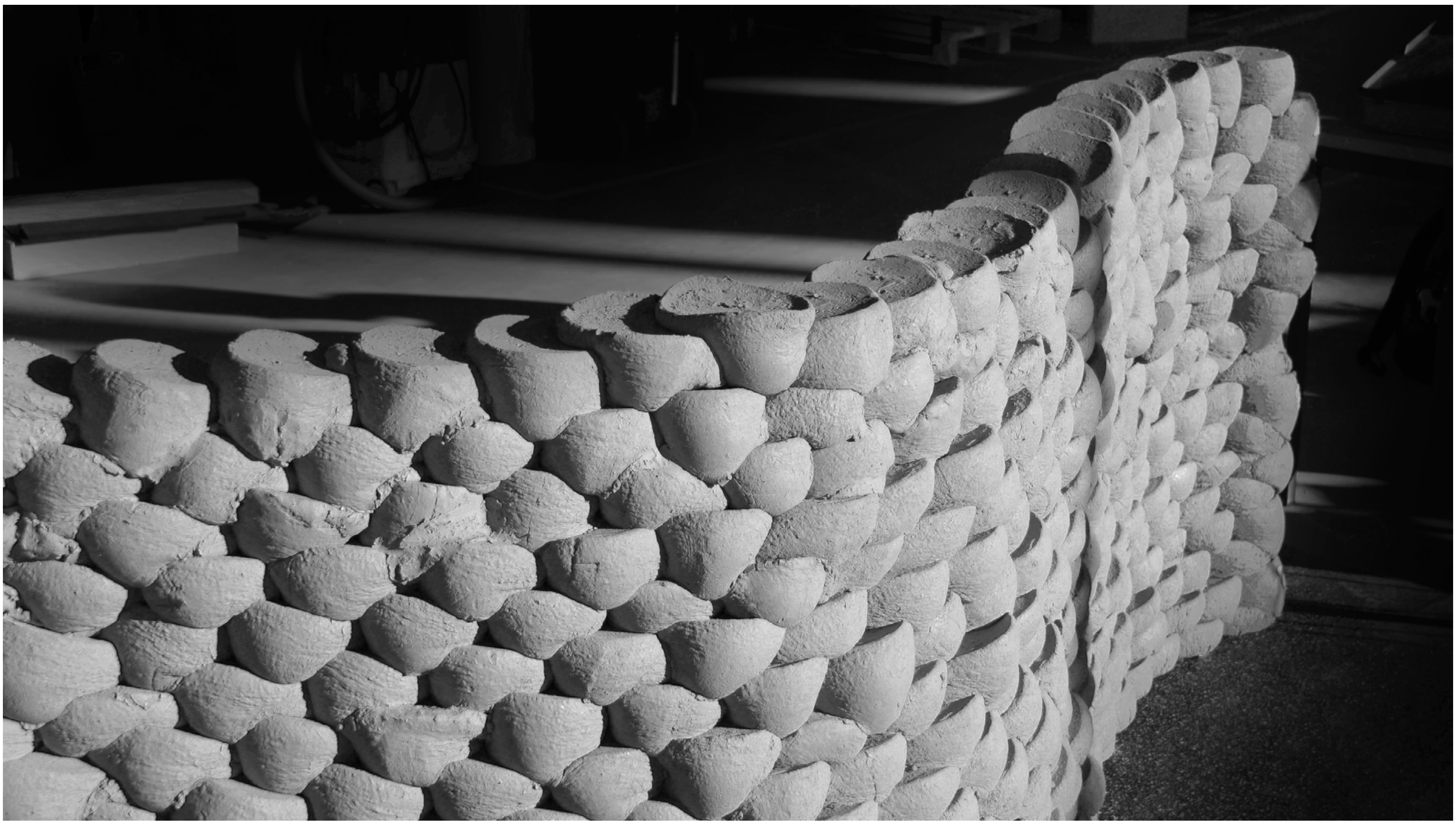
ADAPTIVE CLAY FORMATIONS

Edurne Morales Zúñiga & Anton Tetov Johansson

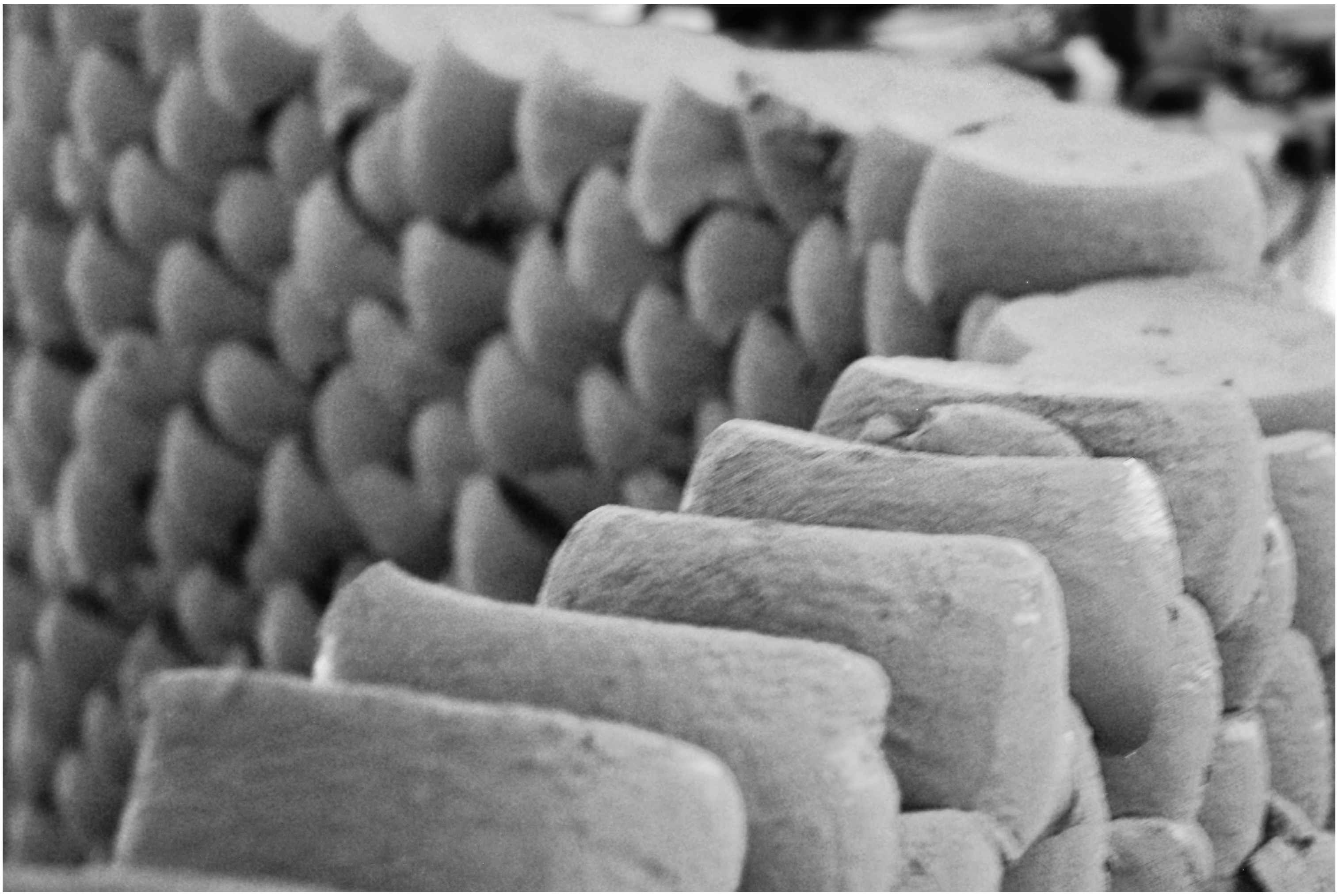


Abstract

Rapid Clay Formations (RCF) is an ongoing research project investigating robotic aggregation of soft clay elements. This thesis presents our research into RCF construction on an architectural scale.

It outlines our development of a fabrication process suitable for the construction of tall and slender structures made out of clay. This fabrication process is evaluated through a series of prototypes and preparations for a three week building workshop.

In our development we have evaluated and tested material behaviour and optimization, geometric sensing, robot trajectory planning and mobile robotic localization. These explorations are combined with design studies for large monolithic clay structures aimed at a rapid construction on site.



original thesis and project titled *Adaptive Clay Formations* were written and undertaken by *Edurne Morales Zúñiga* and *Anton Tetov Johansson* as part of the programme *MAS ETH in Architecture & Digital Fabrication*, jointly lead by *Digital Building Technologies* and *Gramazio Kohler Research* at *ITA*, *D-Arch*, *ETH Zürich*. it was tutored at ETH by *David Jenny*, *Coralie Ming*, *Nicolas Feihl* & *Gonzalo Casas*, all at Gramazio Kohler Research.

this thesis is now presented as Anton's *Degree Project in Architecture (AAHM01)* at *the school of Architecture*, *LTH* in *2021*. Thesis mentor at LTH was *Ana Goidea* and examiner *David Andréen*, both at the school of Architecture

Institute of Technology in Architecture
Faculty of Architecture / ETH Zurich

Contents

1 Introduction

Rapid Clay Formations (RCF) is the name given to a method of robotic clay aggregation that has been explored in the *Master of Advanced Studies in Digital Fabrication ETH* (MAS DFAB) program. MAS DFAB is a one-year full time educational program that teaches advanced methods and technologies of digital design and fabrication and their implementation in architecture and construction (Digital Building Technologies and Gramazio Kohler Research 2019).

This project was a continuation of a ten week design and fabrication project undertaken by the MAS DFAB class of 2019/2020. The previous project's focus was on scaling up an already existing process for creating aggregations of clay cylinders using the *In-Situ Fabricator* (IF), a six axis robotic arm mounted on a platform with hydraulic tracks. The aim was to create a design and fabrication process for a full scale pavilion; a 7.7 m by 11 m undulating thick wall.

The pavilion was set to be built in the summer of 2020 in Rio de Janeiro, which was not possible due to the COVID19 pandemic. A positive outcome of this setback was further time to reflect on our experiences from the MAS DFAB 19/20 RCF project and to improve the large-scale construction method by refinements to the fabrication process and design.

We set out to develop the material system to avoid clay cracking—caused by uneven shrinkage—and further enhance the fabrication process.

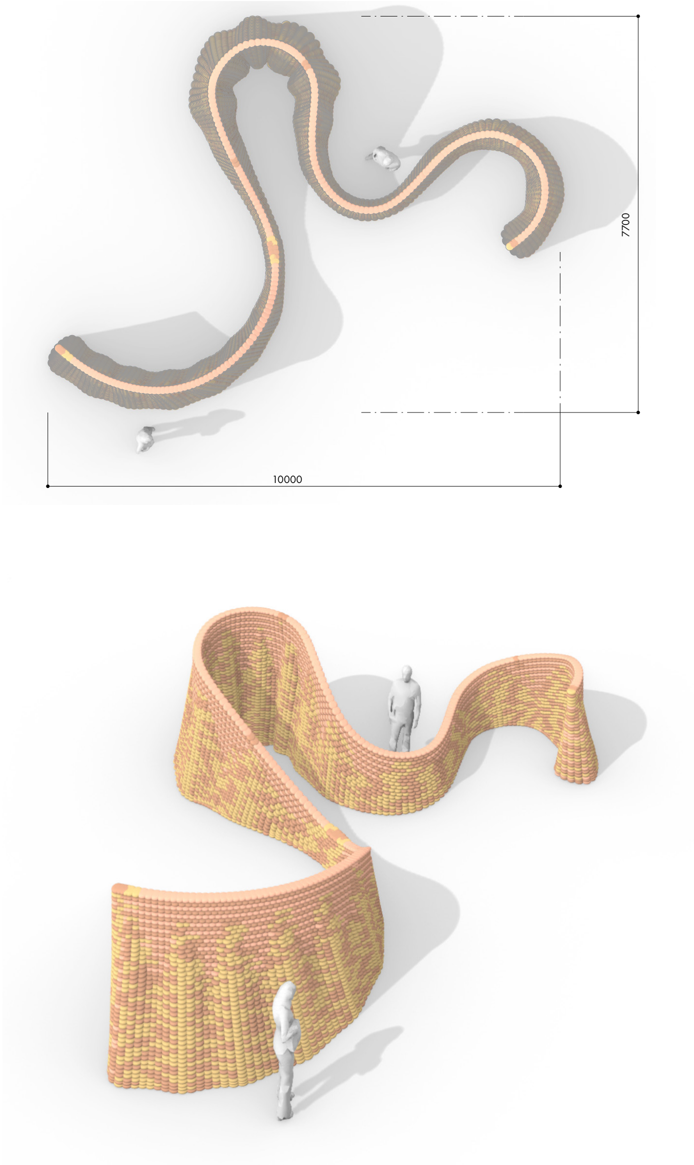


Fig. 1-2 *Pavilion design from MAS DFAB 19/20 RCF*

In particular we wanted to address the fabrication process' lack of adaptability to changes in the built structure. For robotic fabrication using rigid materials such as wood or fired bricks you can assume that the placed element will stay in place. Construction with malleable materials such as clay requires strategies to account for the material's morphability.

We thought that this could be addressed either during the initial design phase or later during the fabrication phase. In the initial design phase by predicting material behavior and anticipating large geometrical tolerances. We considered predicting material behavior using physical simulations, but decided to focus on fabrication centric strategies.

Our hypothesis was that a non-linear fabrication process informed by geometrical or force based sensors would considerably improve the construction method. In our project we explored mapping of the built structure using either 1D distance measurements or 3D-scanning, our a combination of both. We also tested measuring exerted linear force during pressing as an input.

Large-scale construction on a non permanent site with a robot requires relocalization of the robot, since reach is limited and larger installations are not possible. This makes segmentation strategies and methods for joining segments necessary. It also requires precise localization of the *robot coordinate system(RCS)* in relation to the *project coordinate system* (here called *world coordinate system*, *WCS*, by convention).

In this project the hydraulic caterpillar tracks below the robot base was not driven concurrently with movement of the robotic arm. While concurrent movement of arm and base would allow for longer uninterrupted fabrication runs, the platform was deemed too unstable without support from its extendable stabilizing legs.

In the project we also implemented path planning for the robot arm's trajectories to avoid collision with the built structure and potential obstacles, as well as to reduce fabrication time. We will also developed the material mix further and explored RCF typologies with the intention of producing taller, stronger and lighter structures.

All these additions to the process were aimed towards building tall and slender structures.

The project's findings together with the findings of the MAS DFAB 19/20 RCF project was later applied in the design and construction of a large scale structure in September 2020.

2 State-of-the-art

Digital fabrication using clay and earth

Clay and earthen construction has been practiced for thousands of years (Schroeder 2016, 2). The material has sparked interest as a construction material for digital fabrication due to its low environmental impact, as it can often be locally sourced and requires no additives aside from water and potentially aggregates. Currently, large scale clay 3D-printing of walls might be the most common use of clay in digital fabrication.

An example of that is Emerging Objects' project *Mud Frontier*, which addresses the challenge of relocatable robotics for construction through the use of a mobile lightweight 3D printing setup. The materials (soil, chopped straw and water) were sourced from the work site. The result was a double layered undulating/interlocking structure based on traditional indigenous techniques (San Fratello & Rael 2020).

An alternative method to clay extrusion is clay aggregations, an example of large scale robotic clay aggregation is Gramazio Kohler Research's (GKR) *Remote Material Deposition* installation from 2014. In the installation a process of robotic clay shooting is showcased creating a complex large-scale structure that goes beyond the robot's constrained workspace. The shooting targets were based on curves adjusted in height based on 3D scans of the emerging structure (Dörfler et al. 2014).

One of the main differences between clay aggregation and clay extrusion is the adhesion. In 3D-printing the adhesion comes from the viscosity of the material, while in clay aggregation the impact or force binds the material together. This changes design particularities and possibilities, drying behavior and construction time, among other characteristics.

