MORE OR LESS EXACT

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To our parents with love.

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ABSTRACT

More or Less Exact tests the fidelity of material control by hands, by machines, and by the interaction of the two. We overlap two models of exactitude within the discipline of architecture to expose a design space at their intersection. One model, underlying Western practice since modernism, is based on specifications provided by the architect. Distancing designer and builder, this model locates the 'exact' in dimensional stability. The built outcome always approaches, though never reaches, a geometric ideal through correction and repair in an attempt to deny any material transformations due to the process of construction and the passing of time. The other model finds exactitude in the fidelity of actions that control material. This model incorporates a notion of continuous maintenance, as the building no longer needs to approximate a geometric a priori. Setting these two models in dialogue, *More or Less Exact* opens up an undervalued design space: rather than optimizing for the more and more exact, we dynamically navigate the liminal space between the two definitions.

Learning from techniques of shaping clay—manual and mechanized—, we operate in the space between the two 'exacts' by compounding actions that control material. Relocating precision to the design of tools, we conceive of building as continual process: a sequence of actions performed collaboratively between human and nonhuman agents.

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INTRODUCTION

Dear George,

Your subcontractor for Gunite is or undoubtally [sic] should be bound to give you a job where no form-marks are visible to such an extent that they show through the finished coating when applied. I am sure your good conscience and pride in your work would tolerate nothing so derogatory to the work as a whole consequently to your future reputation as a builder—not to mention mine as an architect.

Therefore [sic] will you kindly go over the outer walls and properly prepare them for coating wherever this has not been done. In Gunite work done for me in the past this has been insisted upon and no less should be done here.

I will go over the work with you and point out the defects if necessary. But this should not be necessary as I believe your good conscience should take care of your own interest and that would be my own interest as well.

I will be in town next Monday to go over the building with you.

Sincerely,
Frank Lloyd Wright[1]

1
Megan Chusid sharing Frank Lloyd Wright's letter from October 2, 1958, "How One Simple Material Shaped Frank Lloyd Wright's Guggenheim," Solomon R. Guggenheim Foundation, accessed January 10, 2020, https://www.guggenheim.org/blogs/checklist/how-one-simple-material-shaped-frank-lloyd-wrights-guggenheim

[F]orm marks are characteristic of concrete. Concrete in its plastic condition is poured into a mould generally made of plywood or prestwood or just wood. This wood is removed when the concrete has hardened and leaves its impression upon the surface. This impression can be minimized. Therefore, specifications for exposed architectural concrete require that projections more than 1/16" be reduced by rubbing the surfaces of concrete. Excessive rubbing, however, will expose the aggregate and smoothing by plaster patching will eventually break up and fall off.

George N. Cohen, "A Commentary upon the Exterior Surfaces of the Solomon R. Guggenheim Museum"[2]

2
George N. Cohen, "A Commentary upon the Exterior Surfaces of the Solomon R. Guggenheim Museum," 8 Dec. 1958, fiche id. G204D07, FLWA.

OTHER ANEXACTITUDES

Frank Lloyd Wright's blunt letter to George N. Cohen, his General Contractor at the Solomon R. Guggenheim Museum's construction site, unveils the modernist conception of exactitude.[3] With the letter as his only means of intervening in the construction process, the architect requests that the builder correct the Gunite surface and more closely approach the ideal geometry that he had specified in his drawings. Wright's frustration attests to his inability to impose changes on the built manifestation of his orthographic representation non-verbally, as well as to his fear of a less exact approximation of that representation.

Foregrounded in this misunderstanding between architect and builder is the opposition of form and matter, a dialectic so integral to architecture's disciplinary definition that some—notably, nineteenth-century German aesthetic theory and, consequently, modernism—argued for its centrality.[4] Today, architects, engineers, and designers still toil to minimize the friction between (post-)orthographic representation and its materialization by perfecting mechatronic and optical systems of design and production, further isolating builder and architect. As post-orthographic representation becomes more and more mathematized,[5] these efforts illustrate a scientific dilemma that the seminal philosopher Edmund Husserl tackled almost a century ago. Converting "geometrical-ideal possibilities" to their sensible counterparts is never a smooth translation, Husserl noted.[6] Rather, it is a series (or an infinity) of approximations. Neither perfect copy nor a re-enactment of the form-making process, the outcome is imperfect and "anexact."[7] In this liminal, impure realm between the schema (a "limit-shape" [*Limegestalt*]) and its rough approximation, technological development ceaselessly aims to narrow the gap and move towards perfection.[8]

3
Ibid.

4
"Matter," as the Swiss art historian Heinrich Wölfflin noted in his dissertation in 1886, "wants to spread out formlessly on the ground." It is the "opposing force," the "force of form [*Fromkraft*]" that Wölfflin identified as "the principal theme of architecture," one that finally resists matter's pull. See Heinrich Wölfflin, *Prolegomena to a Psychology of Architecture*; trans. Florian von Buttlar, Ken Kaiser. (Cambridge, MA: 1976), 159.

5
For a discussion of post-orthography's mathematical nature, see John May, *Signal. Image. Architecture.* (Everything is Already an Image) (New York: Columbia Books on Architecture and the City, 2019).

6
Edmund Husserl, *The Crisis of European Sciences and Transcendental Phenomenology: An Introduction to Phenomenological Philosophy*, trans. David Carr (Evanston: Northwestern University Press, 1970), 25.

7
Jacques Derrida coined the term "anexact" in his analysis of *Edmund Husserl's Origin of Geometry, an Introduction.* (Stony Brook, N.Y.: N. Hays, 1978), 123.

In a glib critique, Husserl posits that this quest for perfection—and for approaching the limit most carefully—is futile in the empirical realm.

As the contemporary practice of architecture increasingly conceives of buildings as technical, mathematical objects (the products of digital descriptive geometry and building information modeling), construction processes continue to desire the almost-ideal 'limit-shape' over a larger margin of acceptable 'anexactitude.' However, a recent turn in digital fabrication promotes shifting focus to the emergent properties of materials, a design space delimited by the capabilities of the tools that shape matter.[9] This has the potential to expand the margin of architectural error. Allying with this waning affinity for dimensional stability, we relocate precision to the design of tools and actions. In what follows, we outline a method for working with instability and anticipation rather than numerically predetermined, or even deterministically indeterminate, outcomes. We understand material properties as a subset of larger design intentions that resist mathematization. The result of a material process does not fix the designed object: it remains open for a series of operations, manual or machinic. Compounding actions over time produces precarious objects that carefully balance between structure and total collapse. These destabilized objects open up avenues for working with higher risk and higher tolerances.

8
Husserl, 26.

9
Architect Benay Gürsoy notes that "there are indeterminacies in digital fabrication processes that can be explored as potential design drives." Gürsoy sets forth an ambition that we also follow: finding opportunities in emergent material behavior rather than disciplining matter to more and more exactly approximate a digitally predetermined form. Similarly, the Proceedings of the 38th Annual Conference of the Association for Computer Aided Design (ACADIA) emphasize this turn. The conference chairs celebrate the "inherent, unexpected potential [that is] achievable when the digital and physical spaces do not perfectly align" and propose that this disconnect, within the "language of computation and simulation," opens up the "vast field of operation that inhabits the intersections between materials and production." The majority of papers presented in the proceedings, however, propose to close the gap between the ideal geometry and its material manifestation through the use of computation and/or simulation, further diminishing risk and uncertainty. See Benay Gürsoy, "From Control to Uncertainty in 3D Printing with Clay," Proceedings of the 36th eCAADe Conference, pp. 21-30 (2018) and Phillip Anzalone, Marcella del Signore, and Andrew John Wit, *Recalibration: On Imprecision and Infidelity*. (Bar Harbor, ME: Acadia Publishing Company, 2018).

