-site digital fabrication with non-industrial materials?

The first question relates to what material behaviour to study, while the second tries to answer how to study those behaviours. The third research question seeks the answer to how a designer can engage with the material behaviour as captured by sensing and computational methods, and what possibilities this brings to a construction robotics workflow. The fourth and last question is broader but foundational since the prior questions span multiple disciplines. Its aim is to find which real world constraints need to be present, which constraints can remain unaddressed, and the technological readiness level required, to investigate the prior question.

This is why research question 4 is addressed first, and is a part of the research contribution.

2 Theoretical framework

If the goal is to use local earth and soil there will be large regional variations, and this is were new (quick) ways to get materials tested and accepted for use would help. It could also be circumvented by data capture during (digital) fabrication, since it is possible to record every move of the machine and capture data about the material being worked with. This could be used in material simulations and tests, where more data should make for better and more accurate results. What needs to be tracked carefully is material behaviour, especially for materials that perform non-linearly and unpredictably. Material behaviour is how the material changes when it is exposed to environment or action.

That is true for most materials which have not gone through extensive product testing, such as Portland cementor graded timber. Material behaviour includes physiological processes such as drying, setting and erosion. By observation material behaviour and features in it is possible to adapt the design and process to suit the material. An example of this could be to work with the knots and branches found inside a piece of wood while whittling, instead of forcing your way through hard wood. This is of course the basis of craft, and it's something that is usually described as embodied knowledge. Taking that into the realm of the digital fabrication space would instead require ways to observe and translate those observations into machine instructions.

Material behaviour needs to be adapted to in order to harness the potential of earth as a construction material, it both constrains and drives the design. Theoretical frameworks such as Malafouris' concept of *material agency* [30] describes matter as an active participant when manipulated by a human, in this project, material agency is relevant as behaviour could be understood through computational modelling. This can turn material behaviour into a design driver for digital fabrication. This thinking is referenced in [34] which connects the dots back as early as 2008 to Gramazio & Kohler [18].

Some materials behaves non-linearly, where the relationship between material manipulation and resulting form is hard to predict. This is especially relevant when scaling up material experiments, where larger material accumulations behaves differently. The complexity expands further with an-isotropic materials (like wood) or heterogeneous material mixes (binder mixed with aggregates), which is typically overcome using embodied knowledge. This knowledge needs to be teased out from the tacit knowledge and adapted to digital fabrication processes.

2.1 Design driven by material and process

The modernist movement in architecture saw the material as something to be tamed, and controlled. This was a radical shift caused by the new materials and processes that became available in design and construction. Digital, parameter driven, architectural design has similarly often been an exploration in what new forms scriptable 3D modelling can produce. Carpo saw a second digital turn in the new millennium, where complexity was embraced through computation, algorithms and data [4]. In some ways this could be seen as resolving the tension between designer and material, a return to a material informed workflow where findings about the material and its behaviour drives the design outcomes.

Small adjustments in process parameters or material properties can change tectonic expression

and structure. The path used in 3D print might not be the only driver in the expression of the resulting artefact, with some processes and materials the delays and stops, accelerations and vibrations might impact the impression just as much [9]. Is this a part of the design, or is it just traces of the production method? Cohen shows through his work with delay introduced and exaggerated in concrete dripping how machine delay impacts the end result, and links it to experimental music and art [9]. In his work with Machine Delay he carefully isolated a parameter and studied it closely. In the physical world controlling medium and tools are difficult, an outside laboratory settings' design outcomes become dependent on more variables than just a few input parameters. This is evident in 3D printing, where the same design produces different outcomes due to variations in the material extruded [20].

2.2 Representing design space

Design is communicated through sketches, drawings as well as physical and virtual 3D-models, both during the development of the design as well as in the fabrication stage. This changes if the fabrication stage is completely or partially executed by machines. Then the communication medium needs to changes to something that can be translated into motion commands and input/output (I/O) signals.

A hierarchy of abstraction levels exists in robotics, ranging from electrical signals that move a robot's servo motors via embedded code to code intended to be written by robot programmers (often in a proprietary language like ABB Rapidor URScript) that enables more flexible control logic. There are further abstractions on top of that to facilitate integration with computer-Aided design (CAD) systems such as `Kuka|PRC` [1] and `compas_rrc` [13], both offer interactive and non-interactive program execution. There are also integrations specifically developed for 3D printing clay to integrate parametric design workflows [26].

Recent developments in generative AI extends this hierarchy to possibly include natural language instructions. Complementing this structure, at least on a theoretical level is domain specific languages, that provide specific syntax for specific tasks. In generative design and digital fabrication this would include making grammar [25] and fabrication grammar [43, 41] (both taking inspiration from shape grammar). These are ways to discretise individual actions and changes that impact the material that is worked with.

Outside of prefabrication of houses and house parts, construction takes place outside controlled environments and robot integration needs to be repeated for each project. Automation of on-site construction tasks is desirable, especially for unergonomic, unsafe tasks, or tasks that require precision not possible without machinery. Digital fabrication enables mass customisation, with the potential to reduce or remove the cost of adapting fabrication processes to different designs [5].

Industrial robotics automates labour, and has been very successfully coupled with progressive assembly (assembly lines), where a single operation is repeated for each part. Integration of robotics in factories relies on economies of scale, where the more identical widgets you can build the cheaper the integration becomes. This is paradigm is challenged by cheaper robots, and cheaper programming. Robotic programming, previously done iteratively with through virtual and physical simulation or lead-through programming where the manipulator is driven through the tasks, typically by manually moving it into place, and positions and joint configurations are

recorded. More recently other methods have emerged, such as machine learning coupled with computer vision, where a model could be trained on a video feed of tasks and environments. This is generally well suited for repetitive tasks such as a pick-and-place operations or discrete additive or subtractive actions. 3D printing, however, consists of long continuous print paths that are hard to lead-through program, and unique paths that might be hard to use as training data.

One alternative is to design algorithmic responses to certain local conditions in the 3D scanned environment. Agent-based design, not the same as agentic AI, instead modeled swarm behaviour, could be a helpful here. This builds on modelling of animal behaviour, where agents have a few possible actions a small set of rules available to them to create emergent designs. The simplest one would be moving on top of the scanned surface without colliding.

An example of swarming behaviour could be the bird-like objects (BOIDs), which is a set of rules describing the behaviour of birds in flight, where they keep a distance between each other, they follow the general direction of the swarm, and they have different patterns for avoiding predators, as described by Reynolds [37]. Quite simple rules on its own, but in the end leads to emergent synchronized movement.

3 State of the art of additive manufacturing with a focus on earthen materials

3D printing in construction with materials such as thermoplastics and concrete enables mass-customisation and can be more material efficient through elimination of formwork, as replacement to other materials or through material reduction. 3D printing with both thermoplastics and concrete has been used for building components such as facade elements [27], and for concrete formwork[2] but has not gained widespread adoption [46].

The use of clay and earth in 3D printing, a type ofliquid deposit modelling (LDM), has been explored in research and in industry. Work done in this field shows the variation that can be achieved by tweaking material mixes, and tool-paths. Tiles and bricks can be 3D printed and used in construction [15, 38, 35, 10, 19], but the size and scope is limited by the firing process. Clay and earth 3D printing is part of the digital fabrication sub-field/digital manufacturing of earth construction (DMEC)/ or digitally manufactured earth construction, a name I've taken from a review paper with the same name [17]. This sub-field also includes digital techniques such as automation of rammed earth construction ([see 16]).

Large scale earth 3D printing has been pioneered in projects such as *Digital Adobe*, *Tecla*, and *TOVA* [6], as well *Mud Frontiers* [14]. These projects were printed using polar 3D printers except *Tecla* where a delta printer were used. These printers were built up on site and dismantled after printing, a strategy typical also for concrete 3D printing, which limits the total size of connected construction components to the reach of the printer. Integration of aggregates is limited by what the nozzle can extrude, and compensation for potential changes in the 3D printed material are difficult.

The typical digital fabrication workflow, sometimes called "file-to-fabrication", presupposes a linear flow from design to artefact. There are clear limitations to that model when it comes to materials with more complex behaviours. Adapting digital fabrication workflows to material be-

haviour is explored in projects such as *Craft-Inspired Digital Fabrication* [42], where a process specific human-machine interface were developed that allowed clay carving to be controlled through pushing, pulling and positioning a robot arm over a bed of clay. Another example is the work of Ma et. al. where robotic clay sculpting has been investigated and developed [28], where materiality, tool shape and path planning impact the outcome. (Clay) 3D printing adapted to scanned surfaces, has also been explored through 3D scanning techniques and other sensing mods [3].

4 Methodology

To investigate the potential of material driven and feedback based digital fabrication the research framework *research-by-design* is employed. Research-by-design involves iterative prototyping and material driven experiments [36]. The workflow prescribed by *research-by-design* is explained in figure 1 where we can see initial probes informing subsequent prototypes and demonstrators. The probe is exploratory, while the prototype further investigates feasibility and possibilities. The demonstrator's role is as a validation of the fabrication method to show that it works in full-scale. It shows a research method that develops processes iteratively and design of process as well as the outputs are evaluated at each step.

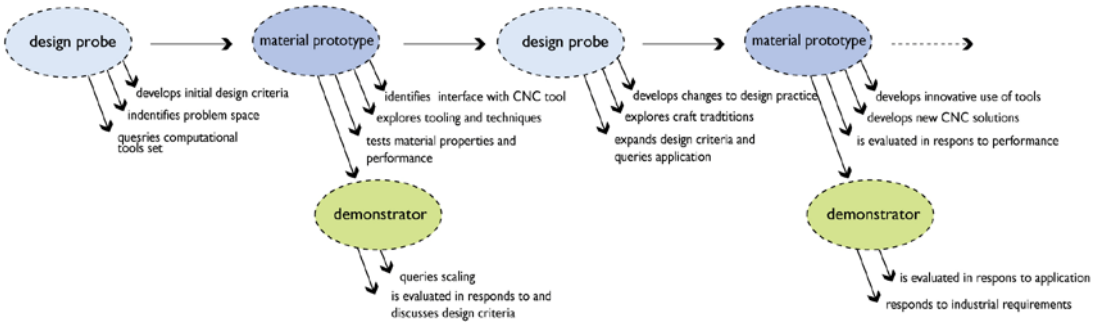

Figure 1: Diagram from Ramsgaard Thomsen & Tamke [36]

The research subject, adaptive construction robotics using 3D printing of earth, will be pursued through the development of a foundation. This is a building component where earth has a clear historical precedent, and requires on site construction since it interfaces with site topography. It also requires an interface with the other building components it supports, which puts it into a larger context of construction practices.