Digital fabrication using a material system that involves clay requires studying material behavior over time. The impact of

Fig. 3 *Portable SCARA robot designed for in-situ printing. ©2019 Emerging Objects*

Fig. 4 *Mud Frontiers II. ©2019 Emerging Objects*

Fig. 5 *Ballistic trajectories of light projectiles through bulb exposure, Remote Material Deposition Gramazio Kohler Research, ETH Zurich, 2014 © Gramazio Kohler Research, ETH Zurich*

Fig. 6 *Reprinted by permission from Springer Nature:*
Hold Up: Machine Delay in Architectural Design ***by Zach Cohen*** *©2019.*

time and delays in fabrication is explored through the fabrication method *Machine Delay Fabrication*. Concrete is extruded from a nozzle in a rectilinear pattern, variation and characteristics are controlled by the delays between fabrication steps.

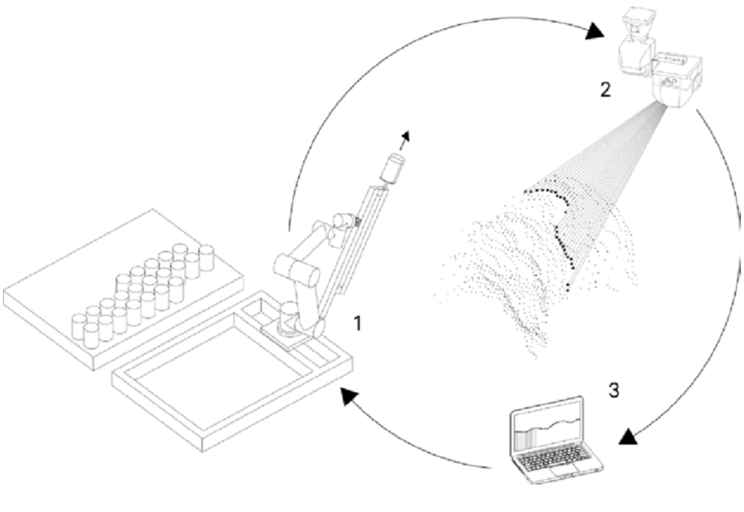
While concrete cures quickly, clay and earth dries slowly and unevenly. This needs to be accounted for during construction. The delays might be days not seconds, in order to reach desired characteristics (Cohen 2019).

Mobile robotics and sensory feedback for robotic fabrication

Remote Material Depositions, the installation mentioned previously, is an example of a sensory feedback used with the unpredictability of the material in mind. This feedback system was based on three main features: digitally planned fabrication, mapping of the material's behavior and adaptation of the virtual model based on sensory data.

The mapping of the material behavior was done by monitoring the aggregation process layer by layer with the use of a 3D-scanner to create a point cloud

Fig. 7 *Diagram of the design-to-fabrication feedback loop, Remote Material Deposition, Gramazio Kohler Research, ETH Zurich, 2014 © Gramazio Kohler Research, ETH Zurich*



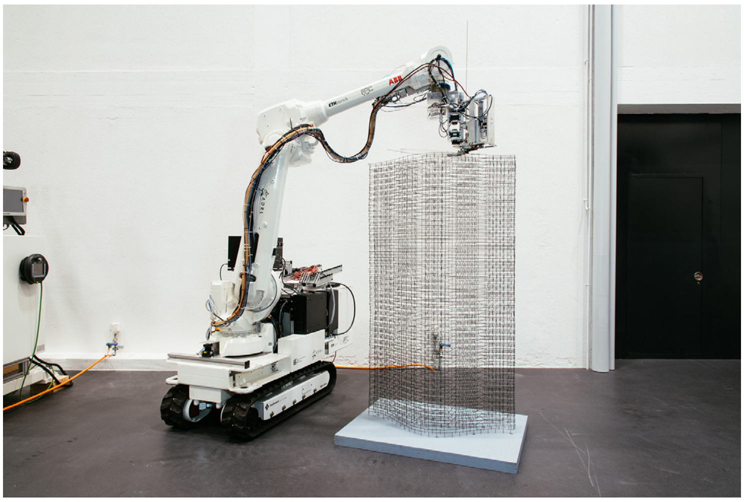


Fig. 8 *IF building a mesh prototype, Mesh Mould Metal, Gramazio Kohler Research, ETH Zurich, NCCR Digital Fabrication, 2015-2018 © Gramazio Kohler Research, ETH Zurich*

containing information of the current height and width of the structure (Dörfler et al. 2014).

As mentioned, in this project we used the *In-Situ Fabricator (IF)*. This robot was developed to explore robotic fabrication on construction sites by a collaboration between GKR and Agile & Dexterous Robotics Lab which was part of the Institute of Robotics and Intelligent Systems (Giftthaler et al. 2017; Agile & Dexterous Robotics Lab 2018).

It was built to tackle the challenges of on site robotic construction, especially when it comes to large building structures. It was designed to be able to operate autonomously with an on-board controller and power supply (Buchli et al. 2018).

Over the last few years the IF has been deployed in several projects. One example is the *Mesh Mould* project, which investigates combining reinforcement and formwork for concrete casting showcased at the DFAB House (Dörfler et al. 2019).

This project utilized two on-board sensing systems, one to measure the current state of the built structure and other for robot localization on the construction site. The first sensing system consisted of a stereo camera pair mounted on the robot's tool. These cameras were measuring the contour of the structure as it was built to adapt to accumulated deviations in the real world structure compared to the virtual model.

The feedback processes of both *Remote Material Deposition* and the *Mesh Mould* project inspired our project.

Localization strategies for mobile robotic construction

A challenge in mobile robotics is localization, nearly all robotic implementations depend on a way to find the robot's position relative to its environment. The IF has been used with multiple localization strategies, one of these methods can be exemplified by the previously mentioned *Mesh Mould* project.

In that case the localization system consisted of a camera mounted on the end effector of the IF, used to detect the position of reference markers mounted on a wall. (Buchli et al. 2018)

The relocalization method used works by matching known RCS positions to positions in a WCS created with the use of a total station. From this, a transformation can be calculated and used for conversions between the coordinate systems (Ercan et al. 2019). This method was applied in the construction of the *Rock Print* pavilion in Winterthur (Aejmelaeus-Lindström et al. 2020)

This method was selected for the project instead of the method used in the *Mesh Mould* project. The method proposed by Ercan et al require fixed reference points to create a WCS, but can then be used to relocalize robot and total station with each other as references. Additionally the range of a total station measuring prisms are far superior to that of a camera measuring printed tags.

Path planning for robotic fabrication

Robotic tools and frameworks can be challenging to use for architects and designers outside the field of robotics. However, there are many projects working towards making robotic control and planning more accessible. One of those are compas_fab, a Python package that facilitates communication with robot controllers using Python (Rust et al. 2018).

Complete setups of robot control backends and planning frameworks can be implemented using containerization, e.g. with Docker, and integrated into 3D modeling software for an integrated workflow (Gandia et al. 2019).

Rapid Clay Formations

The *Remote Material Deposition* installation mentioned previously was GKR's first clay project. The Rapid Clay Formation process was built from the experiences of *Remote Material Deposition* with the aim to create a more precise process, with regards to the forces exerted and positioning. This started as a four week project conducted by the MAS DFAB 18/19 class exploring design and fabrication using the soft bond between clay elements. This was achieved

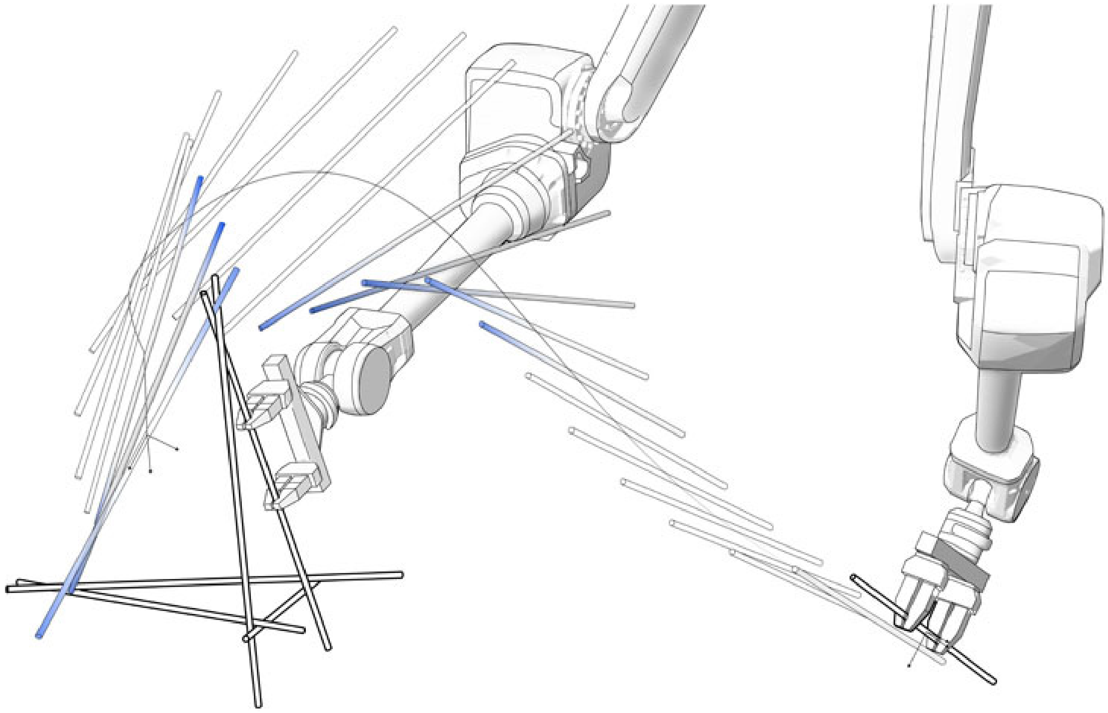


Fig. 9 *Diagram of a cooperative robotic assembly process,*
Robotic Fabrication Simulation for Spatial Structures, *Gramazio Kohler Research, ETH Zurich, 2015-2019*
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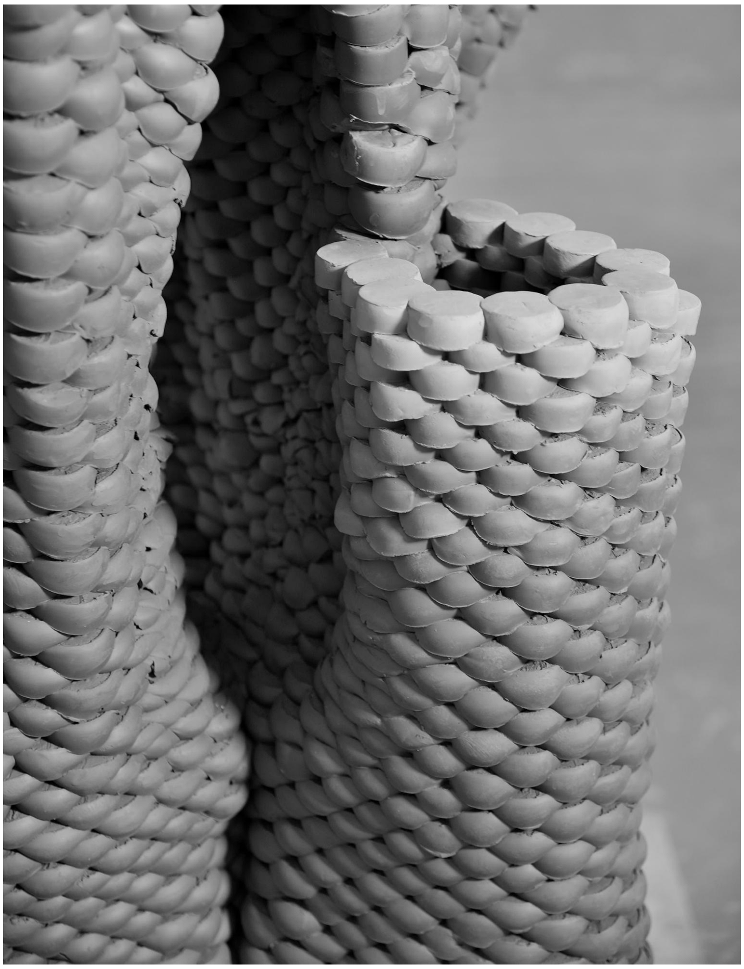
through pressing of 10-20 mm wide and tall clay cylinders (GKR 2018). This was further explored by Nicolas Feihl and Eleni Skevaki in *Computational Coral Clay Cities* (CCCC), a project based on the same procedure but with the scale of a coral reef in mind (MAS DFAB 2019).

Fig. 10 Computational Coral Clay City,
MAS thesis by Eleni Skevaki and Nicolas Feihl,
MAS ETH in Architecture and Digital Fabrication,
ETH Zurich, 2018-2019 (c) MAS ETH DFAB, ETH Zurich



Research continued in spring 2020 by the MAS DFAB 19/20 students with the goal of scaling up the process to an architectural scale. The process was adapted for clay cylinders measuring 90 mm in diameter and 150 mm in height placed. These would be placed by the IF in order to construct a 7.7 meters by 11 meters outdoors pavilion in Rio de Janeiro, Brazil.

To this end a design and fabrication process were developed, as well as robotic tooling and material system.

Since construction of such a large structure using off the shelf ceramic clay would be too costly, a material system involving raw clay was deemed necessary. Material research was conducted into creating a mix using raw clay from the industry partner Brauchli Ziegelei AG, a brick and tile manufacturer.

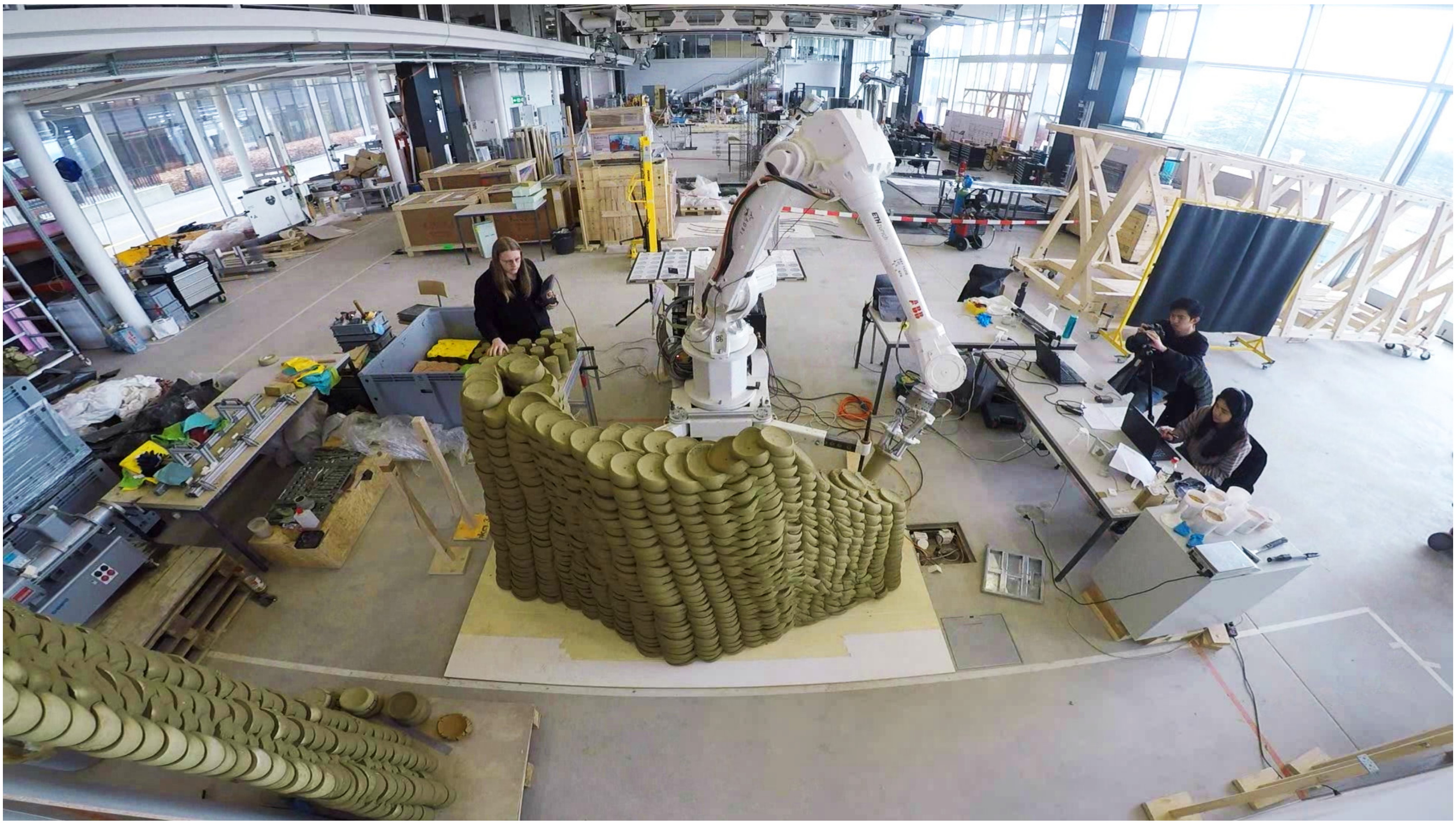


Fig. 11 *Final prototype of the 19/20 MAS DFAB RCF project*

Different bond typologies, or cylinder distributions, were explored at both small and large scale during this stage. Their characteristics mainly converged into two types of bonds: running, based on a shift of half a cylinder at the upcoming layer, and stacked, where cylinders are placed on top of each other.