TWO MODELS

The Guggenheim Museum's visible "form-marks" engage the legacy of specification within the discipline. In this model, the architect makes his idea for a building empirically possible by providing orthographic specifications. These legally bind the builders, his contractors, to approximate the ideal geometry as exactly as they can: in the Guggenheim's case, Wright celebrates that a "true logarithmic spiral has been worked out as a complete plastic building."[10] Specifications, as the architectural historian Michael Osman observes, came to serve as "legal instrument[s] for practice" in industrial society, enabling the separation of the "immaterial products of the mind and the material products of the hand, between art and craft," and simultaneously enforcing this distinction.[11] As the Guggenheim example demonstrates, the modernist architect uses specifications to "[assert his] control over the crafts."[12] While Osman locates the onset of these ramifications in the nineteenth century, recent scholarship has also problematized and theorized the contemporary challenge of the heightened abstraction of representation and making.[13]

Through the instrumentalization of specifications, industrialized, modernist buildings privilege certainty over the instability of uncertainty. These two are, in turn, linked to mechanization and craft: to borrow the eminent furniture maker David Pye's words, mechanized processes of mass-production epitomize the "workmanship of certainty," whereas craft is a "workmanship of risk… in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works."[14] In the Guggenheim's case, an ingenious way of adapting standard specifications for plywood formwork construction displaces the dexterity of the worker's hand.[15] The act of spraying concrete and sanding are low fidelity, repeatable,

10
Frank Lloyd Wright in Joseph M. Siry. "Seamless Continuity versus the Nature of Materials: Gunite and Frank Lloyd Wright's Guggenheim Museum." Siry notes that the final design is not, as Wright had hoped, a 'true logarithmic spiral,' but it is nevertheless a mathematical entity that the architect deems organic. In the Journal of the Society of Architectural Historians 71, no. 1 (2012): 78-108. Accessed January 12, 2020. doi:10.1525/jsah.2012.71.1.78., 87.

11
Michael Osman, "The Augmented Architect." Lecture at the Harvard Graduate School of Design, April 1, 2019, https://www.youtube.com/watch?v=ufHW04DIV8

12
Ibid.

13
See "Imagining Risk" by Scott Marble, where he emphasizes the growing separation between architect and building. In Peggy Deamer and Phillip Bernstein, *Building (in) the Future: Recasting Labor in Architecture*. (New Haven, Conn.: Yale School of Architecture, 2010).

14
David Pye, *Nature and Art of Workmanship*. (Cambridge: Cambridge University, 1984), 4-6.

low risk actions with little room for improvisation (Figure 1).

The Guggenheim example reveals another aspect of modernist building: the constant friction between the building's decay from the geometric ideal and actions of maintenance and preservation that strive to restore that singular state (Figure 2). Maintenance, as architect Hilary Sample writes, "is dedicated to safeguarding the holistic image of an architectural work… [it] represents an investment in the persistence of architecture—both as an image and as an ideal."[16] Imageability thus implicates the building's dimensional stability—how closely it follows its ideal form—as well as its superficial surface qualities. To brush off aging and guard the illusion of permanence, maintenance is often concealed. In 2007, preservators and engineers at the Guggenheim Museum focused their efforts on making "the work almost imperceptible and [adhering] to the building's original form to the greatest extent possible," even after finding that the building was missing crucial steel reinforcement on the sixth floor.[17] Temporarily making the building "better than new,"[18] the 2007 conservation was one of many, as the owners already anticipated future cycles of maintenance and preservation. The modernist model prioritizes the best approximation of the a priori form by acts of correction during construction ("no form-marks") and by cycles of maintenance and preservation to ward off the building's eventual obsolescence.

Last, Frank Lloyd Wright's insistence on the use of Gunite to create a monolithic, seemingly continuous surface lays bare his battle with material properties. As architectural historian Joseph Siry remarks, Gunite "appealed to [Wright] as a plastic mass that embodied his ideal of continuity as a principle of organic architecture, meaning buildings conceived and designed as analogous to living organisms found in nature."[19] Wright invoked the modernist myth of concrete: its reinvention as a new, scientific, monolithic, and infinitely reconfigurable material, obscuring its recurrent pre-modern uses.[20] His organic analogies remained largely symbolic, replacing actual continuity of matter with its pure, "form-mark"-free image. To sustain this illusion, the Gunite contractors omitted vertical expansion joints from the finished

15
See Joseph Siry's description of the Guggenheim's inventive use of Gunite. Siry, 91.

16
Hilary Sample, *Maintenance Architecture*. (Cambridge, MA: The MIT Press, 2016). 7.

17
Robin Pogrebin, "The Restorers' Art of the Invisible," New York Times, September 10, 2007. https://www.nytimes.com/2007/09/10/arts/design/10gugg.html

18
Ibid.

19
Siry, 84.

20
Wright made significant efforts to design the material: as Siry notes, he "gave meticulous instructions as to the composition, color, and size of stone aggregate and sand, seeking a mix that would flow evenly around the steel-wire mesh and steel-bar reinforcing." See Siry, 95. For a discussion of how concrete was recast as a "modern," "pretenatural" material, see Michael Osman, "The Managerial Aesthetics of Concrete," Perspecta 45 (2012): 67-76. http://www.jstor.org/stable/24728116.