5 Experimental platform

The experiments include the setup and validation of the experiment platform as well as the 3D printed artifacts. Some experiments are set out to validate the setup, i.e. check that things work. The validation experiments also lead to deeper knowledge of process parameters and material behaviour, which further inform experiments. The experiments are assess in terms of robustness, predictability, and spatial tolerances.

Through the collaboration between departments within LTH through the Centre for Construction Robotics I have access to an outdoor mobile robotic setup that consists of a 20 ft container

and the robot Elizabeth – a robot arm (ABB IRB4600/2.55) mounted on the base of a repurposed spider crane [24].

Through the project the setup has been deployed in an industrial warehouse in Arlöv, on a temporary square in the developing Brunnshög-region in Lund as well as in the School of Architecture's parking lot.

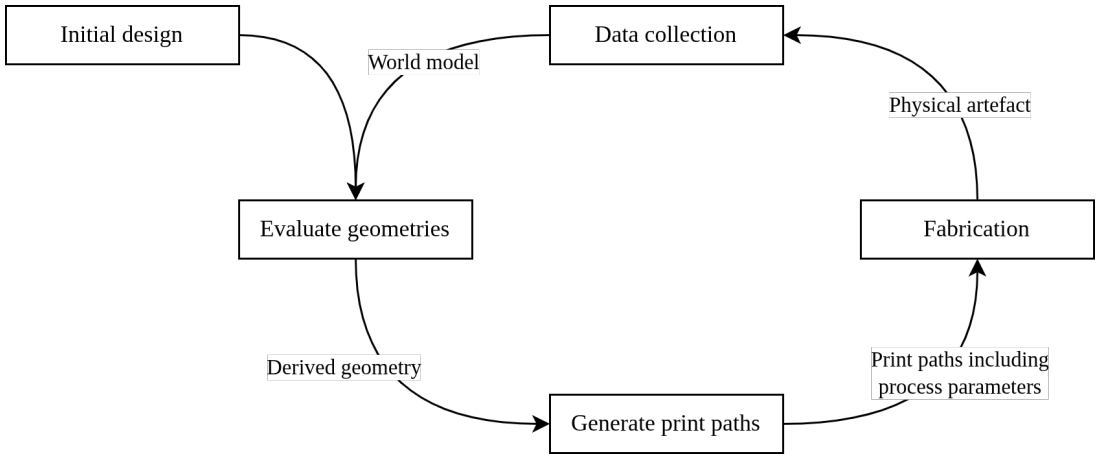

Figure 2: The proposed design and fabrication loops.

Figure2 describes the envisioned fabrication workflow. The starting point is a world model containing just the environment, since no fabrication has begun, and an initial design. These feed into a closed loop that starts by constructing the difference between the world model, the current state, and the initial design.

The world model is constructed from 3D scanning data, where the raw data is a pointcloud. This data is converted into mesh or voxel geometry for processing. The initial design is a volume to fill, but in future experiments this will evolve to a multifaceted design space with constraints and thresholds guiding fabrication and adaptation to material behaviour.

The difference between initial design and environment is calculated in the previous experiments by placing the volume to printed intersecting with the print substrate, and subtracting the environment from the initial design. In this way the design is adapted to its environment. This derived geometry is used to generate prints paths and process parameters.

In the execution phase of the fabrication loop the generated instructions are used to print parts of, or the whole design. The result is then scanned again and the world model is once again compared to the design intent.

As previously stated, part of the work undertaken as part of this research project has been the development and evolution of the experiment platform, most crucially the pump and extruder system and the sensor setup. An industrial robot is a general tool, and Elizabeth has been outfitted for 3D printing of earth and clay. Initially, Mai Pictor3D, a pump system designed for pumping cement for 3D printing applications, was used but was later replaced by Erratic DM80, a pump system specifically made for earth and clay materials. The extruder setup has underwent three iteration: First an in-house adaptation of the VormVrij's Lutum v10 clay extruder, then Erratic T25 extruder, first evaluation of a prototype then the final product. This extruder uses two augers with a motor driver that can be controlled using a CAN-bus interface.

Adaptations necessary to integrate pump systems and sensors have included adapter plates – 3D printed and computer numerical control (CNC) milled – and electronics for controlling the extruder, including synchronisation with the robot controller. Robot motion needs to be coordinated with the extrusion which is controlled by motor and motor controller on the extruder tool, which in this case means that the robot program needs to send a value, using a group output on its I/O board to the motor controller on the extruder, just before the first printing move and adjust it on the fly based on the speed at the robot tool centre point (TCP).

The speed adjustments are possible using a always on controller task (an asynchronous, dedicated thread) that multiplies the TCP speed reading with a speed factor. This value is during program execution multiplied again by a point specific extrusion factor and finally communicated to the motor controller as a signed integer.

The environment reconstruction is done using photogrammetryand experimentally using depth cameras. Depth cameras, in contrast to conventional cameras, which store colour values per pixel (RGB), calculates depth information from two camera sensors and streams both a RGB image as well as a depth map, grey-scale image where the pixel values represent distance. Pointclouds and meshes are constructed using either RGB images or depth maps, and need to be localised in the robots coordinate system.

The ideal approach is to construct the environment geometry from image frames with position information calculated based on the robot arms position. This has worked intermittently in prior experiments, and a stable workflow would improve the setup. The backup solution has been to use photogrammetry, with scale and relative position given by physical markers in the scene. These are then measured in the robot coordinate system using a calibration needle attached to the robot end-effector.

The experiments have been conducted with a material mix based on a local, fatty glaciomarine clay, mixed with sand (2 mm) and water in a 1:1:1/2 ratio. The sand is added to reduce shrinkage. There is potential to improve the mix both in terms of ratios as well as with additives such as fibers.

The actual experiments can be found documented in the visual journal, and the attached paper.

6 Results and Discussion

At this point in the research project research question 4 (regarding experimental setup) can be fully addressed, and research question 1 (material behaviour) and 2 (sensing and computational methods) partially. The research questions are intended to be fully investigated at the conclusion of the research project.

6.1 Prerequisites for on-site adaptive earth fabrication

On-site adaptive digital fabrication with earth requires resolving prerequisites across several categories (equipment, synchronisation, site infrastructure, interdisciplinary skills) that are not addressed in existing literature. This is part of the answer to research question 4, where the need for a research environment is highlighted.

6.1.1 Equipment

Earth 3D printing cannot rely on equipment developed for cementitious or other LDM processes, the rheological demands of earth mixes are fundamentally different. Cementitious mixes are liquid enough to flow into a pump and require less pressure; earth mixes at workable viscosity require both greater pump pressure and a mechanism to actively feed material into the pump. After evaluating two concrete pump systems we worked with a specialist supplier to develop a suitable setup. The same gap exists for extruders — off-the-shelf clay printer extruders lack the throughput needed for construction scale, and larger market offerings are designed for cementitious mixes.

6.1.2 Synchronisation

Precise synchronisation between extruder velocity and robot motion is essential, without this coupling, the main lever for responding to material variability is lost. There are certain workarounds, like adapting the trajectory speed to indirectly control the volume of extrusion per distance. In the first print experiment uneven surface this would have proven inadequate since they extrusion volume was adapted to the layer heights which varied between each point. This was done by adding an extrusion speed factor to each sub-path and having the controller change the extrusion speed after each waypoint reached.

Additionally, output from mounted cameras needs to be transformed according to the current position of the robot joints. The system is tied together with a ROS2 system [29], the source code specific to the setup can be found on GitHub: biodigitalmatter/ros.

6.1.3 Site infrastructure

On-site construction robotics requires a setup that can be deployed and equipment that work outdoors. The container setup has been developed during the project in multiple ways. Among the requirements are electricity, water, and site access, which all need to be coordinated between multiple stakeholders in an environment undergoing rapid change. This is a significant but often overlooked constraint.

Further requirements on-site are local area network (LAN) to connect controller, computers and sensors. Software development, experiments, and collaboration on site required access to internet, in order to download software dependencies and design files. That is why the container is outfitted with a 5G router and networking cabling between the multiple nodes, see Figure 3.

6.1.4 Skills and knowledge integration

On-site adaptive digital fabrication with earth sits at an intersection of disciplines where no single field provides the full skill set. This is highlighted by the challenges encountered during the setup of the experimental platform.

It is not only necessary to understand the robotic hardware and software, as well as the different design tools used, it is equally important to be able to integrate and navigate the technical and design aspects of the work. The subject involves interacting variables that need to be studied holistically in order to arrive at a new type of fabrication workflow. Developing this workflow

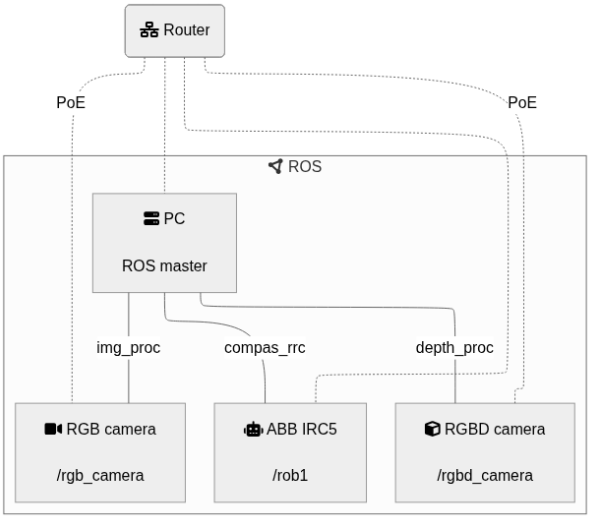

Figure 3: The robot cell network setup.

requires taking on the role of researcher, designer, and technician, and engaging with the fields of architecture, construction and robotics. The resulting setup must be legible to researchers as well as practitioners.

The fabrication outcome depends on both process behaviour and material behaviour, and these cannot be studied independently when the goal is to develop a workflow applicable to robotic construction. The on-site deployment, development and integration of the extrusion system, robot and sensors all contributed to addressing research question 4. The resulting setup is now at a stage where it is possible to execute more complex experiments. However, doing so still requires a broad set of technical and design skills. This combination is relatively uncommon in either engineering or architecture, but in the current team configuration it enables us to explore the other research questions. In order to reach a situation where a larger cohort can engage with the experimental setup, especially independently, further refinement of the technical systems is necessary.

6.2 Timescales of material and fabrication behaviour

There are different timescales involved with fabrication and material behaviour apparent in earth construction. There is the timescale given by the drying time for a specific material mix, which can be measured in days. The other extreme is material behaviour of the clay directly after extrusion. These findings help address research question 1 and 2.

6.2.1 Immediate (during extrusion)

Structural collapse can occur mid print or shortly thereafter, and unexpected air bubbles in the hose feeding the extruder cause immediate changes to the printed structure.