To achieve structural integrity different design strategies were used. The distance between cylinders and their level of compression during placing affects the local structural integrity, while undulations and thickness of the overall design affects the integrity of the whole structure.

Fabrication segmentation was a key issue, since the construction robot is relocated along the structure. The order and separation of structure segments were developed to create a continuous structure while also accounting for material drying. In order to achieve this the cylinders were inclined following the direction of the segmentation split which tapered toward its neighbor.

Fig. 12 *Geometrical strategy to achieve stability developed in MAS DFAB 19/20 RCF*

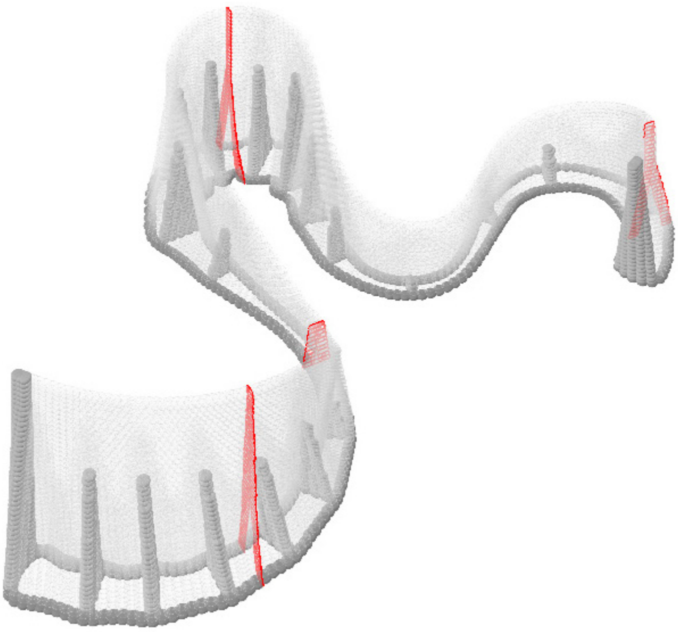


Fig. 13 *Stacking bond*

Fig. 14 *Running bond*

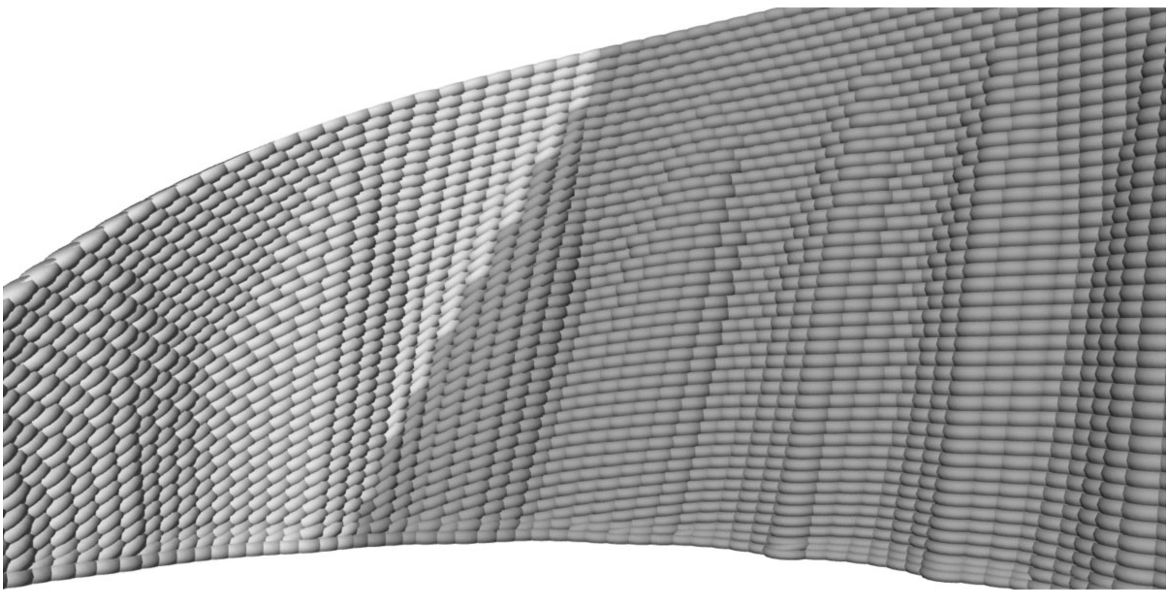


Fig. 15 *Segmentation strategy developed in MAS DFAB 19/20 RCF*

3 Research Questions

The main goal of this research was to develop an adaptive robotic fabrication process for clay to build large scale single layered tall structures. The questions that guided our research was the following:

» How can a robotic fabrication process adapt to changes in a structure built with a malleable material like clay?

» How can we adapt robotic movement to a construction site's layout and potential obstacles while also avoiding collisions with the structure being built?

» Can we create thin but tall structures with clay mix improvements, bond typologies and design strategies?

Our research can be divided into four areas:

Feedback	» Distance measurement and 3D-scanning of the built structure to update the virtual model and robot trajectories. » Possible integration of one or more load cells to measure force used in compression of cylinders.
Fabrication	» Relocalization of robot and sectioning of the structure » Implementation of a path planning algorithm for the robotic arm trajectories to avoid collisions and reduce fabrication time.
Material	» Clay mix improvement to reduce shrinkage, deformation and cracking, improve bonding, compressive strength and drying behavior.
Design	» Locally for good soft bonds between cylinders and globally to increase structural integrity. » Segmentation strategies for bonding, collision avoidance, continuity and shrinkage. » Test of strategies for stability with single layered structures.

4 Method

We investigated these research questions through applied testing of an integrated fabrication process though set milestones in the form of prototypes, to test the different stages of the development based on adaptability, material, geometry and relocalization.

1st work package *Material development*	» Test clay mixes for drying behavior and compressive strength » Improvements of robotic fabrication process
2nd work package *Process improvements*	» Measurements of structure during fabrication by robot » Robot relocalization and design segmentation
3rd work package *Full scale demonstrator*	» Thin undulating wall segment » Design and preparation for large scale mock up

The prototypes were building up to a large scale mockup that was constructed at a building workshop in September 2020.

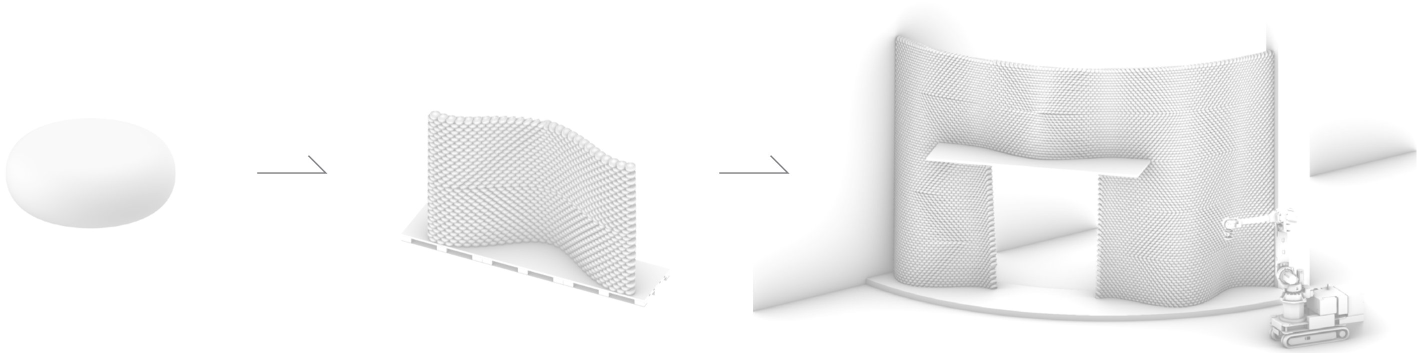


Fig. 16 *Material development, Full scale demonstrator, Large scale mock-up*

5 Fabrication Process

Material system

Clay, water and aggregates was mixed using a small concrete mixer. The clay mix was then compacted into cylinders using a NVA-04S Shimpo pugmill.

After the compaction and extrusion, the clay was cut into 150 mm long cylinders with the use of a custom-made wire cutter.

Picking and Placing

We used the IF for experiments and construction. It is a six-axis industrial robotic arm mounted on a mobile platform, with a custom-designed end-effector.

This end-effector was used to pick up clay cylinders with two spatially oriented needles that activate and pierce the cylinders while the end-effector is held above them. After proceeding to the placing position, the needles were withdrawn from the cylinder and the cylinder is subsequently compressed to its final state through a pressing plate controlled by the robot arm.

Spatial setup

Our production area consisted of a clay extrusion and cutting zone, a picking station, a construction zone and robot control station.

Software setup

Design and fabrication data was created using Grasshopper—a plugin to the 3D modeler Rhinoceros—together with a Python package developed for the project.

Communication with the robot controller was achieved with compas_fab, an open source Python package for planning and execution of robotic fabrication processes (Rust et al. 2018). It was used together with ROS to connect the client to the controller using compas_rrc.

compas_rrc is a Python/RAPID package that provides ABB specific python classes and functions on the client side, and RAPID programs on the server side to communicate with ROS. compas_rrc was developed by Philippe Fleischman and

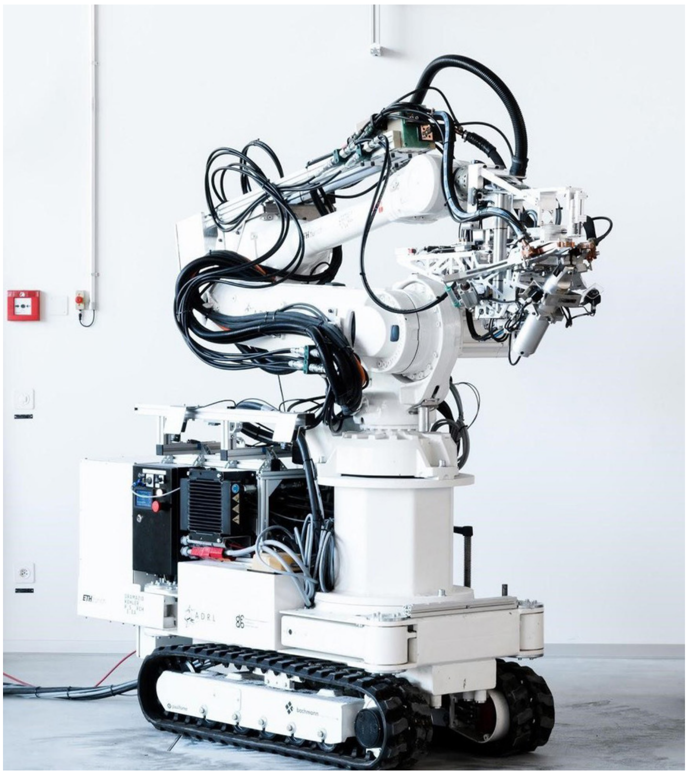


Fig. 17 *The In-Situ Fabricator equipped for Mesh Mould Metal, Gramazio Kohler Research, ETH Zurich, 2015–2018 © Gramazio Kohler Research, ETH Zurich*

Gonzalo Casas at the The National Centre of Competence in Research (NCCR) Digital Fabrication (Robotic Fabrication Lab and Gramazio Kohler Research teams).

ROS, the Robot Operating System, is an open source set of libraries and tools for robotic applications (Quigley et al. 2009).

This setup allowed for procedures and programs to be programmed in Python and executable from Grasshopper, with access to both tools from ROS as well as standard ABB controller communication.