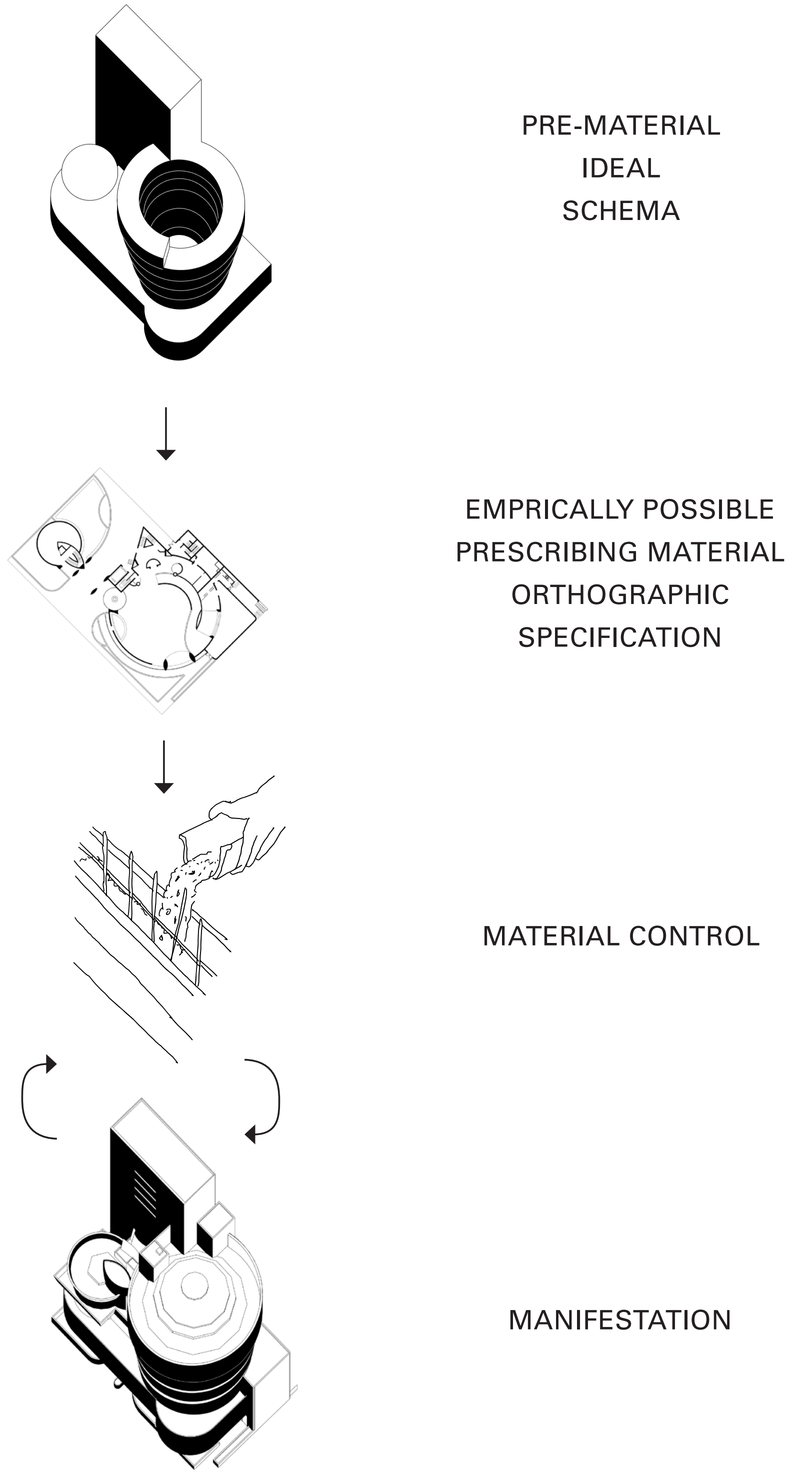


Figure 1. Guggenheim Museum construction

21
Siry, 95.

exterior ramp surface, which led to cracking that the 2007 preservation considered critical.[21] As the final step in the construction process, the Wright-Cohen argument around sanding the surface only reinforced the disconnect between schema and materialization.

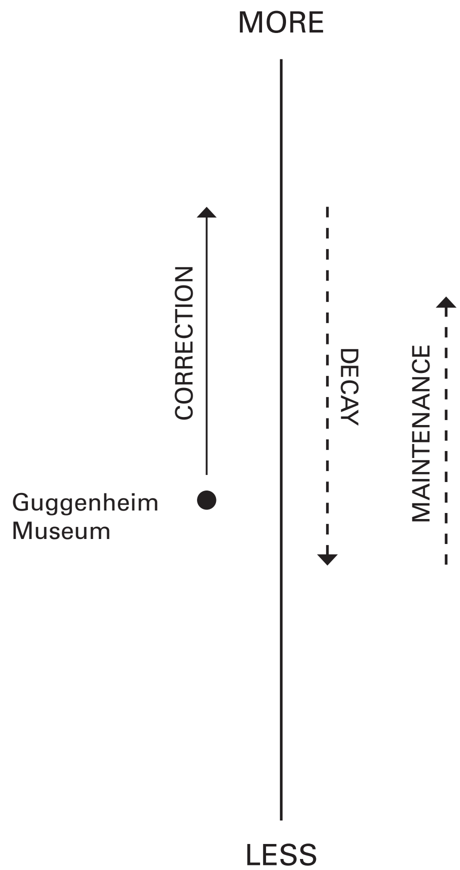


Figure 2. Exactitude as defined by dimensional stability

The modernist model locates exactitude in the precise construction of an orthographically specified ideal geometry. However, while this model dominated Western architecture in the twentieth century, other practices eluded the quest for the dimensionally exact to demonstrate a different attitude towards material use and temporality. Mousgoum *teleukakay*, in northern Cameroon, provide such an example. The extremely thin catenary shells are ornamented with footholds that help in the dwelling's construction as well as its annual maintenance. Ironically, teleukakay, as art historian Steven Nelson explains, have often served as the object of modernist desire, exoticized and labeled absurdity—disbelieving their structural achievement and appropriating their aesthetic qualities.[22] We build on Nelson's fieldwork to highlight how the teleuk provides an alternative to the modernist definition of precision.

Nelson narrates the teleuk's corporeal construction process—where the knowledge of vaulting is kinesthetic and embodied—based on interviews with masons.[23] In a stark contrast to modernism's elusive, white male anthropometrics (think Modulor), here, the master mason's body becomes an integral agent of the construction, rather than a mechanism to predetermine the normative body of the future occupant through specifications. According to a famed mason, Golo Agonon, the first rings of the coil-built earth structure would cover the length "from his elbow to the tips of his fingers."[24] Nelson recites Agonon's description of the performative, although often gendered, process of construction:

> *Once the mason arrived, women gathered the correct kinds of earth, grasses, and animal dung... and brought the water for mixing the clay that would eventually make up the dome… The mason traced the perimeter of what would eventually become the new teleuk on the ground. After establishing the plan, the mason began constructing the teleuk by building the first ring of the wall… After the construction of the first few rings, the mason begins to build the teleuk's 'feet,' which function as outer scaffolding and drainage system for the structure. When the height of the wall exceeds comfortable reach, the mason starts to use the 'feet' as a ladder, enabling her or him to climb the partially completed house… As the wall becomes still higher, the mason begins to taper it… The mason's training is perhaps most vital at the point where she or he begins to taper the teleuk's wall, and this has to be accomplished precisely and at a correct angle, otherwise the teleuk will be uneven, or it will simply collapse.*[25]

In this model, the master mason begins with the inscription of a circle in the ground, building the foundations with his body as measure. The exact actions of the hand, as well as

22
Nelson also highlights the myriad ways in which the buildings have been reproduced—both physically and through images: most recently reclaimed as a Cameroonian national symbol and framed as "eco-friendly" architecture at Expo 2005 in Japan. See the introduction in his book, *From Cameroon to Paris: Mousgoum Architecture in & out of Africa*. (Chicago: University of Chicago Press, 2007).

23
Ibid., 27.

24
Ibid., 29.

25
Agonon, as Nelson highlights, was in his sixties when he began the practice of teleuk construction. Already at the time, "Agonon [was] nearly blind… [thus] touch is not only the primary sense through which he understands the process of constructing teleukakay, but also the only sense upon which he can rely to do it correctly." Ibid., 29-31.

26
Ibid.

27
Ibid.

28
Ibid., 27.

tactile feedback, allow the mason to find the teleuk's shape until it is fully enclosed. Since each building is the result of an interplay between material and embodied knowledge, there is no singular manifestation, nor geometric ideal (Figure 3). The building is constituted through precision relocated to the "correct position and movement of the hand, the arm, and the rest of the body."[26] While there is no explicit orthographic or mathematical representation of the desired outcome, we find exactitude in the dexterity of the hand and the understanding of material properties. In Nelson's words, there is a "partnership between the mason and the clay."[27] Rather than an illusion of material continuity, the teleuk is erected out of a careful mix of clay and organic additives. The dynamic and exact positioning of the mason's body and hand substitute for a static, materialized formwork.

In contrast to the Guggenheim's laborious formwork construction process that followed wood-framing specifications, the construction of the teleuk relies heavily on the lengthy training of masons. The process becomes more and more exact as masons refine actions over time. Agonan describes his unscripted, experiential training as such:

> *Each day I went to the place where teleukakay were being built… I saw hand gestures; [I saw] how to attend to the earth. I saw how one mixed the earth, how one put the grass and other materials together, how one allowed the mixture to ferment, how one erected the teleuk, how one put on the feet to construct the teleuk. Then I was well formed.*[28]

Architect and builder collapse into a single role in this process of embodied construction, acquiring skills through practice and observation.