An example of interactions between material and fabrication behaviour with immediate consequences is the extruder nozzle clearance (or lack thereof), where variation within certain tolerances is unproblematic and gives rise to different surface qualities. Outside of those tol-

erances it leads to extrusions that don't adhere to surface or layer below or material build-up. This variation changes where material accumulates, which also has an impact of subsequent extrusions and layers.

6.2.2 Intra-layer/intra-session

Between layers within a print session, the key question is whether successive extrusions bond sufficiently, and what accumulated deviations can be compensated for before the next layer.

The experiments have shown that, given the setup and material mix, there is very little delamination between layers and paths, suggesting that the clay extruded forms a soft-bond as described by Ming et. al. [31]. This mirrors my own experience as a student and research assistant part of the team led by Coralie Ming that designed and built the *Clay Rotunda* in Bern, Switzerland [22]. In *Clay Rotunda*, the projects leading up to its development, and in the subsequent *Impact Printed Structures* [7] project, the bond is achieved by shooting discrete clay cylinders where the impact bond guarantees the "soft-bond". That the 3D printing workflow achieves the same type of bond is likely dependent on the wetter clay mix used, and the short time between subsequent layers.

In the current workflow, intermittent feedback can compensate for accumulated deviations where a surface reconstruction can inform the height and position of the next layer. Further possibilities include adjusting the flow rate during extrusion, based on measurements taken close to the extruder and continuously during extrusion. Point distance measurements could be used to compare the actual height of the print compared to the expected; force measurements could be used to ensure that the nozzle connects to the print through the extruded clay.

Future work will include a prototype splitting print sessions with longer drying periods as tested [23] and validated with the *Clay Rotunda* [22].

6.2.3 Post-session (days)

Drying over days introduces behaviours that cannot be addressed within a single print session, and that constrain how multi-session fabrication can be planned. These behaviours include shrinkage and cracking, as well as frost damage, but the latter is rather an environmental constraint on scheduling.

There is a threshold between small surface level cosmetic cracks and larger cracks causing fractures in the print. Clay construction literature stresses the importance of filling cracks to avoid cavities that could hold water [32]. The planned multi-day print prototype will test how session intervals affect this threshold, as would a potential exploration into material mix adjustments through added fibres or changes to sand ratio.

6.3 Representation of environment and fabricated geometry

The experiments have highlighted the importance of a virtual model that can be updated incrementally, where the fabrication space and artefact can be tracked and used as an input in the generation of 3D print paths. These results are part of addressing research question 2, which asks what is required of a virtual model to inform adaptive robotic construction.

3D reconstruction using cameras can only be done intermittently in a photogrammetry based workflow, during printing breaks, since the procedure relies on a static environment. Moving parts create noise in the pointcloud and complicates surface reconstruction. The output from surface reconstruction procedures is typically polygonal meshes, whose global topology makes updates to regions unfeasible – surfaces need to be completely reconstructed for each scan.

Surface reconstruction is still useful, especially for adaptation to global changes and behaviours, such as changes to the print surface (the layers already printed). But it is limited by the resolution of the 3D reconstruction, where local changes can go undetected. The 3D reconstruction resolution has implications for all geometrical operations, necessitating a compromise between computation time and detail.

Representing feedback captured during different points in time, potentially from different sources, is possible by storing different surface representations annotated with timestamps. Combining or refining these is more difficult, and might require a volumetric (voxel) model instead of a surface representation. This is explored further in the submitted abstract on adaptive volumetric modelling for the Design Modelling Symposium.

7 Future work

So far, the project has established the conditions for experimentation by developing an initial platform for robotic extrusion, sensing, and digital modelling. Moving forward, the central questions of the thesis are not only whether such a system can be assembled, but what kinds of material, procedural, and design knowledge are required for it to function adaptively in practice. The remaining doctoral work therefore builds on the current platform in order to investigate these questions through iterative probes, prototypes and a full-scale demonstrator. Probes and prototypes will be developed to evaluate and refine the research questions, culminating in a full-scale demonstrator of a building foundation, where the workflow is tested in a realistic construction scenario.

The work is organised through three interconnected parts: *Platform and system integration*, *Iterative prototype development and experimental evaluation*, and *Design methodology and demonstrator* (research by design). Experiments through probe and prototypes follow a progression from controlled probes to integrated prototypes in preparation for the full-scale demonstrator.

7.1 Platform and system integration

The first part addresses the technical foundation for further work for which a stable and flexible experimental platform is needed. Stability is required for repeatable experiments and a clear iterative workflow. Flexibility is required to support different experimental conditions, progressive scaling and varied geometries. Through the work already undertaken the 3D printing setup is sufficiently integrated at the extrusion stage, while the broader closed-loop workflow is not yet mature. The workflow from scan to virtual representation as well as the virtual representation to print instructions need further work. This includes eliminating manual work in scan alignment and scaling, incremental updates of the digital twin, automatic generation of updated print instructions, and a feedback loop between scanning and printing. This work enables the planned experiments and supports the integrated demonstrator.

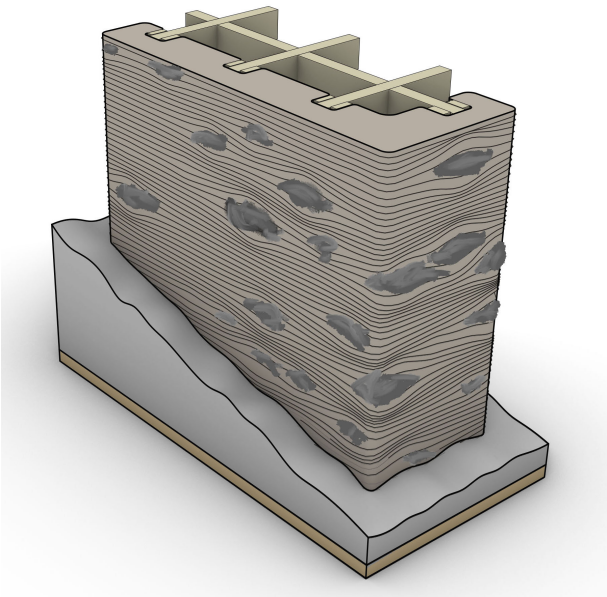

Figure 4: Visualization of foundation build from earth and recovered stones.

Robot repositioning is required for larger prints given the working range limitations of the robot arm. The robot can be driven to a new position mid-print but this puts it out of alignment with the printed artefact. Re-registration of the robot coordinate system in relation to the printed artefact is required to ensure fabrication continuity. This re-registration can be done either by measuring in geometrical features in the environment using the robot, or by analysing the required transformation to re-align registered point clouds. The latter option should be pursued and integrated into the workflow as an automatic process.

The virtual representation of the fabrication environment needs to accommodate incremental updates to the printed artefact while also filtering out noise and temporary changes in the scanned scene. The current workflow discards previous scans, which reduces precision and causes duplicate work. It also uses mesh surface representations which are not well suited to incremental scan integration, and integrating new shapes to represent newly printed material often requires completely rebuilding the data structure. To be able to overlay scans we believe we need to develop a workflow that stores the scanned data as volumetric models in a data representation such as `OpenVDB` [33] where values are stored in a sparse 3D grid.

The end goal is to have a setup that is generalisable and documented, that can be used by other researchers, students, or practitioners, given they have access to a similar setup.

7.2 Iterative prototype development and experimental evaluation

This part constitutes the experimental core of the project and is concerned with iterative prototype development and systematic experimental evaluation. The experiments are designed to investigate the research questions through probes and prototypes. They are organised into three

interconnected strands: *Material and joining*, *Sensing and control*, and *Representation and goal definition*. Across these strands, the work progresses from controlled probes to increasingly integrated prototypes, where results from one line of experimentation inform the others.

These experiments are not only in preparation for the demonstrator, but also contribute distinct forms of knowledge. The material studies investigate how stone and earth interact over time through filling, locking, drying and shrinkage. The sensing studies examine how fabrication can be adjusted through calibration, scan registration and feedback. The representational studies address how the state and goals of fabrication can be described and updated in a design-oriented adaptive workflow.

7.2.1 Material and joining

The focus in this strand is on the interaction between earth-based material and stone. The experiments examine filling, locking, support, drying, shrinkage, and water sensitivity – and how these affect structural stability over time.

The first cluster of experiments includes dry stacking of a wall segment, manual clay reinforcement using the clay pump, monitoring of deformation and drying over days, and finally printing on top of the assembly after drying out. The second cluster takes the same principles but encodes motion and extrusion into machine instructions for the robot to execute. It entails printing around placed stones to secure their placement and fill with clay beneath and in-between stones. This is to further test how clay extrusion can support, lock together and fill cavities between stones and to scale these principles toward multi-layer assemblies.

By incorporating clay as a filler, stabiliser and joining medium in stone assemblies, this strand is designed to develop knowledge about how the materials interact over time. The initial manual experiments help identify relevant behaviours. The transition to robotic experiments explores how these behaviours map onto a digital fabrication workflow.

7.2.2 Sensing and adaptive control

The focus in this strand is on how scan data and calibration methods can be used to maintain fabrication continuity and update robotic actions during production. This includes developing knowledge of how feedback can be registered and acted upon in order to control extrusion volume and path planning around and between stones.

The first cluster investigates how scan data can inform deposition during filling operations between stones. These experiments address how much material is needed to fill a cavity, when deposition should stop, and how print paths can be updated in response to the scanned state of the assembly. This develops knowledge of how sensed geometry can be translated into local fabrication decisions during adaptive construction.

The second cluster focuses on mobile robotics and re-registration after repositioning. These experiments investigate how the robot can be moved during fabrication while maintaining alignment with the built artefact. This develops knowledge of which sensing and calibration strategies are sufficiently robust for larger prints that require relocation of the robot. A planned prototype scales this into an interrupted print sequence in which the robot is repositioned one or more times during fabrication.

The resulting knowledge concerns both localisation and action: where the robot is, what has changed in the build, and how fabrication should respond.

7.2.3 Representation and goal definition

The final strand investigates how the state and goals of fabrication can be represented in an adaptive workflow. The current state, as registered through depth cameras and other sensing methods, needs to be stored and updated in a way that supports both fabrication control and design evaluation. At the same time, the target of fabrication cannot always be understood as a fixed geometry, but may instead need to be expressed as spatial rules, support conditions, or desired relations between materials.

The experiments in this strand are aimed at developing a virtual model of the fabrication process by storing and displaying a series of snapshots containing multiple data points from different stages of production. This work investigates how scan data can be accumulated into a representation of the evolving build state, and how such a representation can support both process analysis and the updating of fabrication goals.

7.3 Demonstrator

This final part addresses the design-method implications of adaptive robotic construction and integrates the preceding work in a full-scale demonstrator. The demonstrator is not only a technical integration exercise, but a design study through which the architectural consequences of adaptive fabrication can be examined. A central question is how design changes when architectural intent is formulated through rules, responses, and evolving material conditions rather than fixed geometry.