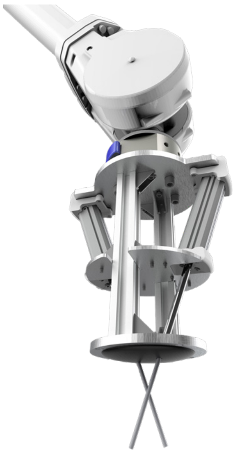


Fig. 18 *Pick and place tool*

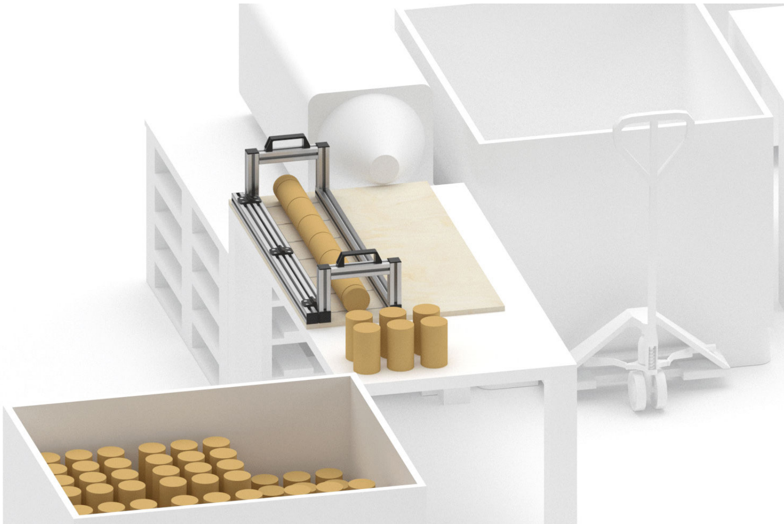


Fig. 19 *Extrusion and cutting station*

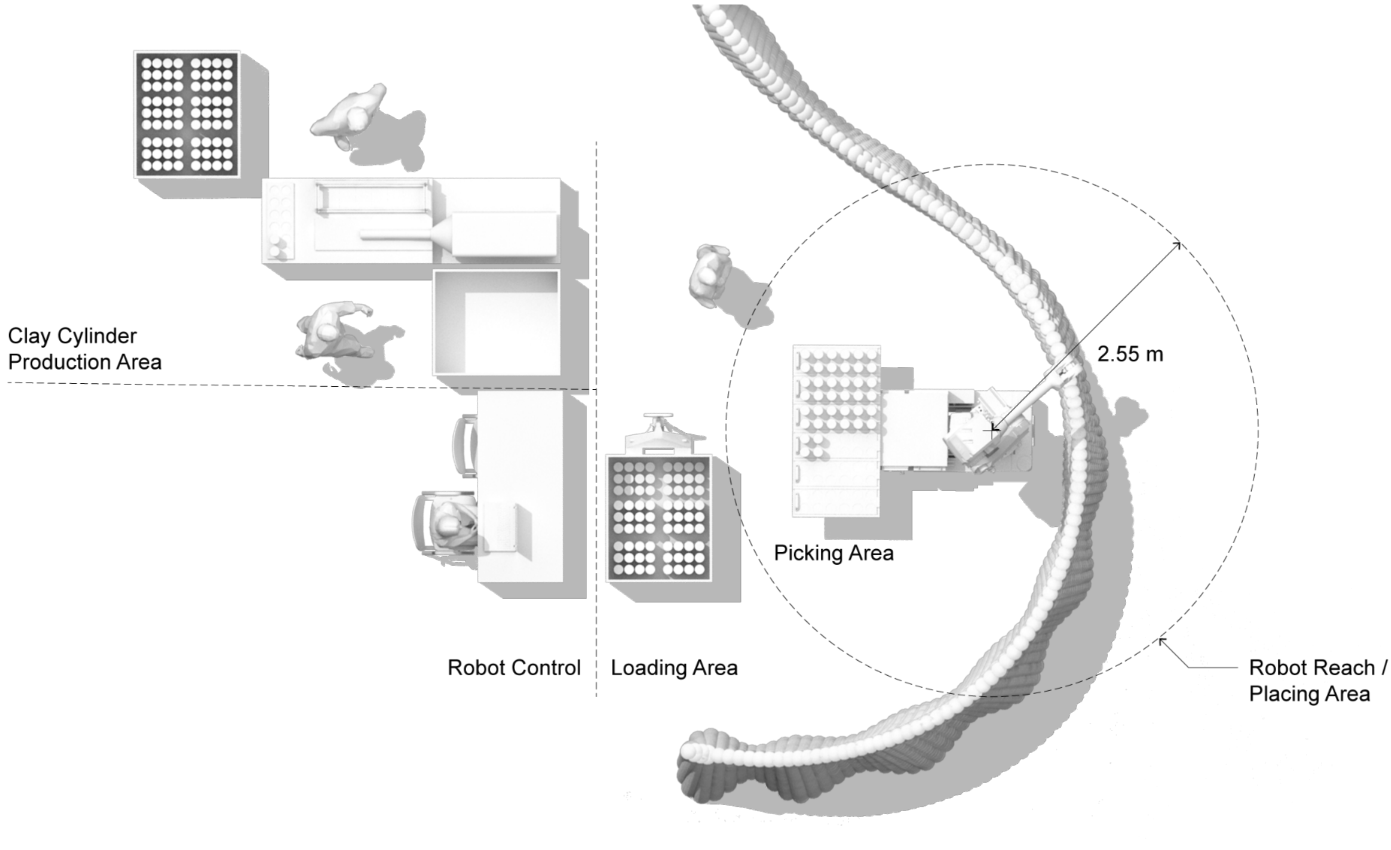


Fig. 20 *Spatial setup*

6 Experiments

Material testing

Material tests have been conducted together with the earth focused construction company Lehmag AG. Our goal was to further optimize the material mix developed in the MAS DFAB 19/20 RCF project, especially with regards to drying behavior.

Based on the prototypes built previously we realized that the placed cylinders deform differently based on neighboring cylinders. This creates variations in the levels of adhesion between clusters of cylinders. During drying the cylinders shrink together in these clusters, and cracks appear between them. Our hypothesis was that more even adhesion and drying would reduce these cracks.

The clay mix from the quarry in Berg was composed of: lime (18%), quartz (14%), clay (35%), silt (53%) and sand (11%). To this an additional 19% of 0-2 mm sand was added as the addition of aggregates were found to lead to less deformation during drying and shorter drying time. This was the mix used in the final prototype of the MAS DFAB 19/20 RCF project.

The cylinders from this mix showed a shrinkage of 11% on the 7th day and 13.6% on the 14th day in a compressed state.

Fig. 21 *Cracks developed during drying due to uneven shrinkage.*

Fig. 22-23 *Landquart and Berg clay tests (respectively)—example of fragmentation and plastic behavior*

With this in mind our intention was to create a mix that can offer sufficient compressive strength and plasticity while minimizing the amount of shrinkage and cracks.

The initial experiments were based on additions of aggregates to the original clay mix. To understand the characteristics and behavior of each material and its reaction to the clay and the process.

We tested different amounts of clay mix, 0-2 mm diameter sand, 2-4 mm diameter stone and water. Some of the mixes were not tested as their characteristics made them unsuitable for the fabrication method being used.

Small prototypes were built with each mix using our robotic fabrication process to build and simulate the behavior of a structure. These prototypes were used to measure the shrinkage, cracking and adhesion.

4 discrete cylinders were compressed with the same percentages as in the prototype (70%, 63%, 56% and 50%) and 6 are kept as extruded to measure shrinkage and compressive strength. The cylinders were measured after extrusion, and then after 7 and 14 days. Further measurements did not show additional shrinkage.

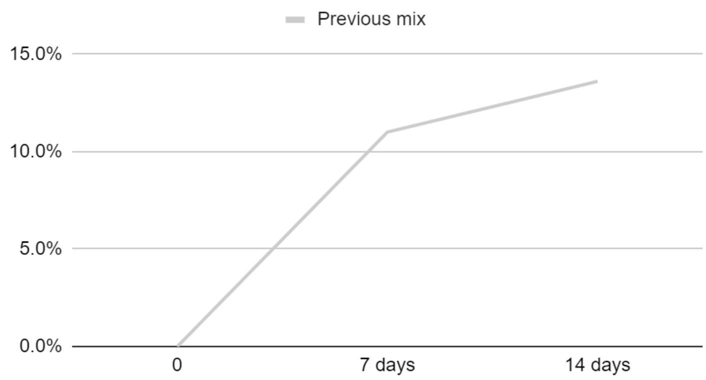


Fig. 25 *Shrinkage of 50 % compressed cylinders*

Fig. 24 *Material composition of the raw clay from Berg*

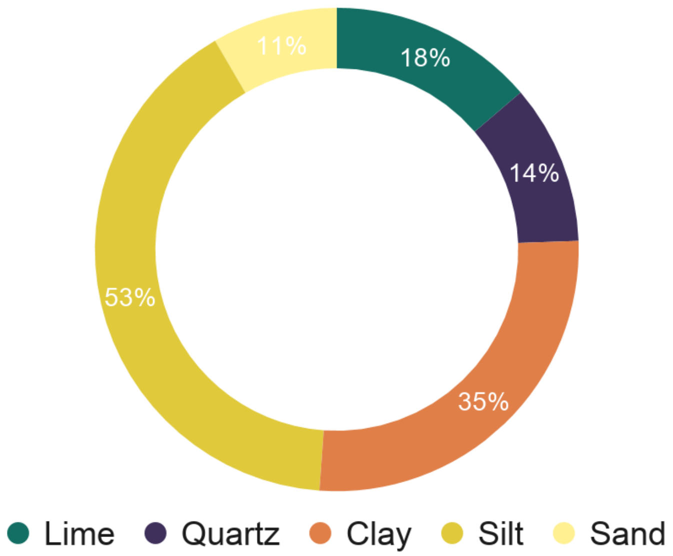
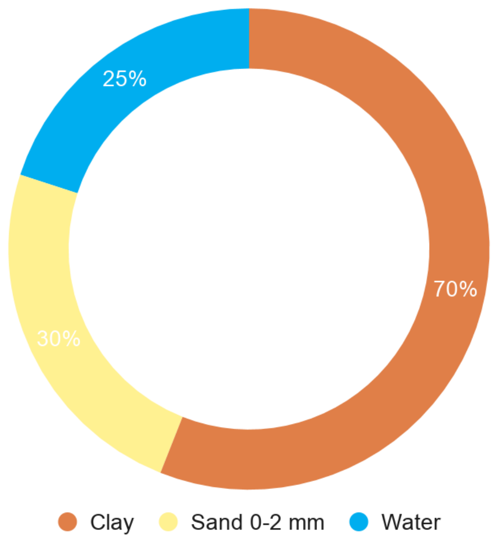
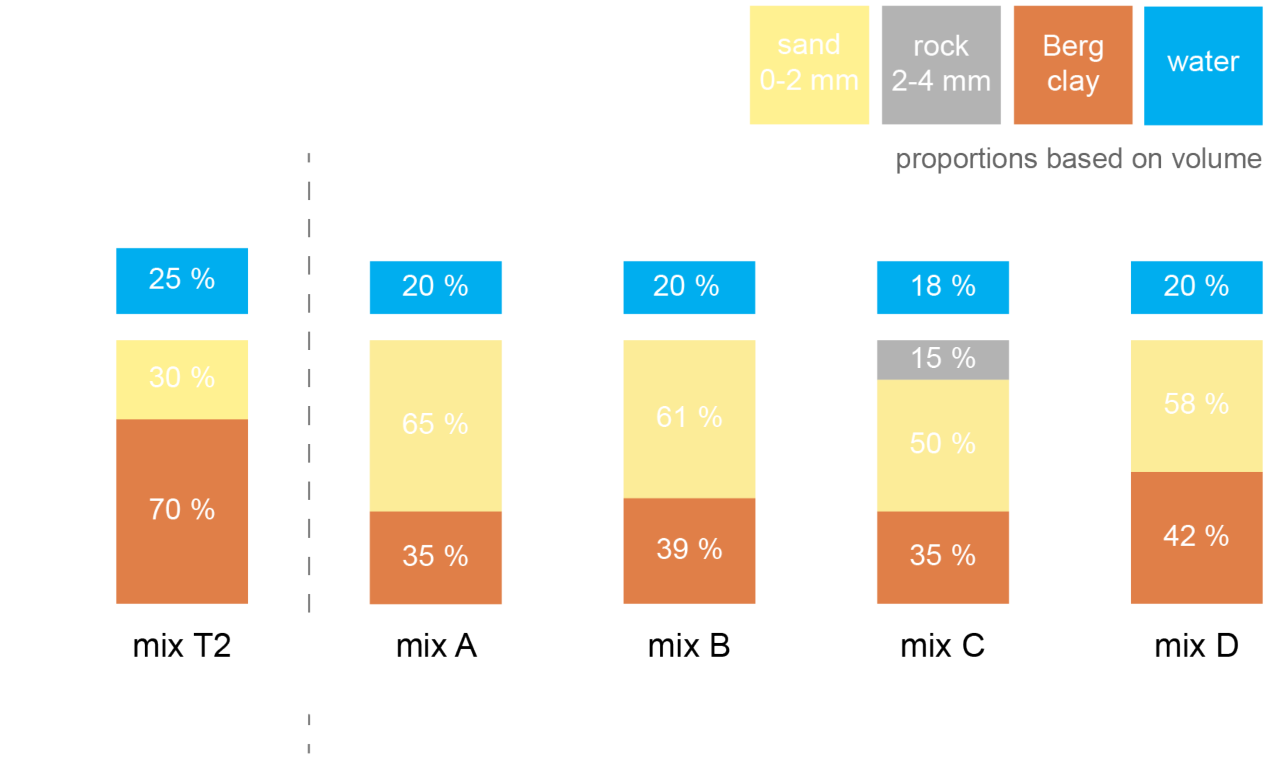


Fig. 26 *Mix developed in MAS DFAB 19/20 RCF project*





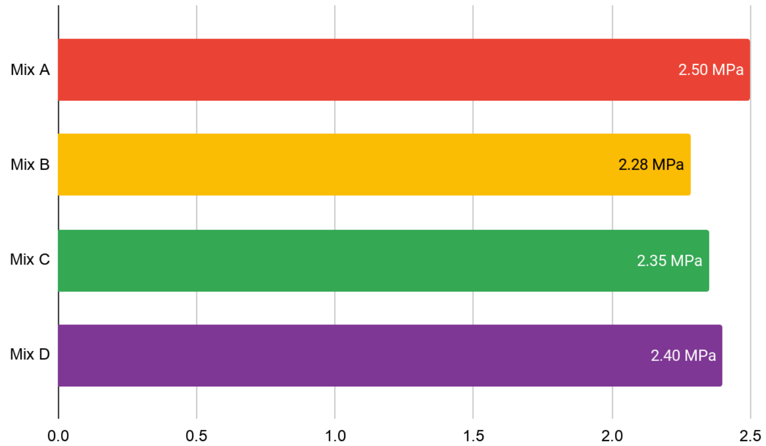
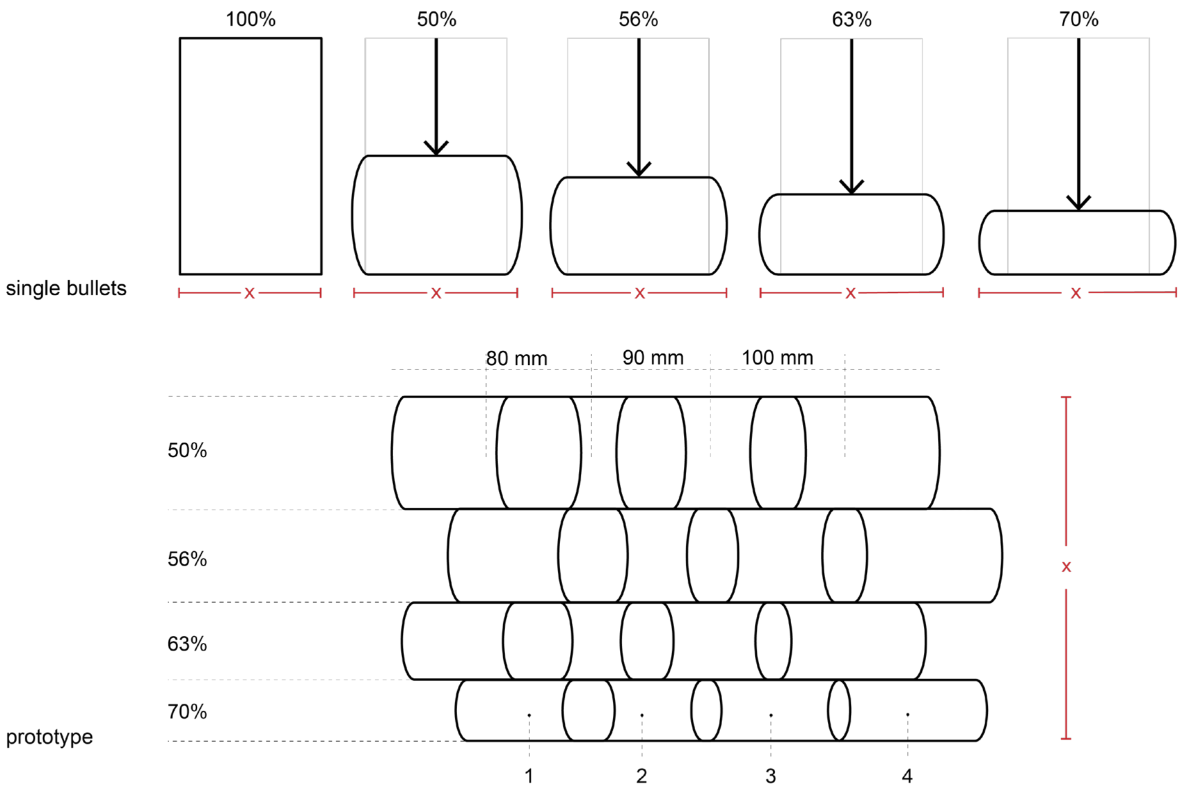


Fig. 27 (top) *Clay mixes*
Fig. 28 (left) *Compressive strength*
Fig. 29 (bottom) *Test samples*