Each teleuk exists in a continual process of construction, where each reconstruction leads to a slightly different manifestation. In this way, the masons and the women who plaster the built house maintain authorship in the face of standardization: evoking Pye's notion of the workmanship of risk, here, each new teleuk is a variation on a similar structural concept, differentiated by different levels of dexterity

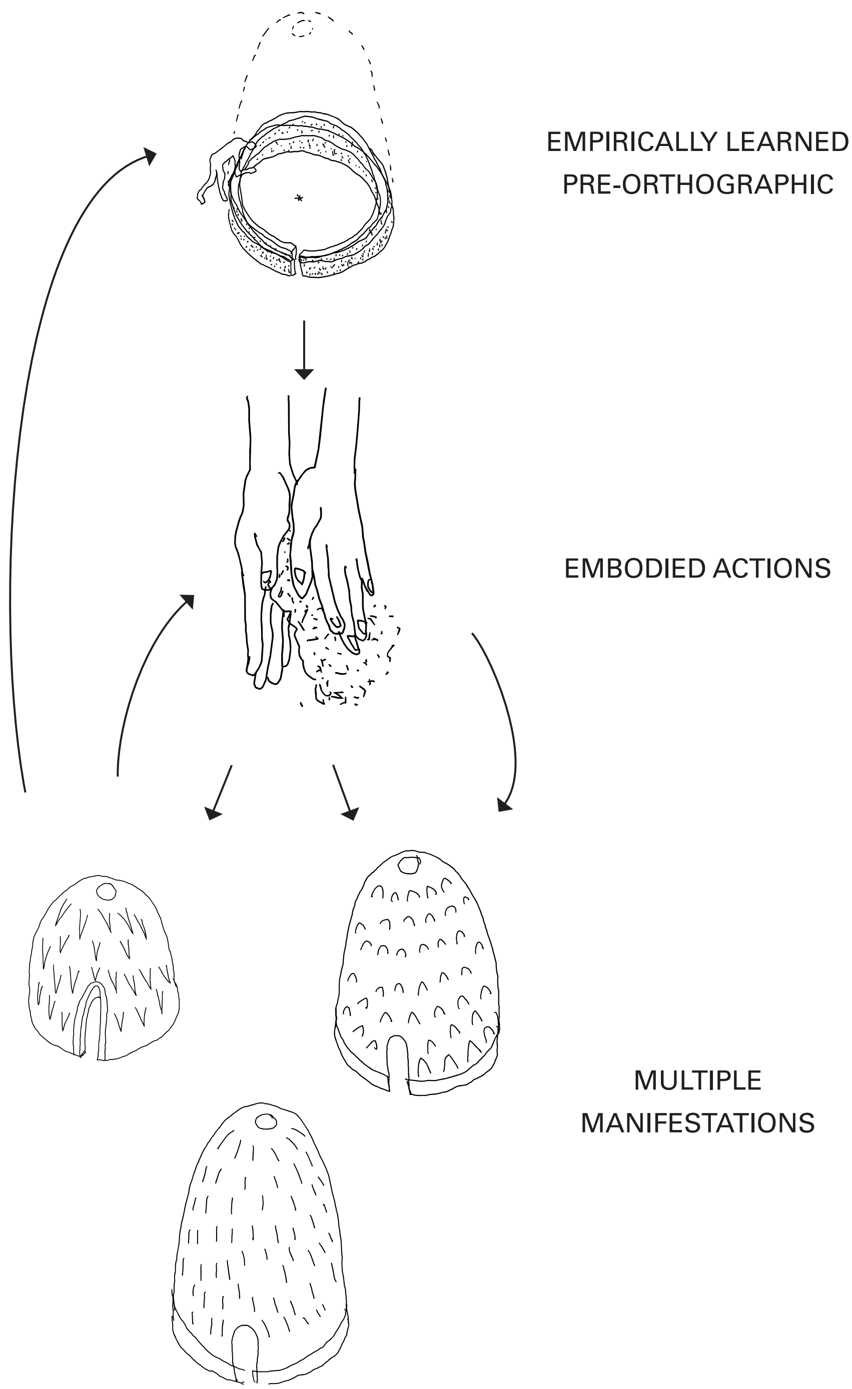


Figure 3. Mousgoum teleuk construction

29
Nelson also notes that although plastering was, and still is, a gendered activity, women have begun to use the building's skin as a canvas for their empowerment. Ibid., 41.

and the quirks of each mason's unique execution. Obsolescence becomes a meaningless concept, as the teleuk is rematerialized with each re-plastering. According to Nelson, "women plaster the houses and walls with a layer of clay to protect the buildings from the deterioration caused by winds and summer rains. To plaster a house is to embellish it."[29] Ornament is instrumentalized to extend the time between repairs. Destabilizing the modernist illusion of immobile time, the teleuk is constantly rebuilt and re-finished, its skin incorporating its means of maintenance (Figure 4).

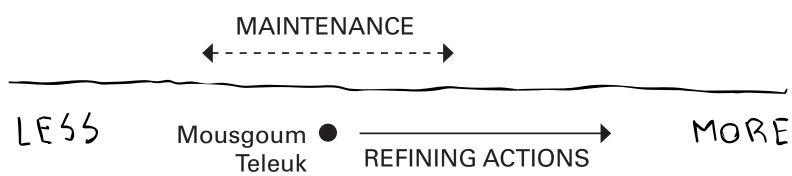


Figure 4. Exactitude as defined by fidelity of material control

While the Guggenheim Museum is more exact considering its dimensional stability—as Wright urges Cohen, the builder, to better approximate his schema—, it is construction with low-fidelity actions: spraying onto formwork constructed according to architect-approved specifications, abstracting concrete as a material that can be totally manipulated to take on almost any form. On the other hand, the teleuk requires a more exact set of actions, a higher fidelity of material control by the precise placement and movement of the hand. However, the building does not follow a singular