References

[1] Johannes Braumann and Sigrid Brell-Cokcan. 'Adaptive Robot Control - New Parametric Workflows Directly from Design to KUKA Robots'. In: *eCAADe 2015: Real Time - Extending the Reach of Computation*. Vienna, Austria, 2015, pp. 243–250. DOI: 10.52842/conf.ecaade.2015.2.243. URL: http://papers.cumincad.org/cgi-bin/works/paper/ecaade2015_100 (visited on 14/05/2024).

[2] Joris Burger et al. 'Eggshell Pavilion: A Reinforced Concrete Structure Fabricated Using Robotically 3D Printed Formwork'. In: *Construction Robotics* 7.2 (July 2023), pp. 213–233. ISSN: 2509-8780. DOI: 10.1007/s41693-023-00090-x. URL: https://doi.org/10.1007/s41693-023-00090-x (visited on 09/02/2026).

[3] Özgüç Bertuğ Çapunaman, Wei Dong and Benay Gürsoy. 'A Vision-Based Sensing Framework for Adaptive Robotic Tooling of Indefinite Surfaces'. In: *Construction Robotics* 6.3 (Dec. 2022), pp. 259–275. ISSN: 2509-8780. DOI: 10.1007/s41693-022-00081-4. URL: https://doi.org/10.1007/s41693-022-00081-4 (visited on 02/04/2024).

[4] Mario Carpo. *The Second Digital Turn: Design beyond Intelligence*. Writing Architecture. Cambridge, MA: The MIT Press, 2017. ISBN: 978-0-262-34124-0. URL: https:

//search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1614726 (visited on 12/10/2023).

[5] Mario Carpo. 'The Sustainable Lightness of Digital Fabrication'. In: *Architectural Design* 94.5 (2024), pp. 14–21. ISSN: 1554-2769. DOI: 10.1002/ad.3092. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ad.3092 (visited on 23/09/2024).

[6] Kunaljit Chadha et al. 'Additive Manufacturing for the Circular Built Environment: Towards Circular Construction with Earth-Based Materials'. In: *A Circular Built Environment in the Digital Age*. Ed. by Catherine De Wolf, Sultan Çetin and Nancy M. P. Bocken. Circular Economy and Sustainability. Cham: Springer Nature, 2024, pp. 111–128. ISBN: 978-3-031-39675-5. URL: https://library.oapen.org/handle/20.500.12657/86890.

[7] Kunaljit Chadha et al. 'Impact Printed Structures: Design Systems and Construction Strategies'. In: *Fabricate 2024*. Creating Resourceful Futures. UCL Press, 2024, pp. 188–195. ISBN: 978-1-80008-635-7. DOI: 10.2307/jj.11374766.28. JSTOR: jj.11374766.28. URL: https://www.jstor.org/stable/jj.11374766.28 (visited on 15/11/2024).

[8] Sasha Cisar. 'Look down Not up! Solving the Building Industry's Wasteful Conundrum with Digital and Earthen Construction'. In: *Architectural Design* 94.5 (2024), pp. 78–87. ISSN: 1554-2769. DOI: 10.1002/ad.3100. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ad.3100 (visited on 23/09/2024).

[9] Zach Cohen. 'Hold up: Machine Delay in Architectural Design'. In: *Robotic Fabrication in Architecture, Art and Design 2018*. Ed. by Jan Willmann et al. Cham: Springer International Publishing, 2019, pp. 126–138. ISBN: 978-3-319-92294-2. DOI: 10.1007/978-3-319-92294-2_10.

[10] Paulo J.S Cruz et al. 'Ceramic 3D Printing – The Future of Brick Architecture'. In: *Proceedings of IASS Annual Symposia* 2017.5 (Sept. 2017), pp. 1–10.

[11] Jelle Feringa. 'Scalable Equals Sustainable: The Infrastructural Imperative of Earthen Construction'. In: *Architectural Design* 94.5 (2024), pp. 64–69. ISSN: 1554-2769. DOI: 10.1002/ad.3098. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ad.3098 (visited on 23/09/2024).

[12] Thomas Fischer and Christiane M. Herr, eds. *Design Cybernetics: Navigating the New*. Design Research Foundations. Cham, Switzerland: Springer, 2019. ISBN: 978-3-030-18557-2.

[13] Philippe Fleischmann, Gonzalo Casas and Michael Lyrenmann. *Compas-Rrc/Compas_rrc: COMPAS RRC*. Zenodo. July 2020. DOI: 10.5281/zenodo.4639418. URL: https://doi.org/10.5281/zenodo.4639418.

[14] Virginia San Fratello and Ronald Rael. 'Mud Frontiers'. In: *Fabricate 2020: Making Resilient Architecture*. Ed. by Jane Burry et al. Fabricate. UCL Press, 2020, pp. 22–27. ISBN: 978-1-78735-812-6. DOI: 10.2307/j.ctv13xpsvw.7. JSTOR: j.ctv13xpsvw.7. URL: http://www.jstor.org/stable/j.ctv13xpsvw.7 (visited on 17/03/2026).

[15] Jared Friedman, Heamin Kim and Olga Mesa. 'Experiments in Additive Clay Depositions'. In: *Robotic Fabrication in Architecture, Art and Design 2014*. Ed. by Wes McGee and Monica Ponce de Leon. Cham: Springer International Publishing, 2014, pp. 261–272. ISBN: 978-3-319-04663-1. DOI: 10.1007/978-3-319-04663-1_18.

URL: https://doi.org/10.1007/978-3-319-04663-1_18 (visited on 22/02/2024).

[16] Mohamed Gomaa et al. 'Automation in Rammed Earth Construction for Industry 4.0: Precedent Work, Current Progress and Future Prospect'. In: *Journal of Cleaner Production* 398 (Apr. 2023), p. 136569. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2023.136569. URL: https://www.sciencedirect.com/science/article/pii/S0959652623007278 (visited on 12/03/2026).

[17] Mohamed Gomaa et al. 'Digital Manufacturing for Earth Construction: A Critical Review'. In: *Journal of Cleaner Production* 338 (Mar. 2022), p. 130630. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2022.130630. URL: https://www.sciencedirect.com/science/article/pii/S0959652622002712 (visited on 27/02/2024).

[18] Fabio Gramazio, Matthias Kohler and Michael Hanak, eds. *Digital Materiality in Architecture: Gramazio & Kohler*. Baden: Müller, 2008. ISBN: 978-3-03778-122-7.

[19] Gamze Gündüz and Mine Özkar. 'A Process-Based Framework for Adaptable Modules in Robotic Clay 3D Printing'. In: *International Journal of Architectural Computing* 22.1 (Mar. 2024), pp. 45–61. ISSN: 1478-0771. DOI: 10.1177/14780771231225698. URL: https://doi.org/10.1177/14780771231225698 (visited on 02/04/2024).

[20] Benay Gürsoy. 'From Control to Uncertainty in 3D Printing with Clay'. In: *eCAADe 2018: Computing for a Better Tomorrow*. Łódź, Poland, 2018, pp. 21–30. DOI: 10.52842/conf.ecaade.2018.2.021. URL: http://papers.cumincad.org/cgi-bin/works/paper/ecaade2018_104 (visited on 12/01/2026).

[21] International Energy Agency. *Breakthrough Agenda Report 2025*. Tech. rep. Paris: International Energy Agency, 2025. URL: https://www.iea.org/reports/breakthrough-agenda-report-2025.

[22] David Jenny et al. 'A Pedagogy of Digital Materiality: Integrated Design and Robotic Fabrication Projects of the Master of Advanced Studies in Architecture and Digital Fabrication'. In: *Architecture, Structures and Construction* 2.4 (Dec. 2022), pp. 649–660. ISSN: 2730-9886, 2730-9894. DOI: 10.1007/s44150-022-00040-1. URL: https://link.springer.com/10.1007/s44150-022-00040-1 (visited on 16/10/2023).

[23] Anton Johansson and Edurne Morales Zúñiga. 'Adaptive Clay Formations'. PhD thesis. Lund, Sweden: Lund University, 2021. URL: http://lup.lub.lu.se/student-papers/record/9041159 (visited on 17/03/2021).

[24] Maike Klöckner et al. 'Bettan - Industrial Robot and Application for Finja Exakt Build System'. In: *Proceedings of the 40th International Symposium on Automation and Robotics in Construction*. Ed. by Borja García de Soto, Vicente Gonzalez-Moret and Ioannis Brilakis. Chennai, India: International Association for Automation and Robotics in Construction (IAARC), July 2023, pp. 86–93. ISBN: 978-0-6458322-0-4. DOI: 10.22260/ISARC2023/0014.

[25] Terry Knight and George Stiny. 'Making Grammars: From Computing with Shapes to Computing with Things'. In: *Design Studies*. Special Issue: Computational Making 41 (Nov. 2015), pp. 8–28. ISSN: 0142-694X. DOI: 10.1016/j.destud.2015.08.006. URL: https://www.sciencedirect.com/science/article/pii/S0142694X15000605 (visited on 14/05/2024).

[26] Odysseas Kontovourkis and George Tryfonos. 'Integrating Parametric Design with Robotic Additive Manufacturing for 3D Clay Printing: An Experimental Study'. In: *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC)*. Ed. by Jochen Teizer. Taipei, Taiwan: International Association for Automation and Robotics in Construction (IAARC), July 2018, pp. 918–925. ISBN: 978-3-00-060855-1. DOI: 10.22260/ISARC2018/0128.

[27] Matthias Leschok et al. '3D Printing Facades: Design, Fabrication, and Assessment Methods'. In: *Automation in Construction* 152 (Aug. 2023), p. 104918. ISSN: 09265805. DOI: 10.1016/j.autcon.2023.104918. URL: https://linkinghub.elsevier.com/retrieve/pii/S0926580523001784 (visited on 09/02/2026).

[28] Zhao Ma et al. 'Stylized Robotic Clay Sculpting'. In: *Computers & Graphics* 98 (Aug. 2021), pp. 150–164. ISSN: 0097-8493. DOI: 10.1016/j.cag.2021.05.008. URL: https://www.sciencedirect.com/science/article/pii/S0097849321000959 (visited on 22/02/2024).

[29] Steven Macenski et al. 'Robot Operating System 2: Design, Architecture, and Uses in the Wild'. In: *Science Robotics* 7.66 (2022). DOI: 10.1126/scirobotics.abm6074. URL: https://www.science.org/doi/abs/10.1126/scirobotics.abm6074.