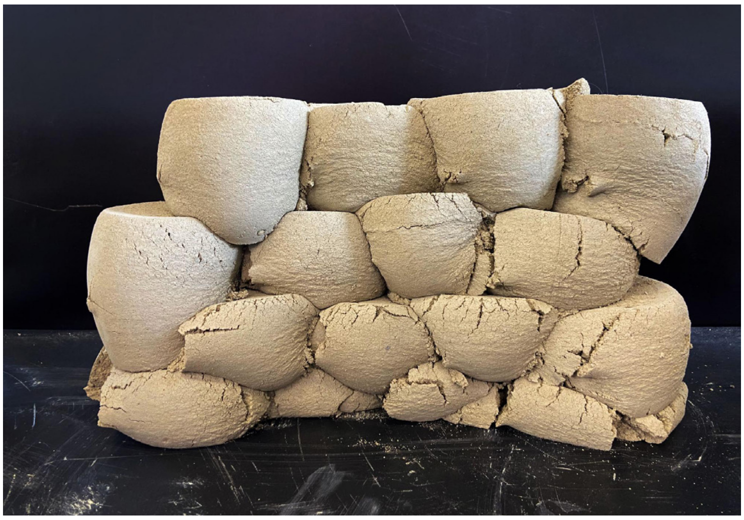


Fig. 30 *Mix A*

Fig. 31 *Mix B*

Fig. 32 *Mix C*

Fig. 33 *Mix D*

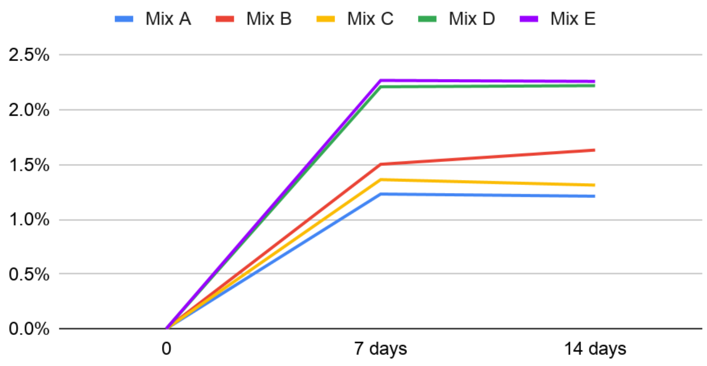


Fig. 34 *Vertical shrinkage of uncompressed cylinders*

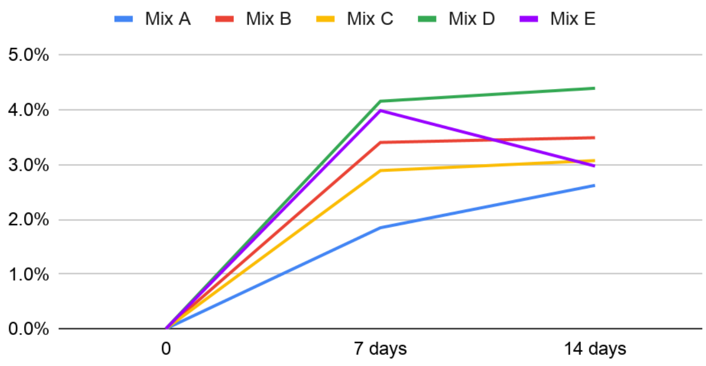


Fig. 35 *Vertical shrinkage of prototypes*

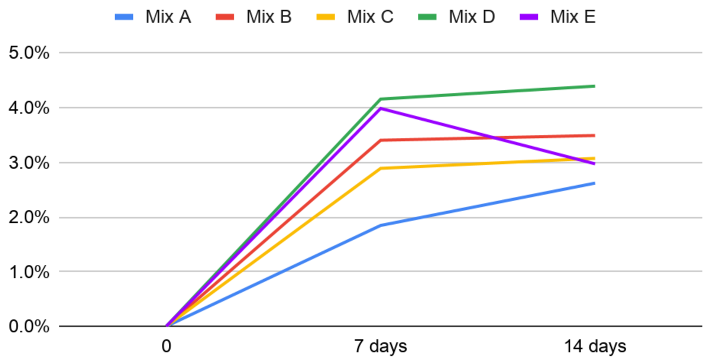


Fig. 36 *Shrinkage of 50 % compressed cylinders*

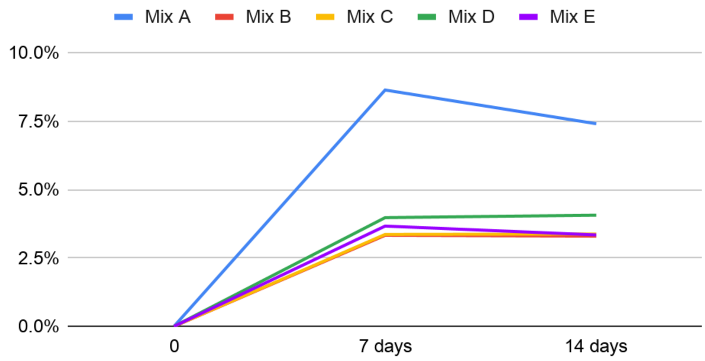


Fig. 37 *Shrinkage of 56 % compressed cylinders*

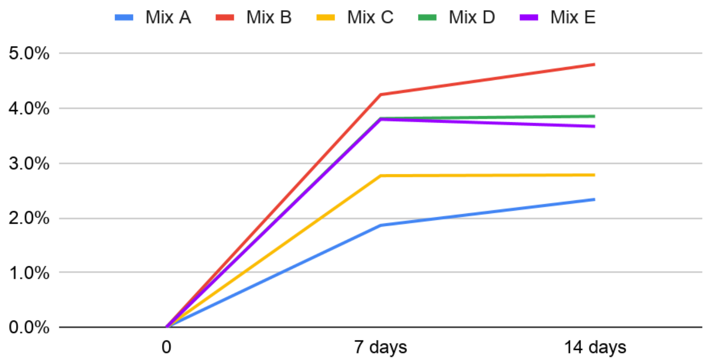


Fig. 38 *Shrinkage of 63 % compressed cylinders*

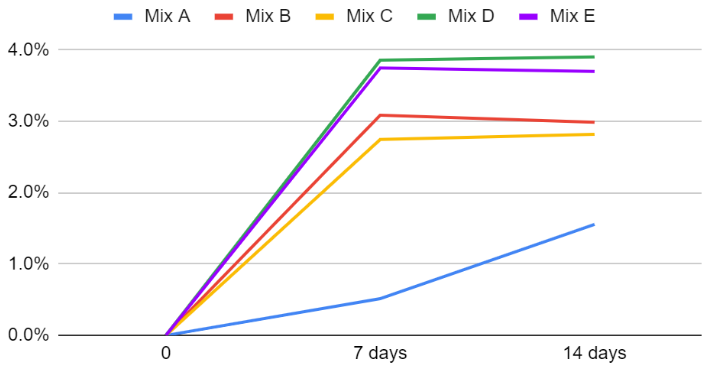


Fig. 39 *Shrinkage of 70 % compressed cylinders*

The uncompressed cylinders showed a shrinkage between 0.98 % and 2.54 %. The compressed samples showed an increase between 1.58 to 2.27 percentage points when compared to the uncompressed ones, with less shrinkage in the cylinders compressed 70 % and 60 % of their initial height. In a general comparison, mix A and C showed the least shrinkage and an improvement from the mix used in the MAS DFAB 19/20 RCF project.

Following the shrinkage tests, compression tests were carried out. Our results from the mechanical compression tests showed an average of 2.38 MPa compressive strength, with small differences between the mixes.

The Lehmbau Regeln from *Sustainable Building with Earth* provides example values for dry compressive strength of earth building materials (Schroeder 2016). Our clay mix are (according to our tests) similar in strength classification to rammed earth for load bearing applications (2 MPa).

We decided to continue with Mix C, as we found this to be the best compromise between shrinkage and cracking during compression.

Building material	**Dry compressive strength [MPa]**
Rammed earth with plant fibre aggregate	2-3
Cob	1
Load bearing earth blocks	2-4

Lehmbau Regeln (Schroeder 2016)

IF localization

The first method developed by Selen Ercan et al works by constructing an orthonormal base from three points, an origin and positive X and positive Y. The coordinates of these points in the robot's coordinate system (RCS) and the coordinate system defined by the total station (WCS) are compared, and a transformation is calculated between the coordinate systems.

If the robot arm's reach is constrained by obstacles on the building site such as the built structure or the IF's platform, the possible distance between the three points might be limited. To circumvent this the location of the robot base frame can be interpolated from arbitrarily positioned points using a nonlinear optimization solver (Ercan et al. 2019).

We evaluated the Three Point localization method using 11 points. We used the deviation between expected location in the world coordinate system and actual location. The expected location comes from the calculated transformation and the actual coordinate is measured using the total station.

Our largest deviation using the three-point method was 17.33 mm. From our tests the relation between expected location and actual location could be explained as a function of the distance between point and total station.

Fig. 41 & 43 from Ercan (2019)
© Gramazio Kohler Research, ETH Zurich

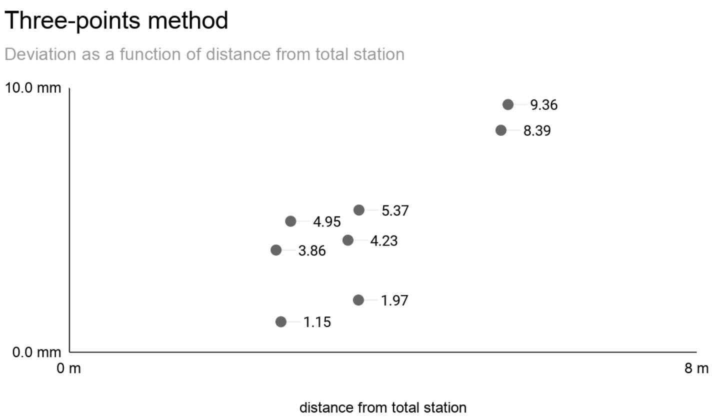


Fig. 40

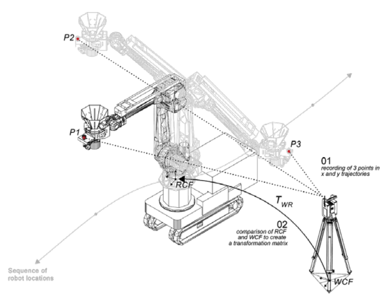


Fig. 41

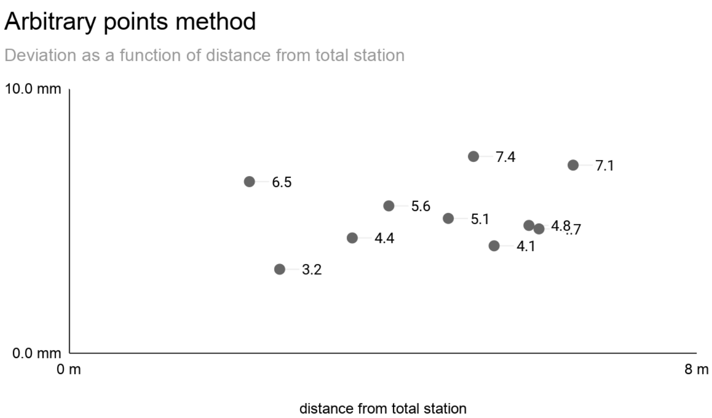


Fig. 42

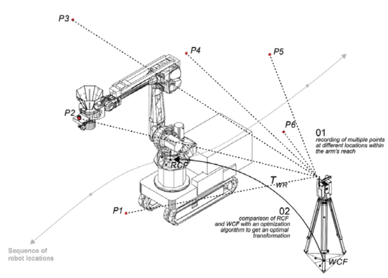


Fig. 43

In the case of the arbitrary point localization method, we evaluated the method using 10 points. These tests showed more promising results with a maximum deviation of 7.44 mm. Here the deviation does not show the same relation to the distance from the total station.

Sensor feedback for adaptive fabrication

Another repercussion of the uneven shrinkage mentioned previously was the displacement of whole segments of structures. As our process was layer based, this displacement caused the next layer to be misplaced in reference to the built structure.

Reacting to this we considered different types of sensory feedback options:

Distance sensors

Initially we considered using of distance sensors in the fabrication process, to measure the deviation of the structure during the drying process and adapt the virtual model which was the basis of the fabrication data.

Different types of distance sensors were evaluated, taking into consideration their accuracy and range. We chose to work with an off the shelf break-out board with a VL53L1X sensor due to its range and size. The VL53L1X is a ranging time of flight (ToF) sensor with a range of 40-400 cm (STMicroelectronics 2018).

In order to include it in the fabrication process we built a holder for the sensor to attach to the robot tool and adapted the robot communication program to store sensor data before placing the cylinder. If the distance differed from the expected distance given by the virtual model, the placing location was adapted within a certain range. If the deviation was considered too big fabrication was halted.

However, due to the complexity of the resultant shapes and the deformation in multiple axes, we found this measurement method insufficient.

3D scanning

We introduced 3D scanning into the process using an Intel Realsense D415. We took readings from the camera while mounted on the robot tool, and filtered the resulting point clouds to only include the top layers of the build structure.

The pointcloud was then reconstructed into a mesh and processed in Grasshopper for further processing.