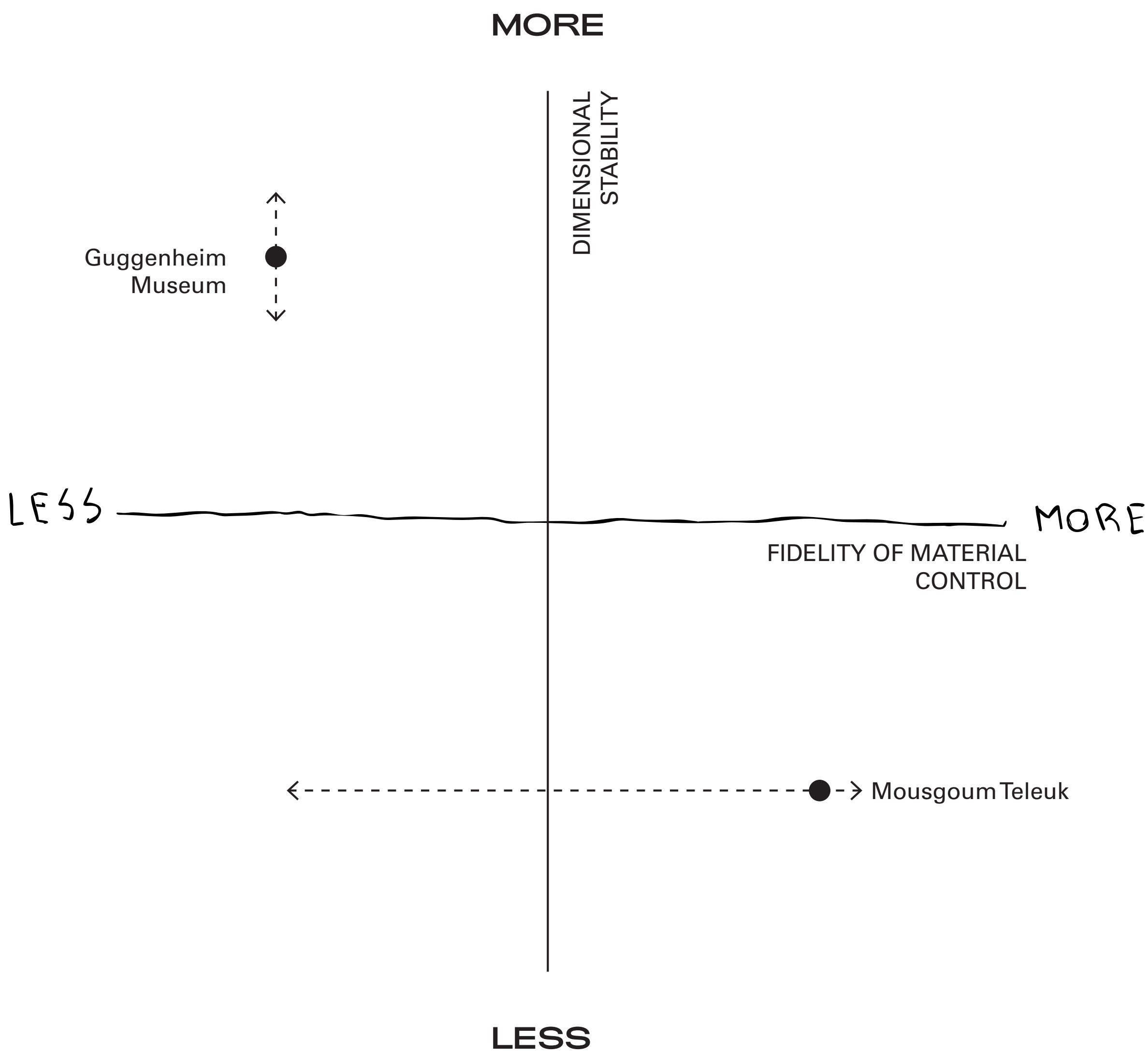


Figure 5. Expanded Exactitude - Two Axes

schema or prescribed geometry. It is never defined but emerges from the performance of myriad exact hand interactions with matter. The two examples allow us to overlap two axes that provide competing, divergent definitions of exactitude (Figure 5). The space produced by the overlap exposes the remaining two quadrants, the lower left and the upper right, as the zones of the 'more and more' and the 'less and less.' In the latter, formless matter faces no resistance. In the top-right quadrant, formless matter struggles to become form through dimensional and material control.[30]

The top-right zone operates under the premises of the high finish, precise actions, low tolerances, and low risk. In stark contrast to Pye's description of high-risk craftsmanship, this quadrant manifests what architect Scott Marble flags as a "broad social and cultural tendency toward knowledge leading to predetermined outcomes (certainty), and despite the association of ideas such as mass customization, variation, and differences with current digital processes, [it is] arguably a continuation and acceleration of a modernist obsession with control, optimization, and efficiency through machine processes."[31] In order to minimize the risk of human error, the workers implicated are frequently deskilled. Paradoxically, as Marble notes, some of these processes reproduce the variation Pye calls for, even though replacing those with low-risk, intervention-free equivalents.[32] This quadrant ensures high-fidelity material control by precisely describing and executing actions, and it reaches for the highest level of dimensional stability by minimizing tolerances.

The upper zone as a whole (above dashed line) establishes an aesthetic regime that rejects the lower left as abject and the lower right as absurd (Figure 6). However, this regime produces waste in two ways: one, by obsessively disciplining matter to approach the desired geometry and therefore producing material discards; two, by implementing planned obsolescence, producing a taste that rejects anything below the line. The secondary consequence of our desire for the perfect is excessive material extraction and consumption. In the shadow of the modernist model, in pursuit of ideal geometries, we extract more and more from limited resources,

30
Deposition systems have the potential to provide an alternative to the modernist myth of concrete and recapture material discards, as we have seen in some efforts to recycle or upcycle shredded materials. However, early projects experimenting with building-scale deposition readily reproduced the modernist conception of exactitude, working towards the more and more: maximum dimensional stability, minimizing construction time, and isolating the machine-as-builder from the architect. They preordained their outcomes by giving totalizing geometric specifications in the form of code. They confirmed the aesthetic regime—the cultural code—of the smooth, the straight, the flat. They controlled—managed—and abstracted materials. If development in deposition continues along these lines, it will only reproduce the previous model under the illusion of "sustainability," creating new "preternatural" materials.

31
Marble, 42.

32
Ibid., 41.

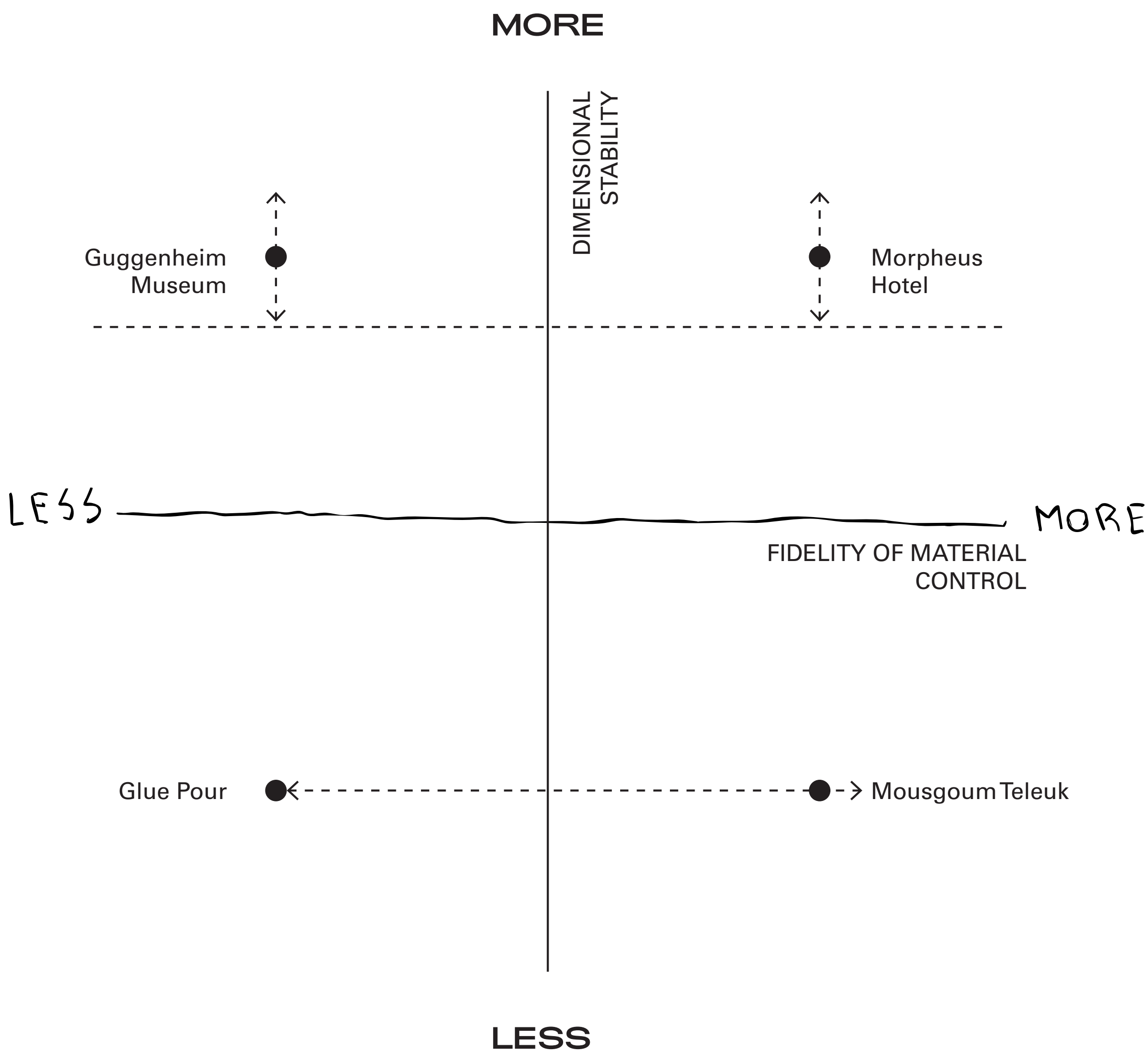


Figure 6. Expanded Exactitude - Examples

33
Branko Kolarevic, "Between Conception and Creation" in *Building (in) the Future: Recasting Labor in Architecture*, 71.

34
Building on Umberto Eco's idea of the open work in *The Open Work*. (Cambridge, Mass.: Harvard University Press, 1989), 9.

35
Gernot Minke, *Building with Earth: Design and Technology of a Sustainable Architecture*. (Basel: Birkhauser-Publishers for Architecture, 2006), 9.

we rely on global infrastructures of material trade, and we reject existing buildings that no longer meet this aesthetic standard. As a result, we are left with tons of construction and demolition waste shredded into grains. What if we treated this shredded material as our site—and challenged our reliance on the linear supply chain? What if we could arrest material in its shredded state to reorient our conception of the grain being on the tail end of decay, and instead to reassemble it into new material hybrids?