[30] Lambros Malafouris. 'At the Potter's Wheel: An Argument for Material Agency'. In: *Material Agency: Towards a Non-Anthropocentric Approach*. Ed. by Carl Knappett and Lambros Malafouris. Boston, MA: Springer US, 2008, pp. 19–36. ISBN: 978-0-387-74711-8. DOI: 10.1007/978-0-387-74711-8_2. URL: https://doi.org/10.1007/978-0-387-74711-8_2 (visited on 22/02/2024).

[31] Coralie Ming et al. 'Impact Printing'. In: *3D Printing and Additive Manufacturing* 9.3 (June 2022), pp. 203–211. ISSN: 2329-7662. DOI: 10.1089/3dp.2021.0068. URL: https://www.liebertpub.com/doi/10.1089/3dp.2021.0068 (visited on 10/11/2025).

[32] Gernot Minke. *Building with Earth: Design and Technology of a Sustainable Architecture Fourth and Revised Edition*. 4th ed. Basel/Berlin/Boston: Walter de Gruyter GmbH, 2022. ISBN: 978-3-0356-2255-3.

[33] Ken Museth. 'VDB: High-resolution Sparse Volumes with Dynamic Topology'. In: *ACM Transactions on Graphics* 32.3 (June 2013), pp. 1–22. ISSN: 0730-0301, 1557-7368. DOI: 10.1145/2487228.2487235. URL: https://dl.acm.org/doi/10.1145/2487228.2487235 (visited on 07/06/2022).

[34] Andrea Quartara. 'Architecture after the Digital Turn: Digital Fabrication beyond the Computational Thought'. In: *Computational Morphologies: Design Rules Between Organic Models and Responsive Architecture*. Ed. by Michela Rossi and Giorgio Buratti. Cham: Springer International Publishing, 2018, pp. 113–131. ISBN: 978-3-319-60919-5. DOI: 10.1007/978-3-319-60919-5_9. URL: https://doi.org/10.1007/978-3-319-60919-5_9 (visited on 20/01/2026).

[35] Ronald Rael and Virginia San Fratello. 'Clay Bodies: Crafting the Future with 3D Printing'. In: *Architectural Design* 87.6 (Nov. 2017), pp. 92–97. ISSN: 00038504. DOI: 10.1002/ad.2243. URL: http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=asu&AN=126016050&site=eds-live&scope=site (visited on 08/04/2020).

[36] Mette Ramsgaard Thomsen and Martin Tamke. 'Narratives of Making: Thinking Practice Led Research in Architecture'. In: *Communicating (by) Design*. Ed. by Johan Verbeke and Adam Jakimowicz. Brussels, Belgium: Sint-Lucas & Chalmers, 2009, pp. 343–352. ISBN: 978-90-813238-0-2.

[37] Craig W. Reynolds. 'Flocks, Herds and Schools: A Distributed Behavioral Model'. In: *Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques*. Vol. 21. SIGGRAPH '87. New York, NY, USA: Association for Computing Machinery, Aug. 1987, pp. 25–34. ISBN: 978-0-89791-227-3. DOI: 10.1145/37401.37406. URL: https://dl.acm.org/doi/10.1145/37401.37406 (visited on 23/01/2026).

[38] Jenny E. Sabin et al. 'PolyBrick: Variegated Additive Ceramic Component Manufacturing (ACCM)'. In: *3D Printing and Additive Manufacturing* 1.2 (June 2014), pp. 78–84. ISSN: 2329-7662. DOI: 10.1089/3dp.2014.0012. URL: https://www.liebertpub.com/doi/10.1089/3dp.2014.0012 (visited on 09/02/2026).

[39] Horst Schroeder. *Sustainable Building with Earth*. Springer International Publishing, 2016. ISBN: 978-3-319-19490-5. DOI: 10.1007/978-3-319-19491-2. URL: https://www.springer.com/gp/book/9783319194905 (visited on 29/04/2020).

[40] Molly Wright Steenson. *Architectural Intelligence: How Designers and Architects Created the Digital Landscape*. The MIT Press, Dec. 2017. ISBN: 978-0-262-34342-8. DOI: 10.7551/mitpress/10971.001.0001. URL: https://direct.mit.edu/books/book/3643/Architectural-IntelligenceHow-Designers-and (visited on 02/09/2025).

[41] Iremnur Tokac, Herman Bruyninckx and Andrew Vande Moere. 'A Programming Grammar for Robotic Fabrication: Incorporating Material Agency into Clay Textures'. In: *Design Studies* 88 (Sept. 2023), p. 101220. ISSN: 0142-694X. DOI: 10.1016/j.destud.2023.101220. URL: https://www.sciencedirect.com/science/article/pii/S0142694X23000613 (visited on 22/02/2024).

[42] Iremnur Tokac et al. 'Craft-Inspired Digital Fabrication: A Study of Interactive Robotic Clay Carving'. In: *Proceedings of the 7th Annual ACM Symposium on Computational Fabrication*. SCF '22. New York, NY, USA: Association for Computing Machinery, Oct. 2022, pp. 1–14. ISBN: 978-1-4503-9872-5. DOI: 10.1145/3559400.3562003. URL: https://dl.acm.org/doi/10.1145/3559400.3562003 (visited on 22/02/2024).

[43] Iremnur Tokac et al. 'Fabrication Grammars: Bridging Design and Robotics to Control Emergent Material Expressions'. In: *Construction Robotics* 5.1 (Mar. 2021), pp. 35–48. ISSN: 2509-8780. DOI: 10.1007/s41693-021-00053-0. URL: https://doi.org/10.1007/s41693-021-00053-0 (visited on 22/02/2024).

[44] United Nations Environment Programme and Global Alliance for Buildings and Construction. *Not Just Another Brick in the Wall: The Solutions Exist - Scaling Them Will Build on Progress and Cut Emissions Fast. Global Status Report for Buildings and Construction 2024/2025*. Technical Report 978-92-807-4215-2. United Nations Environment Programme, 2025. DOI: 10.59117/20.500.11822/47214. URL: https://wedocs.unep.org/handle/20.500.11822/47214.

[45] Norbert Wiener. *Cybernetics or Control and Communication in the Animal and the Machine*. 2. ed., 10. print. Cambridge, Mass: MIT Press, 2000. ISBN: 978-0-262-23007-0.

[46] Peng Wu, Jun Wang and Xiangyu Wang. 'A Critical Review of the Use of 3-D Printing in the Construction Industry'. In: *Automation in Construction* 68 (Aug. 2016), pp. 21–31. ISSN: 0926-5805. DOI: 10.1016/j.autcon.2016.04.005. URL: https://www.sciencedirect.com/science/article/pii/S0926580516300681 (visited on 22/02/2024).

Bilaga 1: Manuskript 1

Shaping design and fabrication processes for sustainable materials through adaptivity: interactive clay 3D printing for heterogeneous material assemblies

Currently under revision after reviewer feedback.

Shaping design and fabrication processes for sustainable materials through adaptivity: interactive clay 3D printing for heterogeneous material assemblies

Anton Tetov Johansson[1][0000-0002-0235-4617], Björn Olofsson[2][0000-0003-1320-032X], Mathias Haage[3][0000-0002-4831-483X] and David Andréen[1][0000-0003-4680-4496]

[1]Department of Architecture & the Built Environment, Lund University, Lund, Sweden
tetov@abm.lth.se
[2]Department of Automatic Control, Lund University, Lund, Sweden
[3]Department of Computer Science, Lund University, Lund, Sweden

Abstract. This paper investigates adaptive robotic fabrication for heterogeneous, low-processed materials, focusing on clay-based mortar deposition on irregular substrates in combination with stone aggregates. While digital fabrication has expanded the geometric and procedural possibilities of additive construction, most workflows remain constrained by deterministic toolpaths and fixed representations that presuppose predictable material behaviour. Our approach identifies three fundamental constraints: sensing fidelity, geometric representation capable of real-time updates, and material behaviour characterisation across multiple timescales.

Two experiments were conducted with a mobile industrial robotic arm equipped with a clay extrusion system. A depth camera mounted on the tool enabled intermittent digital twin updates informing adaptive toolpath generation. The first experiment explored non-planar deposition on an uneven cast substrate, while the second built one the first but introduced further heterogeneous interaction through inclusion of manually embedded stone.

The work identifies limitations in mesh-based reconstruction and discrete feedback cycles. We find that representations must tolerate sensor noise, support local updates, and accommodate multiple material timescales and suggest volumetric models as a path forward. Behaviour-driven toolpath strategies, such as differential growth, proved more resilient to irregularity than deterministic offsets. These results indicate that adaptive fabrication requires both continuous sensing integration and toolpath strategies capable of local responsiveness to material and substrate variation.

Keywords: nonlinear fabrication, digital earth construction, material-responsive toolpath generation, volumetric digital twin, construction robotics

1 Introduction

To reduce the environmental impact of construction, the Architecture, Engineering, and Construction (AEC) industry is presently investigating transformations of existing buildings, reuse of building components, and alternative materials [1]. However, established industrial workflows – optimised for uniform materials and controlled con-

ditions – struggle to accommodate the heterogeneity and irregularity of built environments and many sustainable materials. Robotics, when combined with computational design, offers a means to reconcile scalable fabrication with these emerging material practices [2].

Conventional robotic manufacturing typically operates in highly controlled environments, relying on processes that prioritise precision and repeatability. Construction, by contrast, is characterised by variation, uncertainty, and site-specific constraints. Digital fabrication (DFAB) has helped bridge this gap by introducing algorithmic control, parametrisation, and feedback, enabling more complex geometries and improved material efficiency. Yet DFAB largely remains tied to deterministic, geometry-driven workflows. Robotic fabrication, by contrast, enables multi-directional motion, adaptive behaviour, and the possibility of process-responsive control – capabilities essential when working with materials whose properties cannot be fully stabilised [2].

Our work builds on this distinction by focusing on materials whose behaviours cannot be reliably predicted or constrained, specifically low-processed and naturally variable materials such as raw earth and recovered stone. In these contexts, DFAB methods struggle because they presuppose consistent material properties. Robotic fabrication allows fabrication logic to respond to material deviation as it occurs, shifting from predefined geometry toward co-design processes in which designer, robot, and material jointly negotiate form in real time. This perspective embraces material agency and highlights the need for adaptive workflows that can operate effectively within heterogeneous and in-situ construction contexts.

In response to these limitations, this paper presents ongoing experiments that investigate clay-based mortar deposition combined with stone aggregates and uneven substrates. These experiments explore how design and fabrication systems can adapt to non-standard geometries and nonlinear material behaviour. To support this adaptivity, we develop an intermittent digital-twin framework that integrates depth sensing into the design-to-fabrication process and informs real-time adjustments to both process and toolpath parameters.