Fig. 44 *Example of deformation due to shrinkage from MAS DFAB 19/20 RCF.*

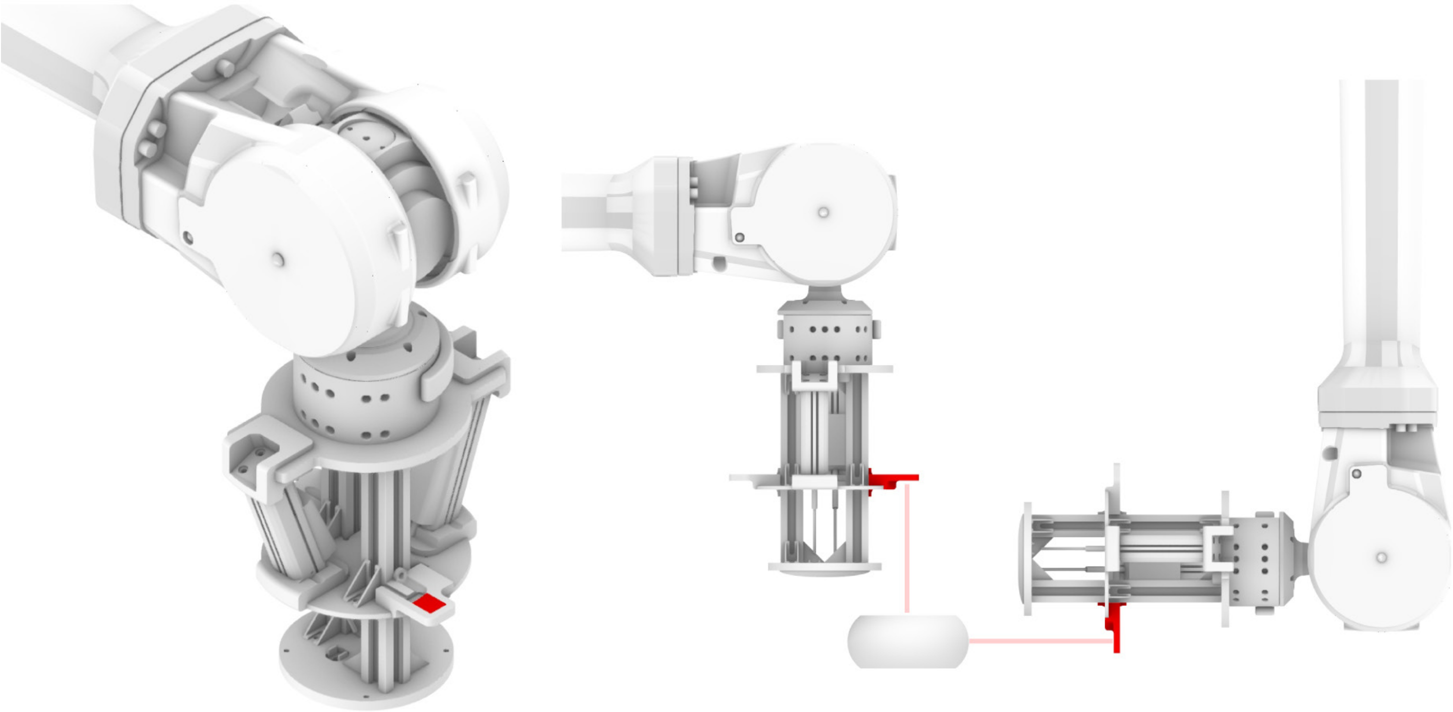


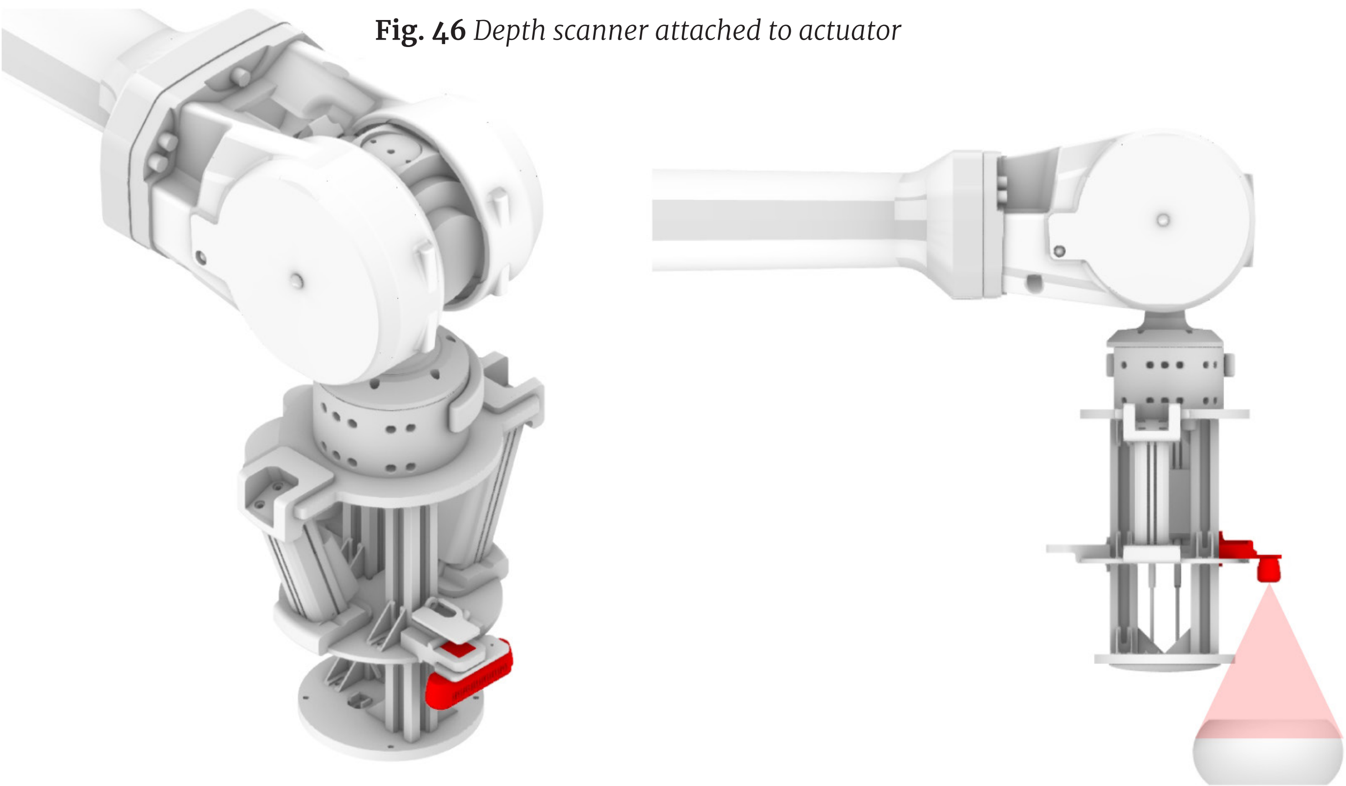
Fig. 45 *Distance sensor attached to pick and place tool using 3D-printed holder*

We constructed a centerline of the top layer and adapted the placing locations to this. The following layers were also adapted, but to a lesser and lesser degree to still reach the intended design.

We decided to add the depth camera to our custom tool to increase the reach of the camera. With the camera on the robotic tool we could also localize the resulting point clouds to our world coordinate system.

In order to orient the mesh to its location in WCS we used the transformation between robot base and depth camera together with the transformation from our localization procedure to orient the camera's coordinate system. We based

Fig. 46 *Depth scanner attached to actuator*



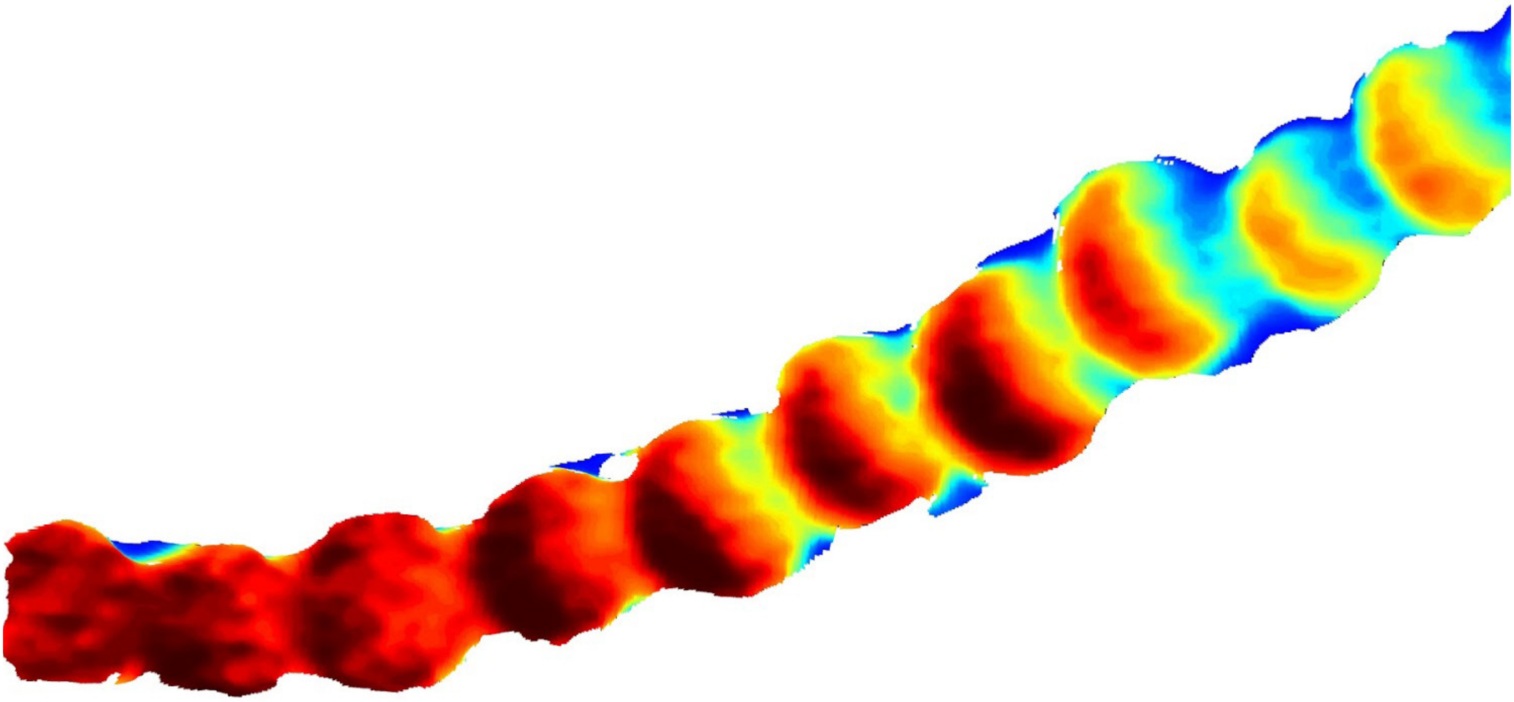


Fig. 47 *Point cloud colored captured using depth camera colored according to distance from camera*

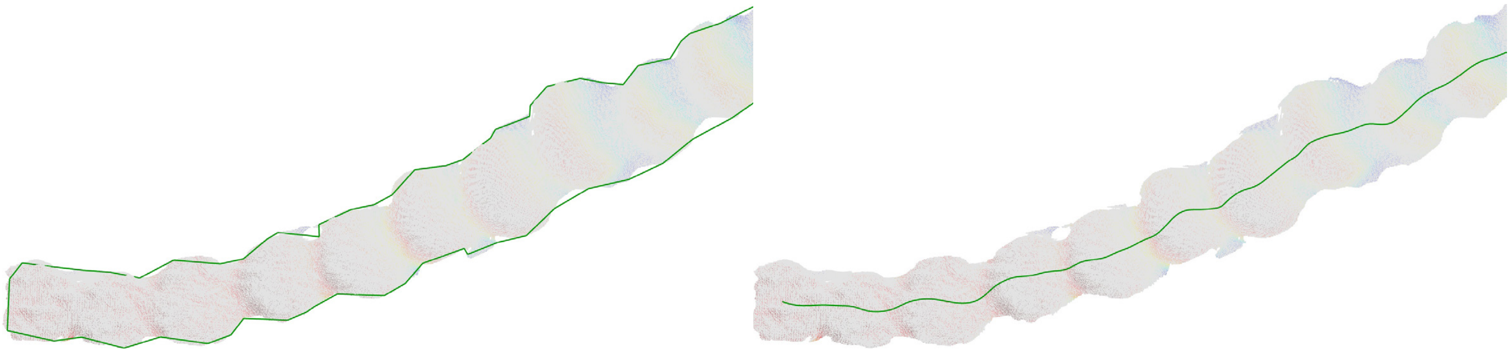


Fig. 48-49 *Edge extraction and derived center line*

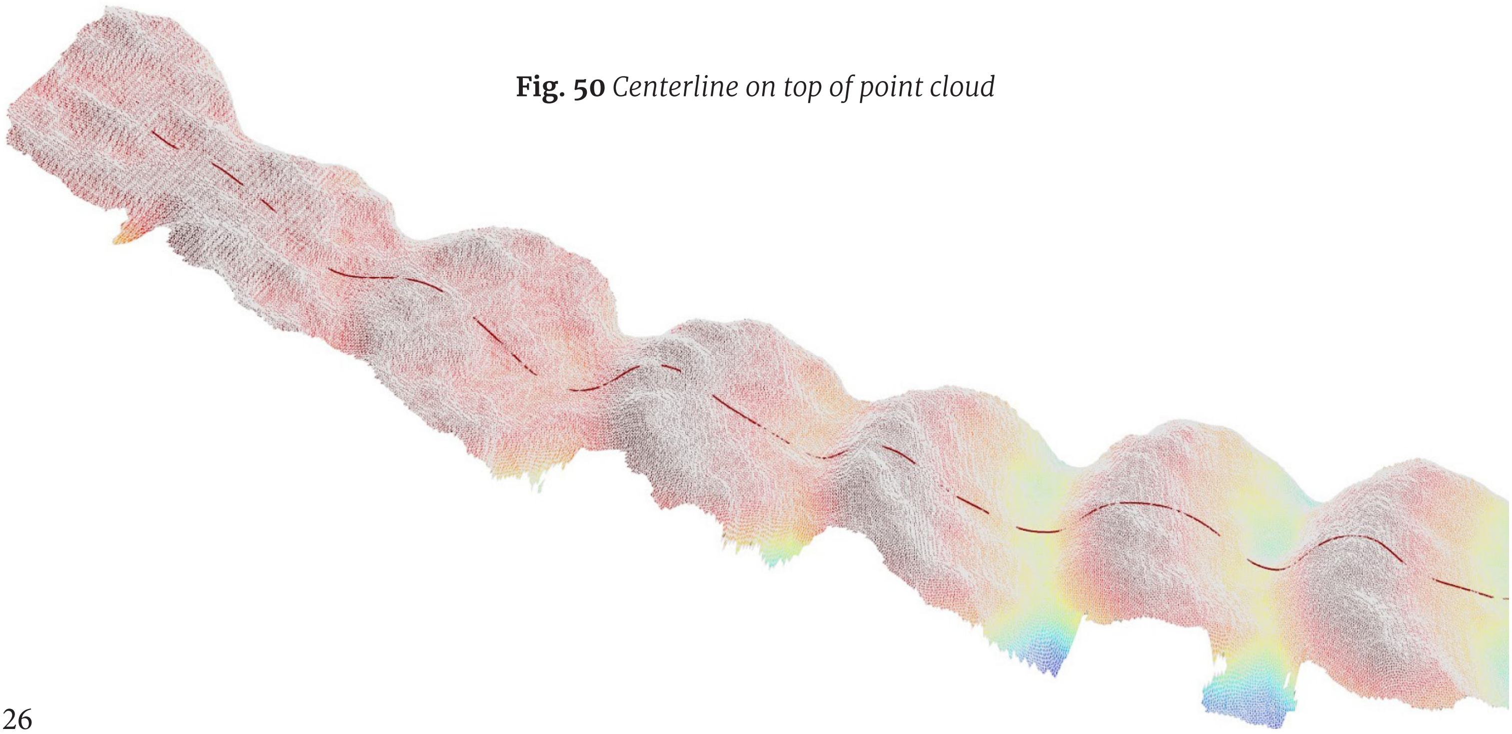


Fig. 50 *Centerline on top of point cloud*

the transformation from depth camera coordinate system to robot base frame on an approximation of the camera's location on the tool.

This method proved to not give us precise results, most likely due to our imprecise localization of the camera. We believe that further calibration would be necessary to get localized 3D-scans with this method.

Linear force sensor

We thought evaluating how much force is exerted for each cylinder placement could give information about the clay mix' properties as well as the properties of the built structure. We already had one feedback system, safety measures enforced by the robot controller to protect the robot arm. For more precise feedback we assessed and planned integration of a load cell on our end effector.

In our initial tests we measured force exerted using an external canister load cell placed between tool and clay cylinder, with steel plates on both sides to spread the load equally. In order to control how much the cylinders were pressed we used our robotic setup for the pressing. We recorded the initial force and the max force for compressions of 50%, 63% and 70% of initial cylinder height, for three of our mixes (A, B, C).

As expected, we saw that more compression requires more force. The distribution however was a bit surprising. This experiment convinced us to pursue integrating a load cell on the tool. To record load using the load cell we needed to allow the pressing plate to move. To achieve this we planned to connect the load cell to the center of the middle plate and to the center of the pressing plate, with the pressing plate no longer fixed to