Exploring the middle of the diagram—the more and the less exact—enlarges the range of the acceptable—the 'within tolerance' both in a geometric and material sense (Figure 7). This broader scope allows us to notice opportunities that neither privilege one axis over the other nor attempt to reach perfection. Working in this zone implies working with higher risk—and, as Marble notes, with uncertainty. Parametric design practices have long celebrated the image of uncertainty: producing random variance with formal constraints. However, most of this effort is image-oriented: fabricated using computer numerical control (CNC) tools, the materialization is often extremely deterministic. In this process of "directed, precise indeterminacy,"[33] designers relocate creativity to the low-risk domain of the digital. Rather than celebrating digital randomness, we plan precise but under-constraining toolpaths and interact with matter real-time to produce moments of instability that we can later repeat with intention. Moving away from complete numeric or formal predetermination, we design an open process where matter follows the path of least resistance to create "a halo of indefiniteness" rather than either produce a fixed outcome or dissolve into complete uncertainty.[34]

Clay became our testing ground for navigating this expanded domain: a material deeply entangled with building technology throughout the development of prehistoric, industrialized, and automated production. As a building material, clay houses about a third of the world's population—more than half in developing countries.[35] Cast aside as primitive under the modernist quest for new materials, clay recently made a reappearance in industrialized countries, gradually

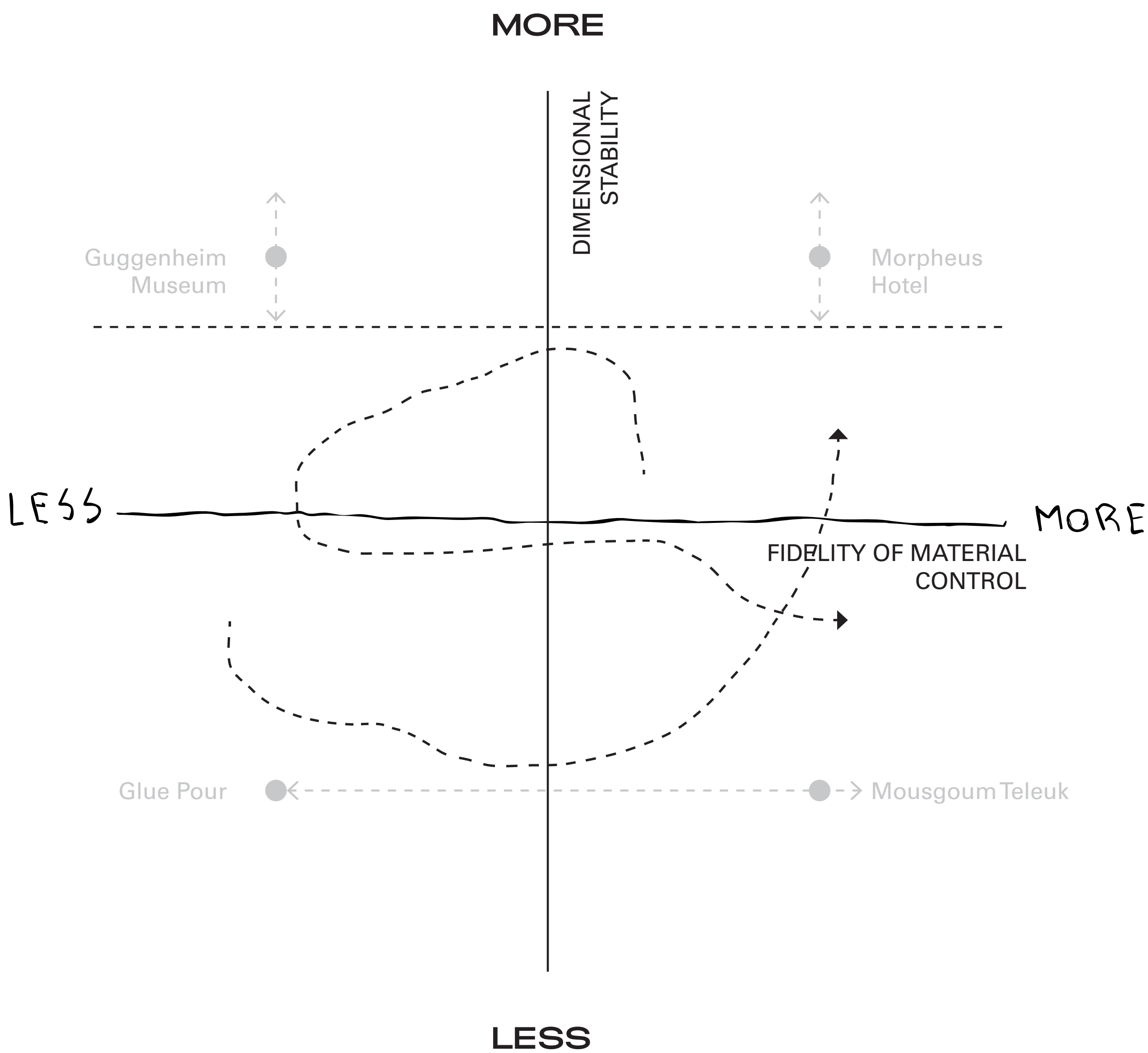


Figure 7. Expanded Exactitude - Navigating the middle

becoming measured, standardized, and "[fragmented] into a vast number of controllable parameters," in a managerial process similar to the reinvention of concrete around the turn of the last century.[36] Clay, however, has qualities that critically differentiate it from concrete, and these qualities allow us to diverge from this managerial impulse and explore the middle of the diagram. First, its potential to be adjusted over time—unless fired—facilitates the performance of a sequence of actions to manipulate the same surface.[37] Second, as a readily available, local resource, clay is already site—if not the ur-site—as well as an apt analogy and a binder candidate for material hybrids.[38] The rich history of building with clay—carving, coiling, stacking, extruding, compressing—provides unending inspiration for contemporary construction.

In the following, we begin with experiments, where we explore the limits of the diagram—its edges (Figure 8). We then formulate spatial strategies, learning from the qualities we found in our experiments and embedding intention in those. Last, we speculate on building as process: building as a sequence of approximations over time, rather than an immobilized ideal geometry. Through these probes, we outline an alternative attitude towards hybrid manufacturing in two aspects: one, we propose working with increased tolerances to allow the material to perform more and the designer to prescribe less; two, we speculate about a different approach to temporality in the design process, where the outcome of a single operation—due to a careful consideration of material properties—does not fix the object in time but allows further transformations by compounding actions. This resists the complete mathematization of matter. We design with instability and anticipation: rather than completely numerically predetermining outcomes, we produce an open score that leads to different manifestations that are consistent within a range, and that fulfill certain intentions. Material and interaction, rather than script and bits, perform this score. This openness carries the promise of reintroducing authorship and promoting different understandings of labor in an otherwise increasingly automated process. It is a risky endeavor.

36
Osman, "The Managerial Aesthetics of Concrete," 67.

37
To achieve this, we created a condensation cube to keep the outcome of one action moist enough for the layering of another action—similar to the pottery technique of enclosing leather-hard clay in wet plastic wrap as it gets ready for trimming.

38
Potters and masons alike have long mixed materials—grass, paper, wood fibers, blood, and the list goes on—into clay to create a composite with their desired structural and aesthetic qualities.