1.1 Hypothesis

The core contribution of this paper is a workflow for adaptive robotic clay printing that integrates continuous scanning, a volumetric digital twin, and multi-modal path generation to accommodate heterogeneous, unpredictable materials in situ. This contribution advances DFAB by demonstrating how material behaviour can inform real-time toolpath and process decisions. We hypothesise that continuous feedback between robotic system, design intent, and as-built conditions can strongly facilitate successful integration of non-industrial, irregular materials. Such a loop would enable autonomous adaptation of fabrication parameters and toolpaths to accommodate material behaviour and geometric irregularities.

Specifically, we propose that by continuously sensing and interpreting deviations between the digital model and the physical environment, it is possible to adjust printing trajectories and process parameters dynamically to maintain outcomes within

aesthetic, structural, and functional tolerances. Central to our approach is a volumetric model that functions as a mediator between sensor data, design intent, and toolpath generation. We suggest that such a model can inform decisions in a dynamic decision space, based on information from multiple origins.

To evaluate this hypothesis, the research addresses the following questions:

- How can design intent be represented in a form that remains meaningful and operable within an automated, adaptive fabrication process involving unpredictable materials and site conditions?
- How can 3D scan data and other spatial modalities be integrated with the design model to enable dynamic adjustment of the fabrication process?
- How can the adaptive responses to material behaviour such as deformation or interaction between materials be systematically encoded into the fabrication process?

1.2 Background

Many DFAB techniques have been developed for controlled environments and rely on standardised materials that are often unsuitable for construction-scale applications. Large-scale 3D printing systems for construction exist, however their integration into real-world building processes remains limited. In contrast, interventions in existing structures or complex environments rely primarily on skilled manual labour, where adaptability and material awareness are essential. These human qualities of improvisation and resourcefulness may prove crucial in emerging paradigms of sustainable construction that prioritise reuse and local material sourcing. The challenge lies in translating these adaptive capabilities into robotic systems capable of operating within unpredictable environments.

The work presented in this paper is situated within Digital Earthen Construction (DEC), an emerging field encompassing clay-based additive manufacturing. Alongside a renewed interest in earth as a building material, through methods such as prefabricated rammed earth blocks [3], its applicability in DFAB is studied by researchers [4]. However, earth construction challenges conventional notions of industrial precision [5]. In contrast, 3D concrete printing for construction has reached a level of industrial maturity, with commercial systems enabling both on-site and prefabrication production. Many of these employ advanced extrusions systems with accelerant injection and material refinement developed through sustained research [6].

Our research investigates how adaptability can be embedded into automated fabrication processes, while acknowledging that human resourcefulness based on contextual reasoning and tacit knowledge are hard or impossible to capture into a digital context [7]. Central to this are feedback loops that calibrate and tune both process and material, an analogue to how a potter continuously adjusts grip and handling of clay on the wheel, where data from sensors directly informs the fabrication process.

Feedback loops are fundamental in robotics, most crucially for low level motion control, but in a wider context for precision, stability, and process control. Current research into motion planning and error correction is in large part driven by industrial automation and autonomous vehicles. However, in DFAB, feedback is often limited

to calibration or error detection rather than design-level adaptation. Incorporating feedback as a design driver, rather than just a control mechanism, requires rethinking how robotic systems interpret material and environmental data. Such systems must not only correct errors in precision but also adapt fabrication logic to material irregularity, surface geometry, and process parameters.

Machine perception implemented through computer vision, and 3D scanning and surface reconstruction are well established in fields such as construction inspection, heritage preservation, and digital archaeology, where they are used to investigate and preserve [8], or to evaluate as-built conditions [9]. Yet, integrating such datasets into automated construction workflows remains a significant challenge. The discrepancy between idealised CAD/BIM geometries and the noisy, irregular nature of real-world data requires intensive post processing in the form of pointcloud segmentation [10].

In adaptive robotic fabrication, 3D scanning could become more than a tool for documentation, it could serve as a real-time input for process control. A digital twin could be constructed through continuous capture of spatial data during fabrication. The central challenge, then, becomes how to integrate design methodology with the digital twin.

1.3 State of the art

This project is situated within a transdisciplinary field spanning architecture, robotics, and material research, with a particular focus on clay-based additive fabrication and adaptive sensing.

Early explorations of sensing-integrated clay fabrication include *Remote Material Deposition* [11], which included a lidar-constructed pointcloud to verify the impact of launched clay cylinders guided by a robotic arm. This ballistic deposition method represents a departure from deterministic control since each element's location cannot be precisely predetermined. The use of a dynamic reconstruction of the developing structure during fabrication establishes a precedent for integrating real-time environmental sensing into clay-based workflows, enabling verification of actual rather than assumed conditions.

Çapunaman et al. have developed a sensing-informed fabrication workflow through two complementary studies. Their 2022 paper introduces a vision-based framework for adaptive robotic tooling on indefinite surfaces, using a stereo camera mounted on the robot end-effector with interchangeable implements, and detailing multi-scan surface reconstruction methods [12]. Their 2023 follow-up extends this system into a practical material-in-the-loop clay 3D printing workflow using mouldable sand formwork [13]. Similarly, Breseghello et al. have advanced adaptive 3D concrete printing through particle-based simulation tuned via empirical calibration, enabling visualisation and prediction of material behaviour as part of the design process [14], as well as robot-assisted concrete printing on 3D-scanned complex terrain [15]. Together, these works demonstrate how 3D reconstruction and material behaviour can inform adaptive fabrication processes.

Beyond sensing and reconstruction, a parallel body of work explores algorithmically generated toolpaths that embed material behaviour, structural requirements, or

environmental constraints directly into the deposition logic. Breseghello et al.'s toolpath-based design for concrete printing, for example, uses performance-informed path generation to reconcile structural optimisation with printing constraints [14]. In composite printing, Chen et al. develop a field-guided toolpath framework where stress-derived vector fields inform adaptive fibre orientation [16]. Such approaches shift from geometry-first workflows toward behaviour- or field-driven fabrication strategies, an orientation that aligns with the generative methods explored in this paper.

Goidea et al. contribute to this trajectory through a voxel-based methodology in which particle-spring systems and volumetric fields encode multiple functional requirements – such as airflow conduits, locally graded densities, or structural openings – within 3D-printed building envelopes [17]. Their work demonstrates how volumetric representations can mediate between algorithmic design decisions and heterogeneous material behaviour at multiple scales. This resonates with our aim to develop an adaptive, interactive fabrication system in which design intent is expressed through process logics and volumetric representations rather than fixed geometry.

2 Methodology

This study adopted an exploratory research-by-design methodology [18], using iterative prototyping to examine how sensing, computation, and material behaviour can support adaptive robotic fabrication. Working at the intersection of digital design, robotics, and clay-based material performance, each experiment served to test hypotheses about how feedback can accommodate nonlinear and heterogeneous material conditions.

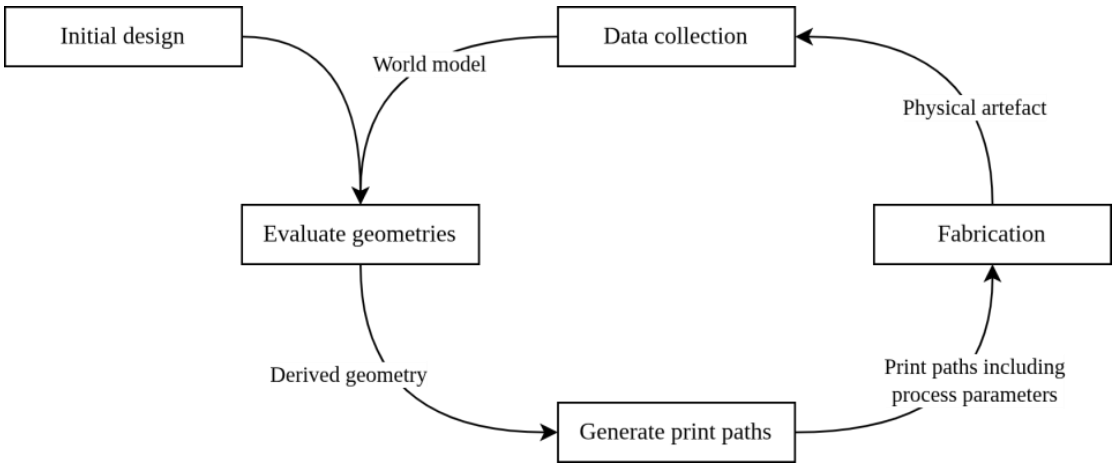

Fig. 1. The proposed design and fabrication loop.

Fig. 1 illustrates the overarching closed-loop workflow guiding the research. A target design and contextual model generate a derived geometry, from which toolpaths and process parameters are produced. Fabrication is followed by sensing, reconstruction, and an update of the digital twin, enabling reassessment of the discrepancy between

intended and actual states. This loop may be executed once or repeatedly, and the present work explores how its iteration frequency can progressively increase.

The design scenario used to ground the experiments is a small building foundation inspired by contemporary interpretations of vernacular rubble-and-mortar construction. Building foundations, otherwise typically realised with concrete, carry significant ecological impacts due to embodied carbon and their disruption of site ecologies. By combining locally available stone rubble with clay-based mortar, opportunities arise for reduced material impact, improved circularity, and integration with heterogeneous site conditions. Robotic fabrication and computational design offer ways to scale such craft-based techniques through improved efficiency and performance assurance.

2.1 Experimental setup

Fig. 2. A: Construction Robotics Lab. **B:** Clay extruder connected via hose to pump.

All experiments were performed in an outdoor mobile fabrication cell, Fig. 2A, reflecting the ambition to study robotic construction in realistic site conditions. A 6-axis industrial robot was mounted on a construction-grade mobile base [19] and fitted with a clay extruder supplied by a pump designed for viscous materials (Erratic DM80 and T25, Fig. 2B). A stereo depth camera (Luxonis OAK-D-S2) was co-mounted on the tool to capture depth data during and between fabrication steps. Point clouds were captured from multiple viewpoints and registered to the robot base frame via the robot's kinematics, ensuring consistent localisation without requiring repeated manual calibration.

2.2 Fabrication feedback loops

Adaptive fabrication was structured around a feedback loop in which the as-built state was intermittently scanned, reconstructed, and compared with the target geometry, Fig. 1. Each iteration consisted of: (1) scanning the printed geometry, (2) updating the digital representation, (3) generating new toolpaths informed by the discrepancy between intended and actual conditions, and (4) continuing deposition.

Experiment 1 used a single iteration of this loop, while Experiment 2 added a second update following the insertion of a manually placed stone. The workflow is intended to scale toward higher-frequency or continuous feedback as sensing and representation methods mature.

2.3 Print path and robot program generation

Toolpaths were generated in Rhinoceros® using Grasshopper and COMPAS [20, 21]. Sequences of tool-centre-point frames with associated velocity and extrusion parameters were streamed directly to the robot controller via COMPAS RRC [22].