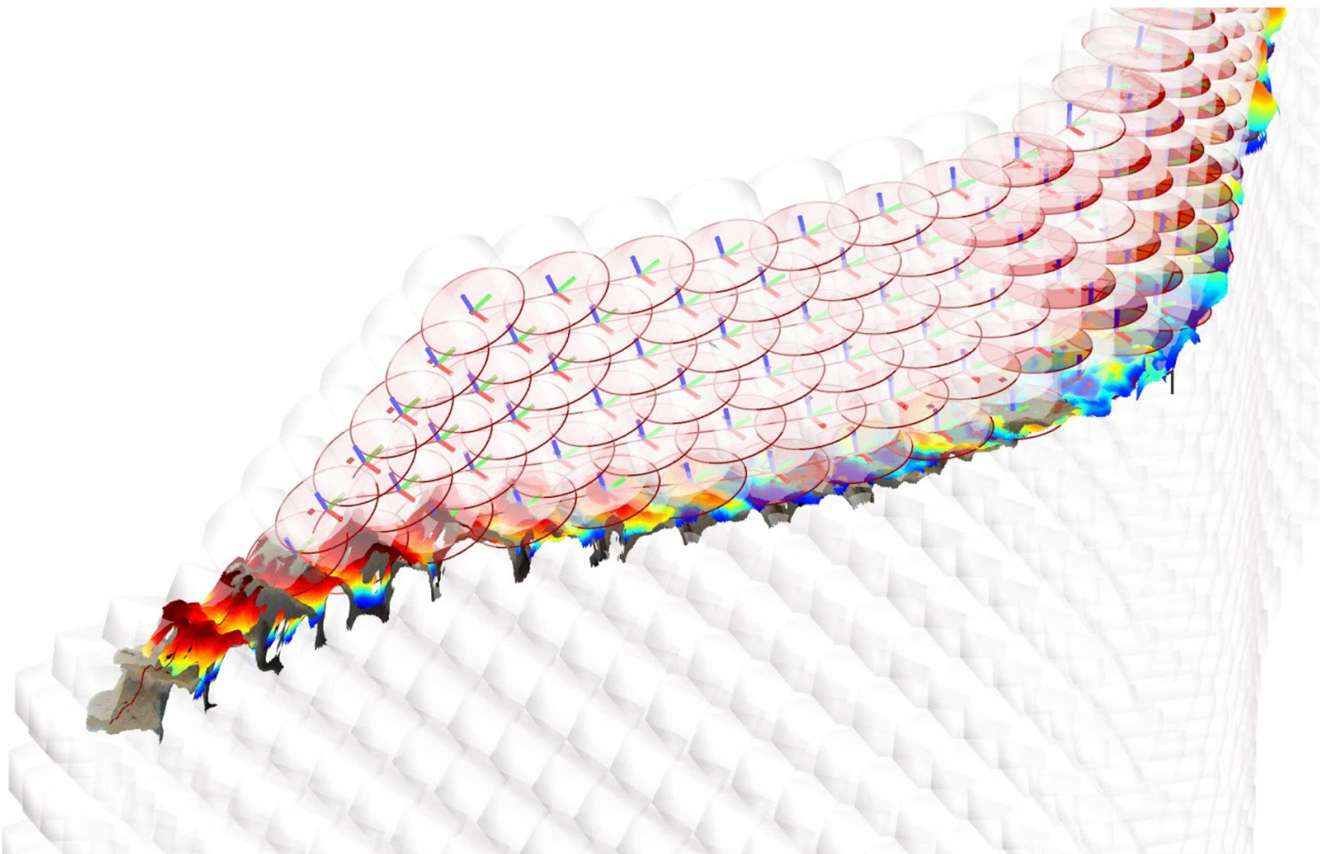


Fig. 51 *Planes adapted to state of construction*

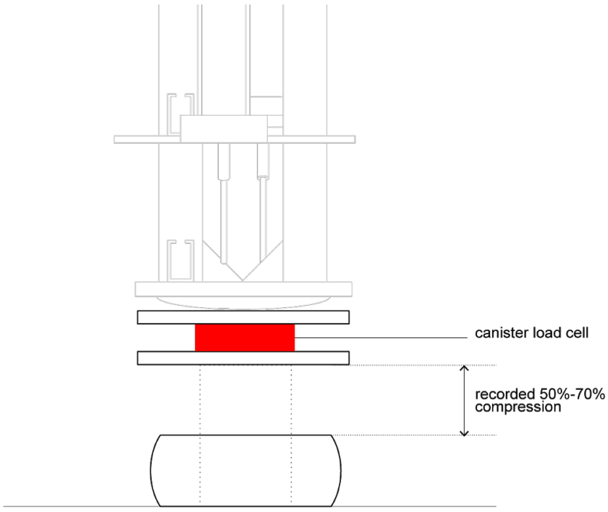


Fig. 52 *Load cell test setup*

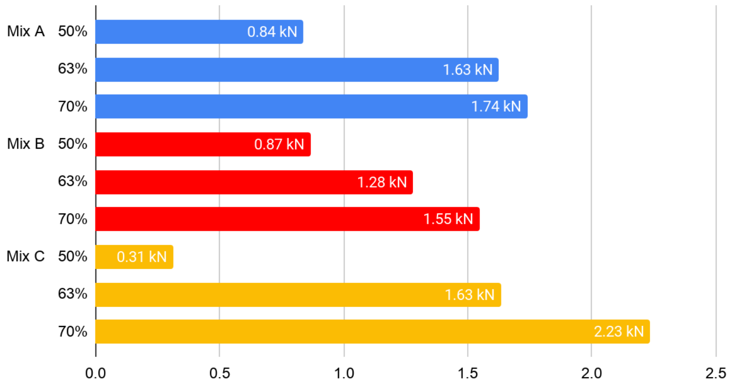


Fig. 55 *Maximum force exerted during compression*

the rest of the tool. We also planned limit the pressing plate to vertical movement using metal plugs.

While we had the new parts and the load cell ready we never had time nor wanted to risk fabrication downtime to modify our end effector in this way.

Fig. 53-54 *Planned load cell integration*

Path planning for pick and place trajectories

The RCF fabrication process used parametrically constructed paths using frames set in the virtual model. These path parameters were manually evaluated and adapted during fabrication, requiring experience and constant attention. We wanted to replace this process using algorithmic path planning, to reduce work, increase safety and create more efficient paths.

During the process we also found that repositioning of the robot made the path creation even more complex, as it was necessary to test the new positions in between frames considering a new environment, consider the position of the

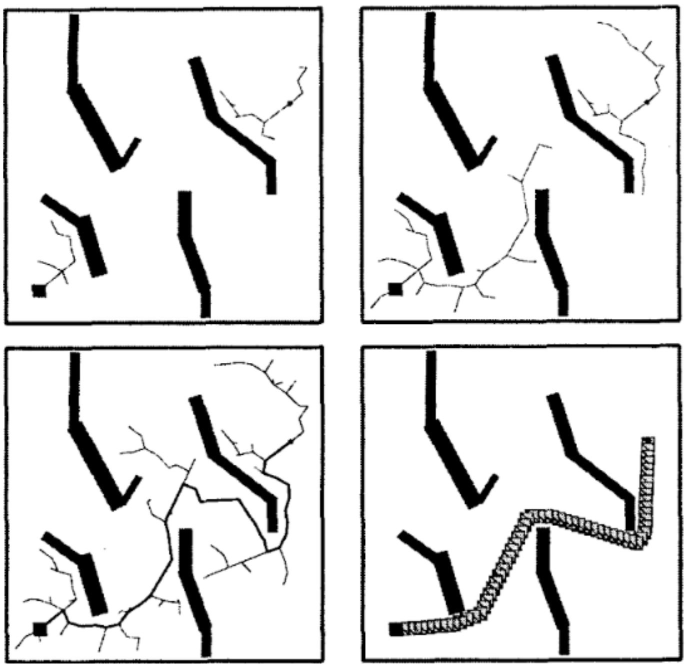


Fig 56. *Two rapidly exploring trees growing towards each other.Diagram from Kuffner and LaValle (2000).* ©*2000 IEEE*

new built elements and the path of the robot was sometimes unpredictable due to its built in configuration.

We implemented path planning using the Open Motion Planning Library (OMPL) in MoveIt, a tool for mobile manipulation developed for ROS (Sucan, Moll, and Kavraki 2012; Coleman David 2014; Quigley et al. 2009). Communication with ROS was done again with compas_fab and motion planning requests were sent from Grasshopper (Rust et al. 2018). This workflow was based on research by Gandia et al, utilizing Docker containers for reproducible ROS environments (Gandia et al. 2019).

The paths were planned to and from placing position, including pressing motions. The travel motion starts from a given frame above the picking station and ends at a frame 300 mm offset from the placing location frame. The pushing motions consisted of Cartesian motions in two steps, the first with the needles on the tool extended and the second with the needles retracted. The last trajectory was calculated from the last configuration (defined by joint positions for each joint on the robot arm) in the pressing motion to the previously used frame above the picking station.

The goals for each trajectory depended on the designed location of each cylinder. The motion planning request for each trajectory consists of a start configuration, goal configuration, optionally additional constraints and some instructions to the planning framework.

Obstacles are defined as collision meshes located in RCS. Either permanent like the platform of the IF (relative to the robot arm) or added and removed during planning. Collision meshes can also be attached to the robot and move with the robot, e.g. an end-effector.

The path planning algorithm we used is called RRTConnect, it consists of two Rapidly Exploring Random Trees (RRT) growing from start to finish. RRT randomly samples configurations in a n-dimensional solution space. They grow incrementally trying to connect a random configuration to its preceding configuration (Kuffner and LaValle 2000).

This algorithm is fast but stochastic and has no optimization objectives. This can give unexpected results, but goal and path constraints can effectively guide the algorithm towards good trajectories. It was initially selected based on its low planning time during tests, with the intent to move to a slower but more consistent planner. In the end we found the algorithm consistent even in very restricted environments, and continued to use it.

Path planning also proved to be a great tool while planning fabrication and design segmentation. Robot locations could be tested and evaluated in advance by trying to path plan between given robot location and cylinder locations. We also saw a reduction of cycle times from an average of 38 seconds per cycle to 25 seconds, using the same fabrication data and evaluated in ABB RobotStudio.

Demonstrator

The findings from the other experiments were applied in a demonstrator of 1.2 m x 2.9 m, with a base curve of 3.2 m, consisting of 634 cylinders compacted to 63 % of their height. We decided to use a running bond in this phase of the research as it has shown to be the most efficient combination of adhesion and strength.

The design was initially 1.9 m high but the end result was adapted to the material system's time requirements.

This was a test of a design strategy were the wall takes the shape of a sinus curve that slowly reduces its amplitude as it reaches the top. This geometric strategy was proposed by our structural engineering consultants at SEFORB with the intent to increase structural stability given the slenderness of the structure.

This model was also used to test segment connections for single layered structures. The connection principle came from the MAS DFAB 19/20 RCF project and consisted of angled cylinders forming a slope. This was proven in the previous project to produce good connections while avoiding collisions between tool and placed structure.

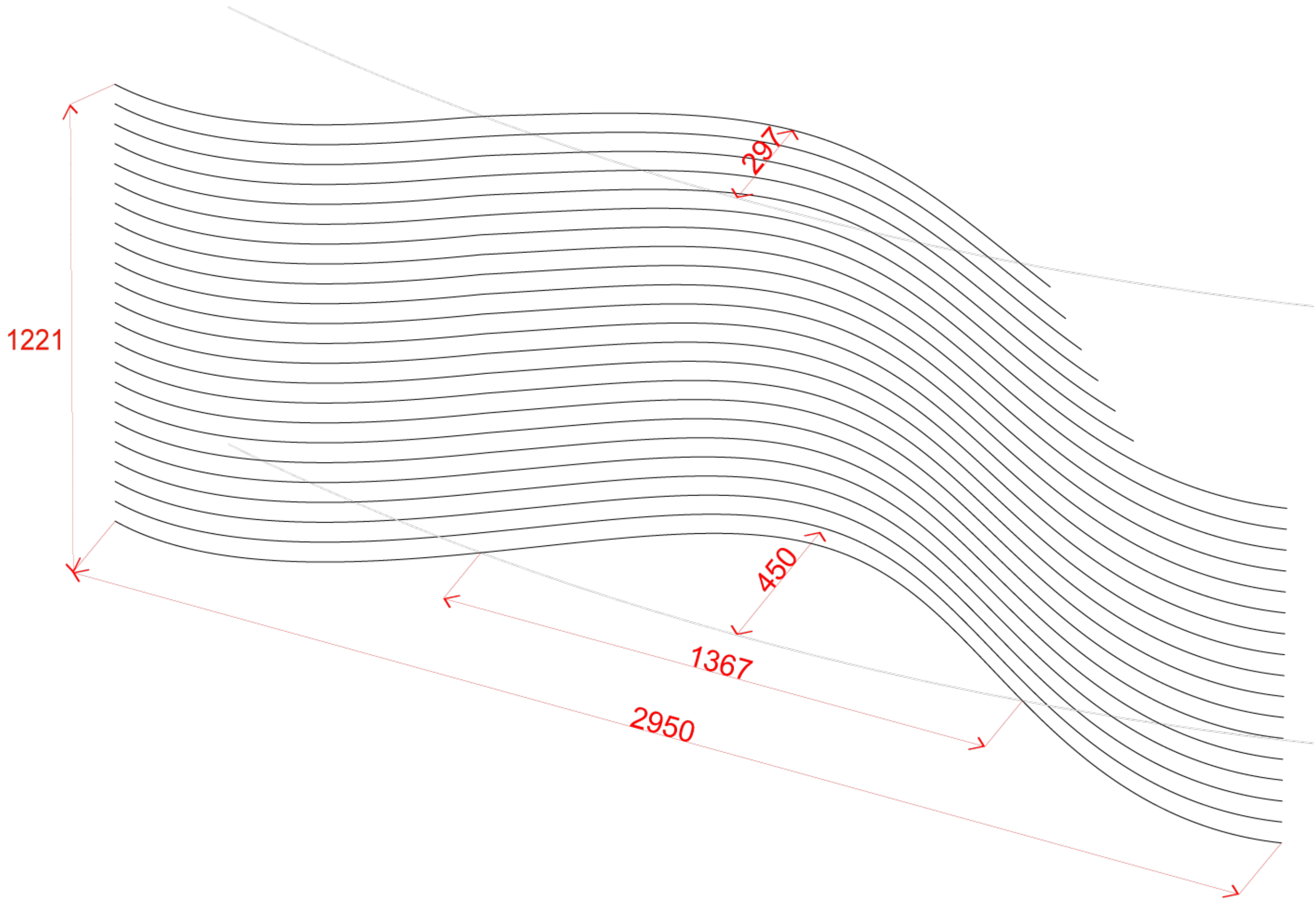


Fig. 57 *Dimensions*

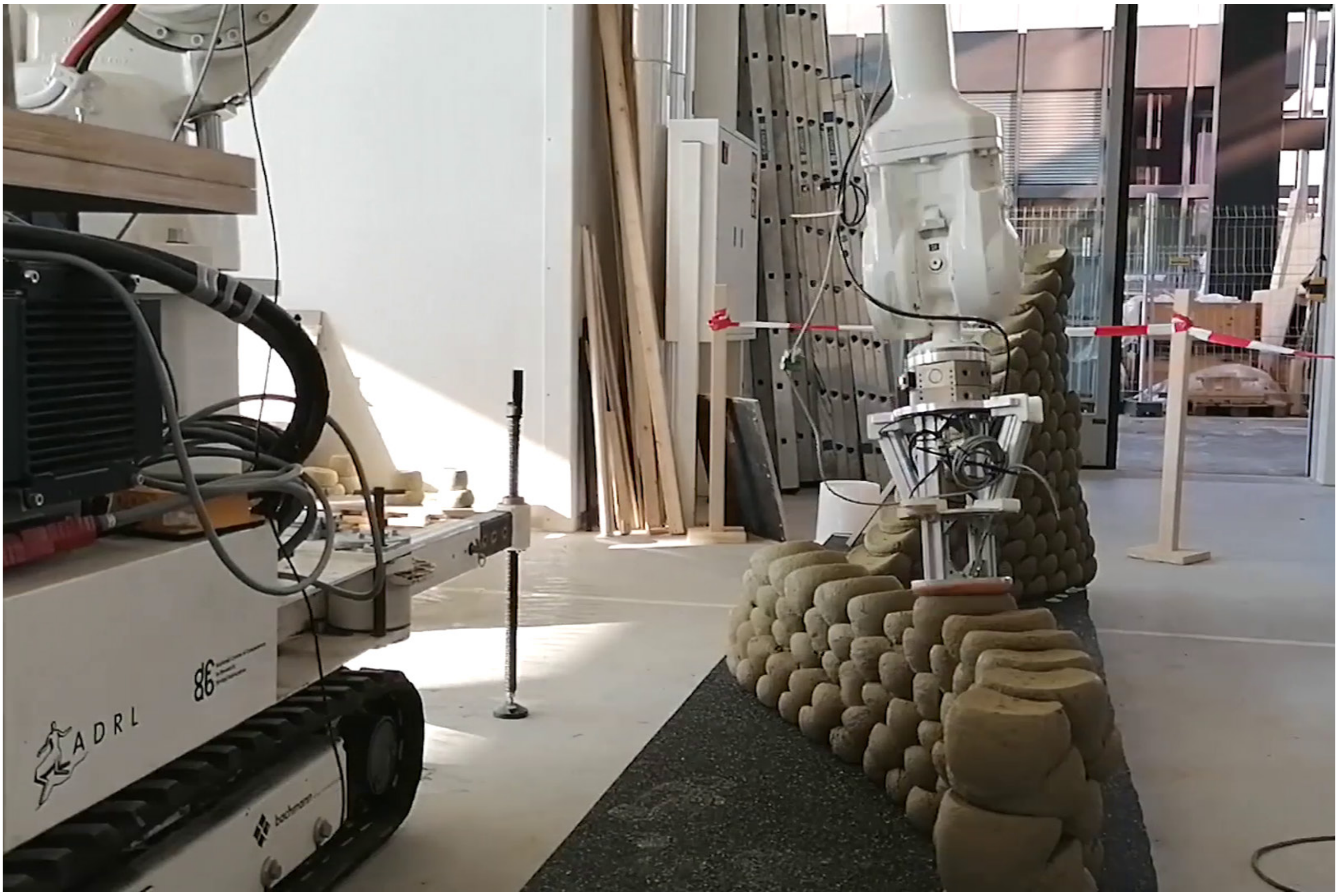
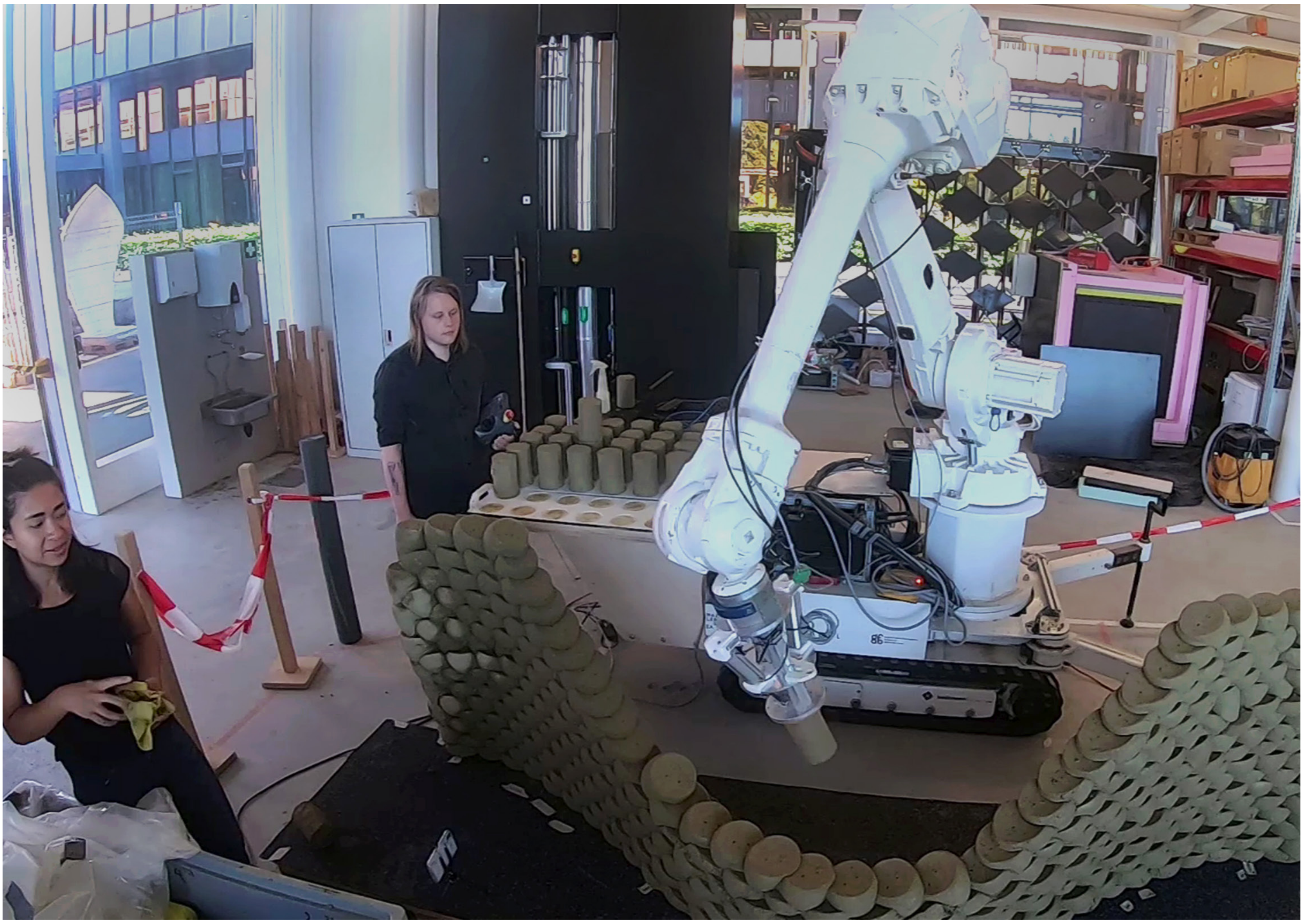