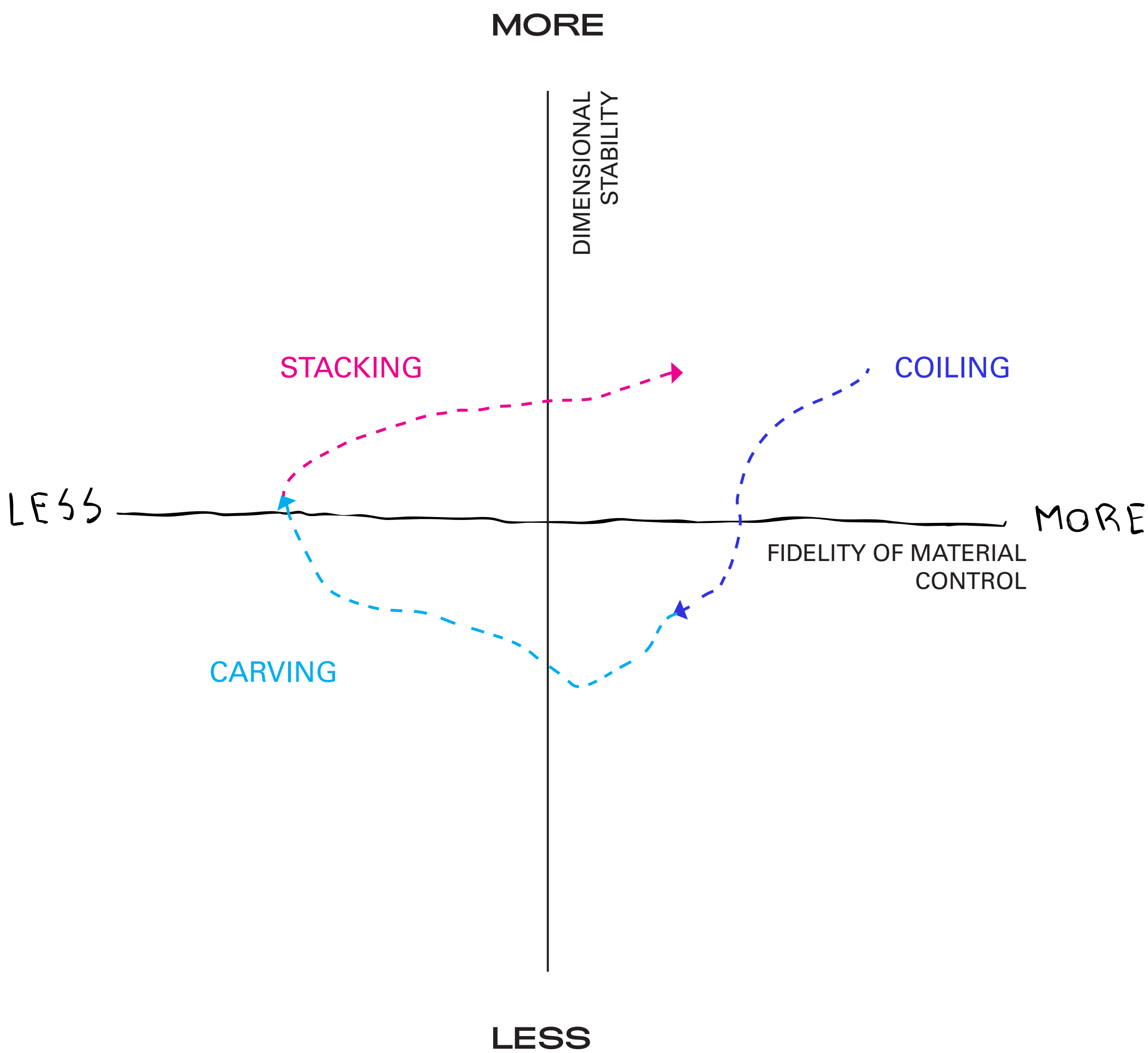


Figure 8. Expanded Exactitude - Compound actions

ACTIONS

Designing, modifying, and iterating on our own tools not only expands the architect's role from specifying form to specifying actions and tools that perform those actions, but it also defines and constrains the space that we operate in. Instead of using the machines and tools currently available for clay manipulation,[39] we decided to design and fabricate most of the machine parts. This decision came partly from our ambition to overcome the symptomatic divide between those who specify (architect) and those who deliver (builders). Without a consolidation of entities between designer and fabricator, the embodied knowledge that stems from the friction between formal-numeric specification and matter—crystallized through the set of actions that deliver the form—is lost. As such, our motivation was not to improve on previous designs but to gain understanding and flexibility in modifying the experimental setup, effectively inducing ourselves to perform both the role of the specifier and that of the builder. Looking at existing extruder designs as a starting point,[40] we created and modified our own CAD geometries and mechanical connections as our extruder design evolved, as discussed below.

In this study, the basis of material control is established by the uniform extrusion of matter.[41] We used a mechanical ram extruder that allows for constant volumetric extrusion. In the initial design, clay was hand-loaded into a 3" inner diameter rigid polyethylene terephthalate (PETG) tube (Figure 1-2). On the rear end, the PETG tube was connected to a piston driven by a 1.9 Nm stepper motor with a 3:1 reduction gear. On the front end, the PETG tube was connected to an 8 mm inner diameter, 1200 mm long flexible polyurethane tube via a custom high-density polyethylene (HDPE) pipe reducer. The flexible tube fed clay into a custom-made nozzle assembly attached to the KUKA KR6-900 arm (Figure 9). This setup was a rather wishful design, and we quickly realized that the pressure built up over the length of the hose was much greater than the motor's capacity. We increased the water ratio in clay to compensate for this, and found that the increased moisture content (~35%, slip-like) made clay easier to push through the tube at the cost of its structural stability.

39
Some of these systems are entering full commercialization and mass production, such as 3D Potter's machines that sell in the range of thousands of dollars. Other designs are either completely or partially open-source, a famous example in the clay deposition community being Jonathan Keep's delta printer.

40
Such as Stoneflower's open-source design, or Olivier Van Herpt's iterations. See Olivier Van Herpt, "3D Printing Ceramics." Accessed January 12, 2020. http://oliviervanherpt.com/3d-printing-ceramics/ and Anatoly Berezkin, "Open Source Print Head For Clay by Stoneflower." Accessed January 12, 2020. https://www.stoneflower3d.com/opensource/.

41
While clay extruders are omnipresent in today's deposition industry, they are not new. These extruders combine the ancient pottery technique of coiling and the industrialized process of clay extrusion. See Willi Bender and Hans H. Böger's discussion, "A Short History of the Extruder in Ceramics," in *Extrusion in Ceramics*. Berlin: Springer, 2007.

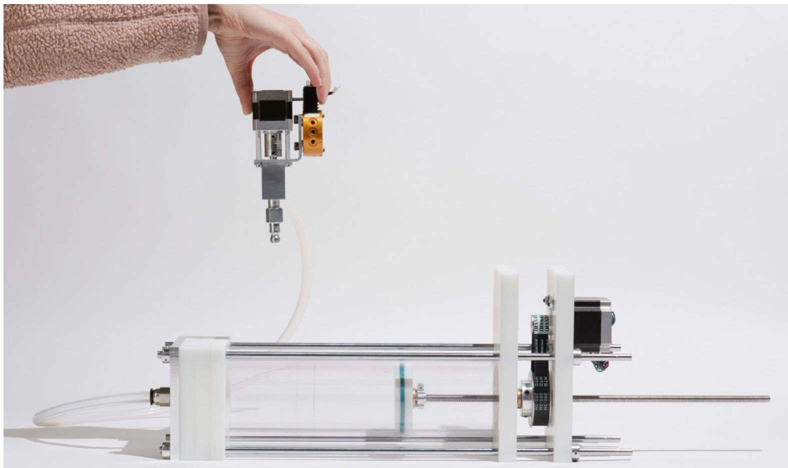


Figure 9. Initial extruder design

Had we purchased an existing extruder, we would have worked around the limitations of the tool by altering the composition of the material. However, since we designed the extruder ourselves based on open-source examples, we were able to modify the tool itself. We proceeded to modifying the motor and the diameter of the hose itself, upgrading to a 4.0 Nm stepper motor and an 80:1 worm gearbox, combined with a 0.75″ inner diameter, 5-foot long, high-pressure, braided flexible polyvinyl chloride (PVC) tube—to have more extrusion force and to reduce the pressure build-up over the length of the 5-foot tube (Figure 12). This allowed us to use a clay body with close to 28% moisture content—what ceramicists refer to as "throwing" consistency, and what was much more structurally stable.[42] We tested the limits of the clay body by directly using the pre-mixed clay we bought (with around 25% moisture content), and we found that despite the motor having sufficient torque, other parts of the extruder assembly began to fail. The piston shaft started buckling, and eventually, the rigid PETG tube cracked. At the lower limit of moisture content, the clay also did not have enough viscosity to adhere to the previous layer.