In Experiment 1, non-planar layers were created by interpolating between the scanned substrate and a flat target surface, followed by offsetting each layer boundary to produce a continuous contour path. A smoothed NURBS surface was reconstructed from the scan to enable reliable offsetting.

In Experiment 2, planar contouring was used. The scanned substrate and manually inserted stone geometry were subtracted from a base volume prior to infill. Continuous, non-repeating infill paths were generated using a differential-growth algorithm [29]. After half of the layers were printed, the stone was inserted, the geometry rescanned, and new toolpaths generated to integrate the stone within the printed mass.

Extrusion flow was modulated according to tool speed and, in Experiment 1, locally adjusted based on layer height to compensate for substrate irregularities. The clay mix viscosity was determined through empirical testing.

3 Results

Fig. 3. A: Experiment 1. **B:** Over-extrusion in first layer. **C:** Tapering visible in extruded line.

Two prototypes were fabricated corresponding to the two experiments, prototype 1 and 2. Both were printed on the same pre-made irregular concrete substrate, and the results are shown in Fig. 4 and Fig. 5.

In practice, the digital twin was updated intermittently rather than continuously. A major obstacle was point-cloud noise, which made it difficult to reconstruct accurate geometry from individual scans. Merging multiple point clouds reduced noise and improved fidelity, but this strategy is only feasible when scanning occurs in discrete steps. Continuous updating, by contrast, would require each captured cloud to be immediately converted into reliable geometric representations, a process that is both computationally demanding and sensitive to noise.

A further challenge involved localisation of successive scans. Any repositioning of the robot requires recalibration of the scan data relative to the robot base frame, which is time-consuming and undermines rapid iteration. Mounting the camera directly on the robot tool mitigated this issue, enabling consistent localisation of point clouds through the robot's own kinematics.

All reconstructed geometry was represented as polygonal meshes, allowing standard CAD tools to be used for subsequent processing. While this approach is adequate for intermittent updates, it depends on high-quality scans and requires each update to be integrated holistically into a new global mesh. Local, incremental updates based on partial scan data were not practically achievable. This limitation suggests that mesh-based representations may become prohibitive as feedback cycles increase in frequency or as the system moves towards continuous, real-time adaptation.

Experiment 1. The initial layer of the first prototype (Fig. 4B) was slightly over-extruded, however, the adhesion to the surface area was good, with both alignment and layer height remaining within adequate parameters. As subsequent layers were printed, the variable extrusion rate (which was also manually scaled at times during the print), achieved the desired layer heights, gradually reducing the unevenness (Fig. 4C) and resulting in a horizontal and planar surface (Fig. 4A).

The sub-optimal material buildup (both due to the intended variability and the variability resulting from bad tuning and uneven material flow) led to a result that was visually messy but functionally adequate.

Finding an appropriate extrusion rate accounting for clay viscosity was challenging in the first experiment, as evidenced by over-extrusion in regions with closely spaced layers. A compromise between over-extrusion at one extreme and under-extrusion at the other lead to material build-up since under-extrusion compromises layer adhesion and creates discontinuities in the printed structure. Alternating the path directions between layers, while efficient since it eliminated travel moves, meant that the following layer was printed on top of the just extruded, wettest, clay.

Experiment 2. The layers were "stepped" along the sloping surface, resulting in over- and under-extrusion. However, this did not lead to any complications, as the earth's fluidity was sufficient to accommodate for the discrepancies. The differential growth algorithm used in the second experiment filled out the desired layers in a stochastic

fashion that eliminated stacked paths. The delamination that occurred due to drying resulted in cracks that often followed the joint between extrusion paths, indicating that this strategy achieves higher overall cohesion and strength.

Fig. 4. A: Experiment 2, visible receptable for stone. **B**: Clay meeting sloped substrate. **C**: Infill around embedded stone.

The placement of the stone in the resulting cavity was easily achieved, with intended orientation of the stone being readily evident. However, air gaps or cavities resulted on many sides of the stone, indicating that the cavity was too large, or that the clay fluidity was too low. To compensate for this, an additional step was introduced where the intersection between stone and top layer was used to generate an extra print path, pushing additional material into the cavity, fig (Fig. 5C). This step posed additional path planning challenges to avoid robot self-collision but resulted in an adequate solution to the issue.

In the final print path, a new factor of unpredictability was (unintentionally) introduced in the form of a boundary curve being insufficiently offset. This led to collisions with the inset stone, and deformation of the extrusion nozzle. The resulting chaotic extrusion is seen in Fig. 6. However, the outcome could be partially mitigated by manually increasing the extrusion rate, and subsequent layers adapted better to the intended outcome.

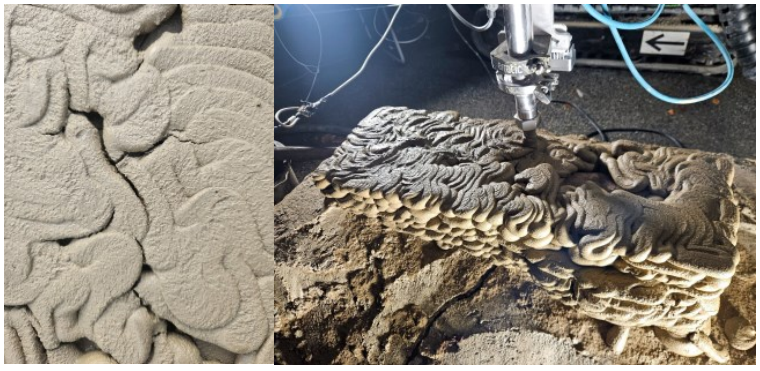

Fig. 5. A: Close-up of differential growth extrusion **B:** Extrusion at the wrong height, partially compensated for by increased flow.

4 Discussion.

4.1 Sensing and model updating

The experiments demonstrate that adaptive fabrication is strongly constrained by sensing quality and geometric representation. The digital twin could only be updated intermittently, as individual scans contained substantial noise and required merging into a global model to produce reliable geometry. This workflow enabled coarse adjustments between printing stages but prevented meaningful local or continuous updates. The need for frequent recalibration further limited iteration speed, even with the camera mounted directly on the robot tool.

A strategy for future work could be to incorporate local sensing in terms of point distance sensors mounted before and after the nozzle, which could measure the immediate extrusion. Similarly, a load cell mounted between nozzle and flange could give insights into actual material flow. Analysing the video streams from the already mounted camera could enable detection of problematic material behaviour such as cracking or displacement.

Representing the as-built state as polygonal meshes proved adequate for low-frequency feedback cycles but unsuitable for higher-resolution adaptation. Mesh updates required complete reconstruction rather than incremental refinement, making it impractical to capture small, localised deviations such as sagging, material accumulation, or deformation around embedded stones. These limitations indicate that mesh-based world models may become prohibitive as adaptive processes demand shorter feedback loops.

The results suggest that volumetric or voxel-based models would be better suited for adaptive fabrication involving heterogeneous, deforming materials. Unlike meshes, volumetric models can integrate uncertain scan data, store partial information, and be updated locally. Such representations may form the basis for higher-frequency feedback, enabling deviations in material behaviour to be interpreted in ways that inform process parameters and toolpath adjustments. Addressing these representational and sensing bottlenecks is therefore essential for advancing from intermittent corrections to continuous, real-time adaptation.

4.2 Process-Driven Form and Material Behaviour

Although these sensing and representational constraints currently limit the frequency and resolution of adaptive feedback, they also illuminate how fabrication logic can emerge from the interaction between material behaviour and algorithmic strategies. With this context, the prototypes can be understood not only as geometric outcomes but as evidence of how different path-generation approaches negotiate variability, robustness, and design intent.

The prototypes reveal how process tolerances and material variability can generate aesthetically valuable features rather than defects. The tapering effect visible in Prototype 1 (Fig. 3C), the organic flow of the differential growth paths in Prototype 2 (Fig. 4A), and material-driven surface texture across both prototypes collectively contributed to formal complexity. The self-organising algorithm in Experiment 2 leverages this variability more effectively than the top-down organisation Experiment 1, producing visual outcomes that demonstrate aesthetic characteristics reminiscent of process-driven systems in nature, such as trees, geological formations and coral.

4.3 Encoding Design Intent as Behaviour

This aesthetic tolerance aligns with craft-based fabrication approaches, where the maker responds to material feedback during production, though our robotic process operates at different scales and speeds. To exploit this, design intent should be encoded not as explicit form but as process parameters and algorithmic behaviours: extrusion rates, path generation algorithms, and adaptive responses. From these parameters, form emerges from the interaction between instructions, the robot's capabilities, and material behaviour.

Experiment 2's differential growth algorithm exemplifies this approach. Instead of specifying exact toolpaths, the algorithm defined growth behaviours that generated continuous, weaving paths responsive to the local boundaries (Fig. 4B). This maintains fibre continuity throughout the structure, eliminating the systematic weak planes created by offset contour strategies where parallel extrusion lines create seams propagating through all layers (compare Fig. 3C to Fig. 4A). The translation from algorithmic to fabrication involves multiple parameters: point spacing, blend radii for robot motion, and extrusion rates. Each parameter represents a design decision concerning process control versus adaptation latitude. These layered encodings provide multiple scales at which design intent can accommodate or constrain variability.

Notwithstanding over-extrusion in the Experiment 1 and collisions in Experiment 2, the process resulted in acceptable outcomes, showing the interplay between the precision of the robotic instructions and execution and the adaptivity of the material.

4.4 Representation and Feedback Across Timescales

Building on the sensing and reconstruction limitations outlined earlier, a further challenge concerns how geometric representations support feedback at different fabrication timescales. While polygonal meshes allow compatibility with conventional CAD workflows, their reliance on complete surface reconstruction makes them ill-suited for situations where only local, incremental updates are needed. This mismatch becomes evident when attempting to capture small-scale deviations such as local sagging, accumulation of material, or deformation around embedded stones: phenomena that occur rapidly and unpredictably during deposition.

At the same time, clay-based construction processes unfold across multiple temporal layers: immediate effects during extrusion, mid-range effects as the material settles, and slower transformations associated with drying and cracking. Each of these

timescales demands distinct forms of feedback, yet mesh-based representations require full updates that are too slow and fragile to support such differentiation.

A more flexible approach is therefore needed, which can absorb heterogeneous, noisy, and partial data without requiring global reconstruction at every step. Volumetric or voxel-based models offer this potential, as they allow localised updates, accommodate uncertainty, and can integrate multi-modal information such as depth data, local force cues, or material-thickness estimates. Such representations would enable feedback cycles calibrated to the temporal dynamics of the material, linking rapid sensing during deposition with slower assessments of structural or drying-related behaviour.

Taken together, these insights suggest that advancing adaptive fabrication requires not only improved sensing but also representational models that can operate effectively across multiple timescales [23], translating material behaviour into meaningful, time-appropriate adjustments to the fabrication process.