Fig. 58-59 *Photos from fabrication process*



This was done by reducing the length of every other layer and angling the cylinders 0-30°, which creates a continuous slope instead of a stair.

The placement order of the cylinders was also adapted to reduce risk of collision between already placed cylinders and the end-effector.

These strategies proved successful, there were no collisions while depositing and the connection principle produced a homogeneous structure.

We noticed that a part of the structure that was designed to lean deformed rapidly due to the placing force, lack of support and weight of the wall. Measurements of the structure showed that this part had moved laterally towards the orientation of the slope.

Based on this we decided to build the other side of our structure without any leaning, this part showed minimal displacement.

Fig. 61-64 *Collision avoidance as design driver*

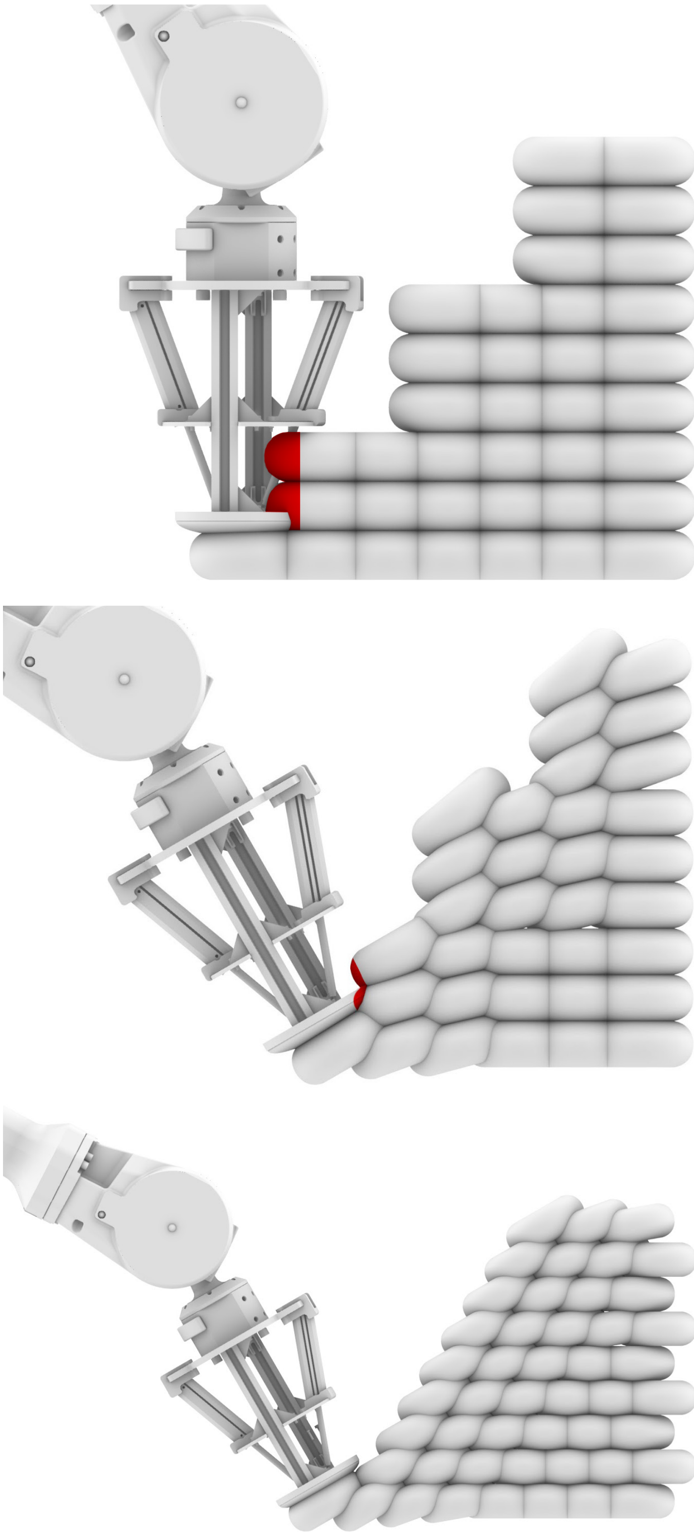


Fig. 60 *Diagram showing segmentation of structure*

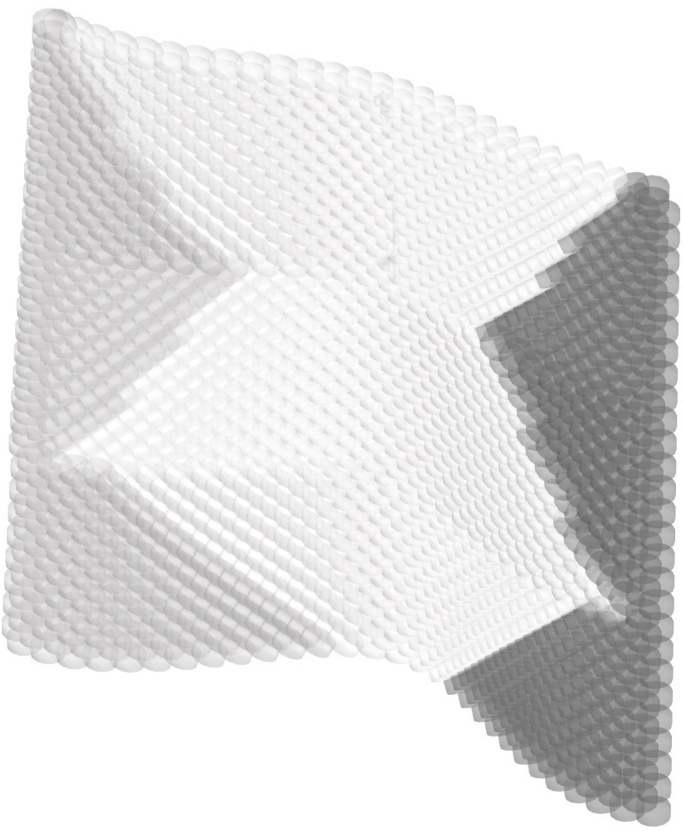
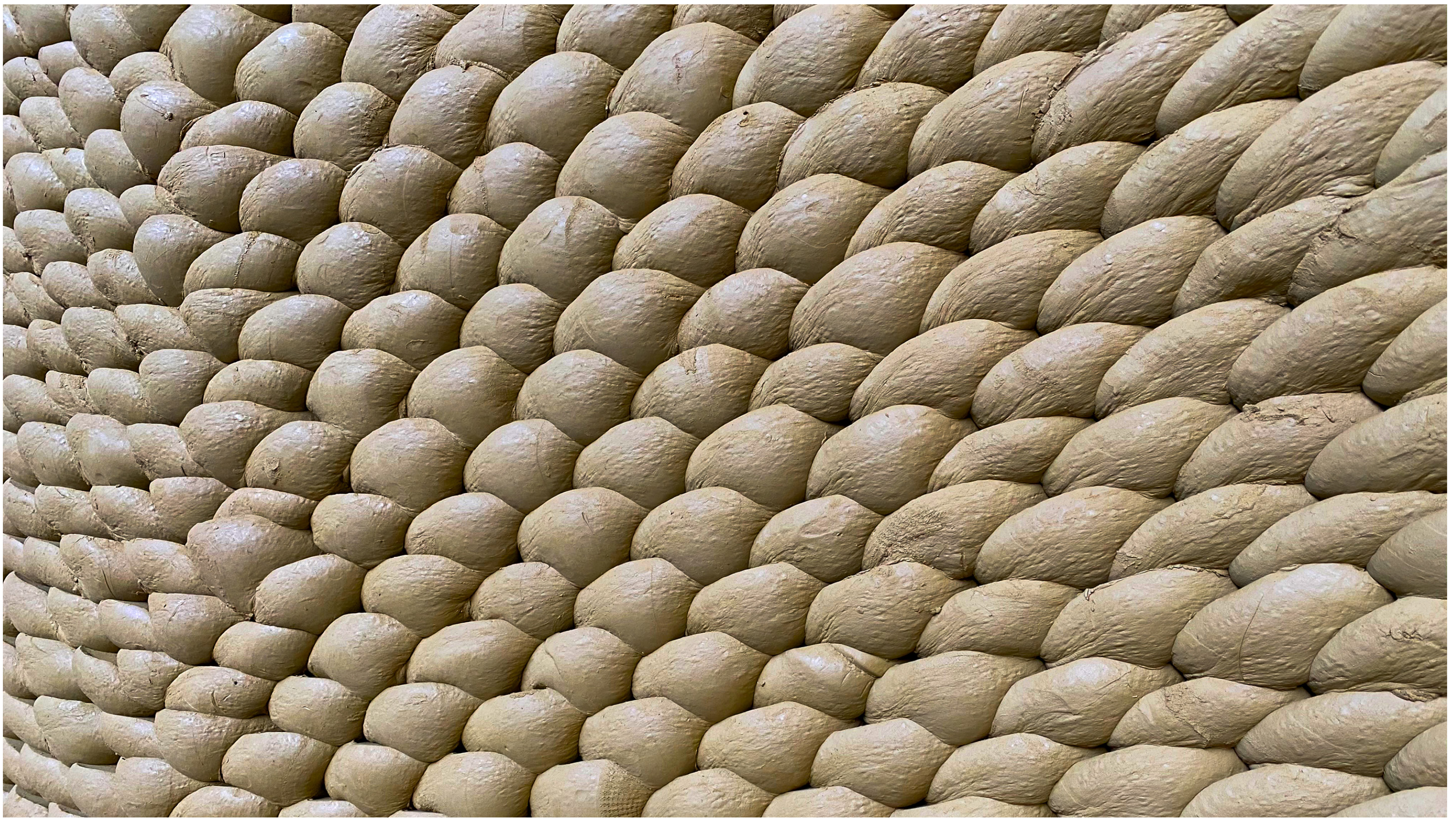


Fig. 65-66 *Photos of demonstrator*



7 Conclusions

In our thesis project we have developed and enhanced the fabrication process from the MAS DFAB 19/20 RCF project to be more stable and adaptive. Our material development and enhancements to the robotic process—such as path planning—has increased the methods viability. We have explored geometrical and force-based sensors integrated into the process and worked on design strategies for large scale construction.

Further development into force measurements during pressing and more generally the physics of clay pressing is something we would like to explore or see explored. It could be an input for motion control as well as a design driver.

We still see a lot of potential in 3D-scanning of construction sites for collision information, as well as live measurements of the structure to adapt to material changes. To fully take advantage of 3D-scanning targets such as AprilTag2 (Wang and Olson 2016) could be used together with the total station measurements to relate point clouds to a WCS.

A constant topic for discussion during the project was tolerances. On one side there is the repeatable accuracy of the robot arm and the precision of the localization method and on the other the malleability of the clay and its dynamic material properties. Together it amounts to a variable positional tolerance, both for absolute positioning as well as "workable" positioning. The clay is forgiving, The clay can take a variable amount of pressure and still perform.

If a robot arm placing a brick presses into another brick either one of the bricks break or the robot arm does. A positional error of 5 mm in our process is hardly noticeable, as long as the "collision" is clay meeting clay.

This also raises the question of how much the design should adapt to accumulating differences between the physical and virtual model caused by positional errors. Should the process be self correcting—trying to minimize the deviation from planned execution?

In our project we planned for an indoor structure, and further work would be needed to build outdoors. Erosion and drying behavior would need to be taken into account, additives or treatments such as rendering could be one way. Planning and designing for expected shrinkage and erosion of built structure could be a very interesting avenue of research.

We hope to see more clay and earthen materials used in digital fabrication processes in the future, leveraging the variability of material properties and expanding the possibilities in construction. Digital fabrication could be seen as a way to codify skilled craftsmanship, and that might be what is needed to bring more clay into construction.

8 Acknowledgments

We would like to thank our collaborator Felix Hilgert at Lehmag AG as well as our tutors—David Jenny, Coralie Ming, Nicholas Feihl & Gonzalo Casas at Gramazio Kohler Research—for their guidance and counsel. We also want to thank our industry partner Brauchli Ziegelei AG.

Thanks also to Michael Lyrenmann, Philippe Fleischmann and Andi Ruesser at the Robotic Fabrication Lab at NCCR Digital Fabrication.

This project started where the MAS DFAB 19/20 RCF project left off, and would not have been possible without all the hard work our classmates put in.

Finally, this project would not have been possible without the support of Aaron Togher and Linn Hübinette.

Fig. 67 *Authors and robot*
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