5 Conclusion

The experiments demonstrate that adaptive robotic fabrication of heterogeneous, low-processed materials is both feasible and constrained by the interplay between sensing fidelity, geometric representation, and material behaviour. By integrating depth scanning, a digital twin, and behaviour-driven path generation, the prototypes successfully adapted extrusion paths to irregular substrates and embedded objects. These outcomes validate the potential of adaptive workflows for construction contexts where geometric variability is the norm rather than an exception.

At the same time, the work reveals the limitations of mesh-based representations as world models for real-time adaptation. The need for complete geometric reconstruction at each update inhibits high-frequency feedback, makes incremental corrections impractical, and exposes a fundamental mismatch between conventional CAD workflows and the realities of noisy, heterogeneous data. This suggests that future adaptive fabrication will require digital twins capable of accommodating uncertainty, integrating diverse data sources, and updating locally rather than globally.

The comparison between the two path-generation strategies further highlights the importance of encoding design intent as behaviour rather than fixed geometry. The differential growth algorithm absorbed geometric irregularities more effectively than deterministic offset paths, producing more coherent layering and better structural continuity. This indicates that adaptive fabrication benefits from process logics that negotiate material deviation rather than attempting to constrain it.

Finally, the experiments underscore that clay-based construction unfolds across multiple timescales – from immediate deformation during extrusion to slower effects such as drying deformation or adaptation to other building components. Effective adaptive systems must therefore operate through nested feedback loops calibrated to these temporal dynamics, linking rapid sensing during deposition with slower responses to material change.

Together, these findings outline a path towards robotic fabrication systems that couple sensing, representation, and behavioural design intent to work productively with the inherent variability of sustainable, locally sourced materials. Such systems have the potential to expand DFAB beyond deterministic file-to-factory workflows and toward genuinely adaptive construction processes suited to ecological and material realities.

References

1. Rivera-Lutap JA, Dela Cruz OG, Jacinto JM, et al (2024) Alternative Building Materials for a Sustainable Built Environment: A Literature Review. In: Sun Z, Das PK (eds) Proceedings of the 10th International Conference on Energy Engineering and Environmental Engineering. Springer Nature Switzerland, Cham, pp 235–246
2. Carpo M (2024) The sustainable lightness of digital fabrication. Architectural Design 94:14–21. https://doi.org/10.1002/ad.3092
3. Minke G (2022) Building with Earth: Design and Technology of a Sustainable Architecture Fourth and Revised Edition, 4th ed. Walter de Gruyter GmbH, Basel/Berlin/Boston
4. Gomaa M, Jabi W, Soebarto V, Xie YM (2022) Digital manufacturing for earth construction: a critical review. Journal of Cleaner Production 338:130630. https://doi.org/10.1016/j.jclepro.2022.130630
5. Morel J-C, Charef R, Hamard E, et al (2021) Earth as construction material in the circular economy context: practitioner perspectives on barriers to overcome. Phil Trans R Soc B 376:20200182. https://doi.org/10.1098/rstb.2020.0182
6. Ahmed GH (2023) A review of "3D concrete printing": Materials and process characterization, economic considerations and environmental sustainability. Journal of Building Engineering 66:30. https://doi.org/10.1016/j.jobe.2023.105863
7. Brooks R (2025) Why today's humanoids won't learn dexterity. In: Rodney Brooks. https://rodneybrooks.com/why-todays-humanoids-wont-learn-dexterity/. Accessed 30 Sept 2025
8. Guidi G, Russo M, Angheleddu D (2014) 3D survey and virtual reconstruction of archeological sites. Digital Applications in Archaeology and Cultural Heritage 1:55–69. https://doi.org/10.1016/j.daach.2014.01.001
9. Liu J, Xu D, Hyyppä J, Liang Y (2021) A survey of applications with combined BIM and 3D laser scanning in the life cycle of buildings. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 14:5627–5637. https://doi.org/10.1109/JSTARS.2021.3068796
10. Perez-Perez Y, Golparvar-Fard M, El-Rayes K (2021) Segmentation of point clouds via joint semantic and geometric features for 3D modeling of the built environment. Automation in Construction 125:103584. https://doi.org/10.1016/j.autcon.2021.103584
11. Dörfler K, Ernst S, Piskorec L, et al (2014) Remote material deposition: Exploration of reciprocal digital and material computational capacities. In: What's the Matter: Materiality and Materialism at the Age of Computation. pp 361–377
12. Çapunaman ÖB, Dong W, Gürsoy B (2022) A vision-based sensing framework for adaptive robotic tooling of indefinite surfaces. Constr Robot 6:259–275. https://doi.org/10.1007/s41693-022-00081-4
13. Çapunaman ÖB, Iseman EK, Gürsoy B (2023) Material-in-the-loop fabrication: a vision-based adaptive clay 3D printing workflow on indeterminate sand surfaces. In: Turrin M, Andriotis C, Rafiee A (eds) Computer-Aided Architectural Design.

INTERCONNECTIONS: Co-computing Beyond Boundaries. Springer Nature Switzerland, Cham, pp 410–424
14. Breseghello L, Naboni R (2022) Adaptive toolpath: Enhanced design and process control for robotic 3DCP. In: Gerber D, Pantazis E, Bogosian B, et al (eds) Computer-Aided Architectural Design. Design Imperatives: The Future is Now. Springer, Singapore, pp 301–316
15. Breseghello L (2023) Shape-env - camera-enhanced robotic terrain-shaping for complex 3D concrete printing. In: Dokonal, W, Hirschberg, U and Wurzer, G (eds.), Digital Design Reconsidered - Proceedings of the 41st Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2023) - Volume 1, Graz, 20-22 September 2023, pp. 539–548. CUMINCAD
16. Chen X, Fang G, Liao W-H, Wang CCL (2022) Field-Based Toolpath Generation for 3D Printing Continuous Fibre Reinforced Thermoplastic Composites. Additive Manufacturing 49:102470. https://doi.org/10.1016/j.addma.2021.102470
17. Goidea A, Popescu M, Johansson AT, Andréen D (2024) Algorithmic modeling of functionally graded metamaterials in 3D printed building envelopes. ARIN 3:25. https://doi.org/10.1007/s44223-024-00068-x
18. Ramsgaard Thomsen M, Tamke M (2009) Narratives of making: thinking practice led research in architecture. In: Verbeke J, Jakimowicz A (eds) Communicating (by) Design. Sint-Lucas & Chalmers, Brussels, Belgium, pp 343–352
19. Redacted
20. Robert McNeel & Associates (2023) Rhinoceros
21. Mele TV, Casas G, Rust R, et al (2024) compas-dev/compas: COMPAS. https://doi.org/10.5281/zenodo.2594510
22. Fleischmann P, Casas G, Lyrenmann M (2020) compas-rrc/compas_rrc: COMPAS RRC. https://doi.org/10.5281/zenodo.4639418
23. Goidea A (2023) Transcalar design : biological principles in architecture through computational design and additive fabrication. PhD thesis, Lund University, Lund, Sweden

Bilaga 2: Abstract 1

Adaptive Volumetric Modeling for On-Site Robotic Fabrication of Hybrid Stone-Clay Structures

Abstract for future submission.

Material-driven design with local, low-impact materials requires designers to articulate intent while navigating uncertainties in material behaviour, construction sequencing, and site conditions. In conventional practice, such intent is communicated through drawings, models, prototypes, and verbal instruction, where priorities and tolerances remain largely implicit and open to interpretation. In digital fabrication (DFAB) workflows, however, the translation of design into machine instructions requires explicit specification, leaving little room for on-site improvisation. This raises a central modelling question: how can architectural intent be represented computationally in a way that remains adaptable, negotiable, and responsive to on-site conditions rather than fully predetermined?

We investigate this question through an on-site robotic fabrication setup based on an adaptive, earth-bonded rubble masonry system combining natural stone and clay. In the experiments, irregular stones are manually stacked, while infill, support, and levelling are provided through robotic clay extrusion. This hybrid process reimagines traditional stone foundations, historically used to negotiate uneven bedrock and establish a level interface for timber structures.

This system requires a digital representation of the physical construction environment, commonly referred to as a digital twin, but here understood as a partial and evolving model rather than a complete mirror of the site. We employ sensors to map the environment and its changes, including the fabrication taking place. This forms the basis for a virtual environment where we have designed a responsive planning framework that evaluates state and design intent to formulate print paths for the 3D printing process.

The possible operations for the machine, in this context, are clay extrusion for filling voids and shaping the structure. The latter could be described as the gradient between the current state and an interpretation of the design intent. While the former – extrusions in known locations but with uncertain volume – are discrete depositions where the semi-viscous clay assumes its shape from the surrounding geometry. The extrusion volume would need to be calculated beforehand or determined based on detected material accumulation.

Design intent and environmental state are represented through a set of coupled volumetric models that act as a shared substrate for sensing, evaluation, and path generation. Within this representation, regions of space are annotated with data relevant to the fabrication process. One volumetric layer expresses spatial suitability for material deposition as a graded field, ranging from 0, where deposition is discouraged, to 1, where extrusion is preferred. Other aspects of design intent (e.g. preferred growth directions, local continuity, patterning, and constructive logic) are not encoded explicitly as geometry but are instead embedded in the behavioural rules and evaluation criteria of the path-finding framework that operates on this volumetric substrate.

Obstacle information for the tool and robot arm is represented in a separate volumetric layer – optionally at a different resolution – where binary values distinguish free space from collision objects. This data is derived from 3D scanning, with recent and frequently detected points weighted more strongly. The weighting strategy allows limited contact with freshly extruded clay while strictly avoiding dried material and fixed obstacles.

Additional sensor data is used to give location-based information. Together, the data stored in the model enables print path generation through a multi-agent framework. Agents either traverse registered geometry to record their paths, or interconnect to simulate differential growth, directly generating toolpaths. Their programmed behaviours include rules such as step length,

and a set of preferences in terms of direction, as well as constraints based on gravity and geometry (collision avoidance). In this context, the agents function as local interpreters of distributed design intent, translating graded spatial preferences and behavioural rules into situated fabrication actions under continuously changing material and environmental conditions.

The model is updated during fabrication and paths are recalculated based on new data. The design is developed through changes to parameters and behaviours, and potentially through manual changes to the design intent, i.e. changing voxel values.

The presented work explores a modelling approach in which design intent and environmental state are combined within an updating volumetric representation that informs robotic fabrication on site. By encoding intent as scalar fields rather than fixed geometry, and by generating toolpaths through adaptive, agent-based processes, the model supports continuous recalibration of fabrication decisions as construction unfolds. This shifts the role of design modelling from defining precise outcomes to framing conditions for action, allowing digital fabrication to accommodate uncertainty while remaining grounded in architectural intent and material logic.