We also tested controlling the start and stop of the extrusion using an auger extruder at the nozzle end, using the Stoneflower OpenSource auger design as a starting point.[43] We had issues with the nozzle leaking at the coupling. Since our material feed tube increased in size from 8 mm inner

42
In some cases, we have seen the whole extruder assembly mounted directly onto the robotic arm, but in our case, there was an absolute weight limit of the KUKA arm we were using (6kg) which we could not alter.

43
Berezkin

Figure 10. Universal tool holder for carving tools

Figure 11. 6 mm nozzle, elongated tip to prevent potential collision

diameter to 0.75″ inner diameter to accommodate lower moisture content and larger particles in the clay bodies, our initial auger design was no longer compatible with the system, thus we have not pursued this option further. In this case, we designed around the limitations of the tool by incorporating a reversing toolpath that produced 'seams'—which in turn informed and influenced the design decisions of the trajectories, as discussed later.

Both carving tool and nozzle designs open up a large design space within the same toolpath definition and clay body. We 3D printed and tested several nozzle types for some of the basic actions we studied (Figure 11). We used circular and square dies in nozzle diameters from 1 mm to 8 mm. We also tested, but moved away from, non-platonic die-shapes, which have a large potential for future explorations, especially in a 6-axis setup.

Initially, we created a series of adjustable universal tool holders for the carving tools (Figure 10) , integrating hand tools into our digital-to-physical workflow. The use of carving tools—in what achieves subtractive manufacturing—highlighted the challenge of precise calibration, both of the carving tool itself and of the extruder nozzle; any error in the calibration of the extruder was compounded by the error of the calibration in the carving tool. Moreover, as clay began to shrink and deviate from its originally prescribed position, the carving tool traced the prescribed geometry and carved away materials that deflected to the point of taking off a whole chunk of the surface. This prompted us to consider 3D scanning (in our case, photogrammetry) as an intermediary step between two actions.

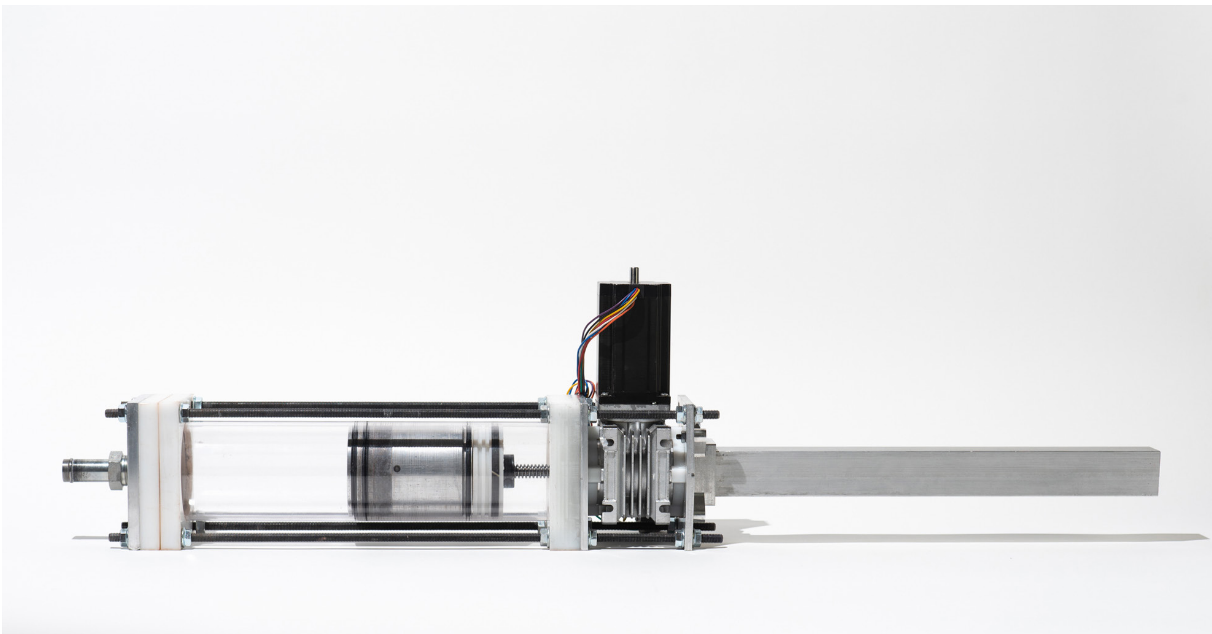
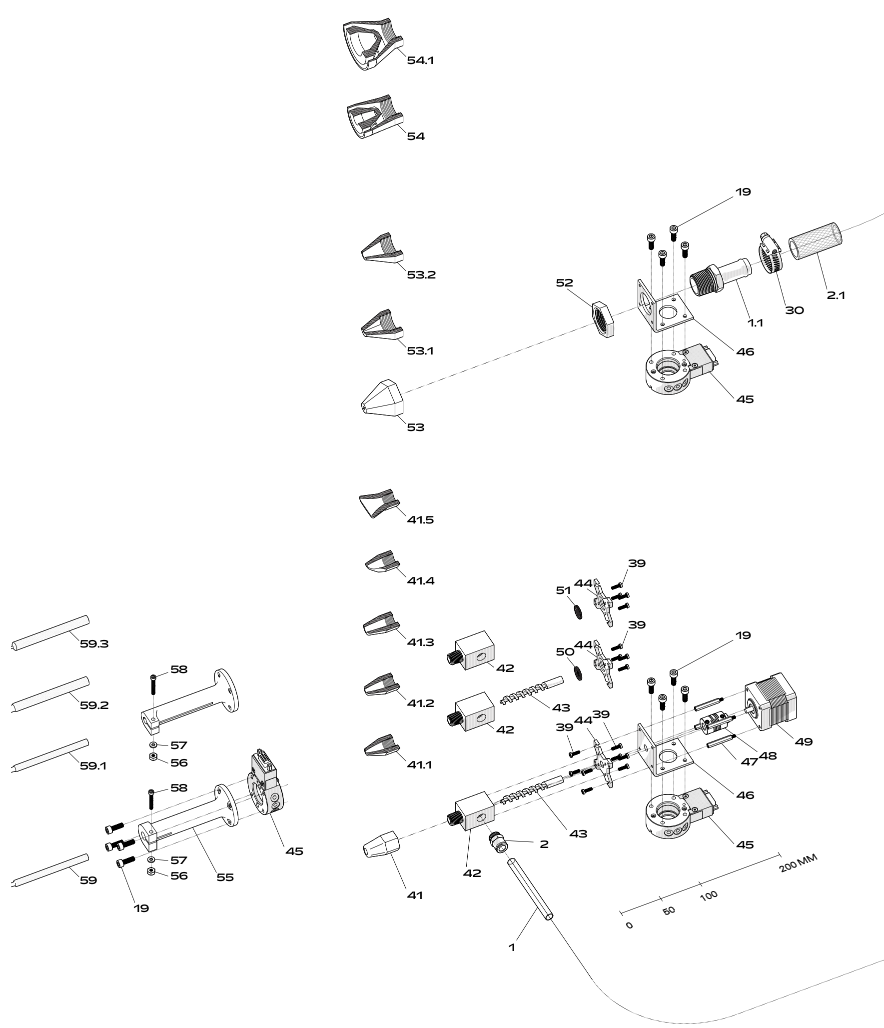
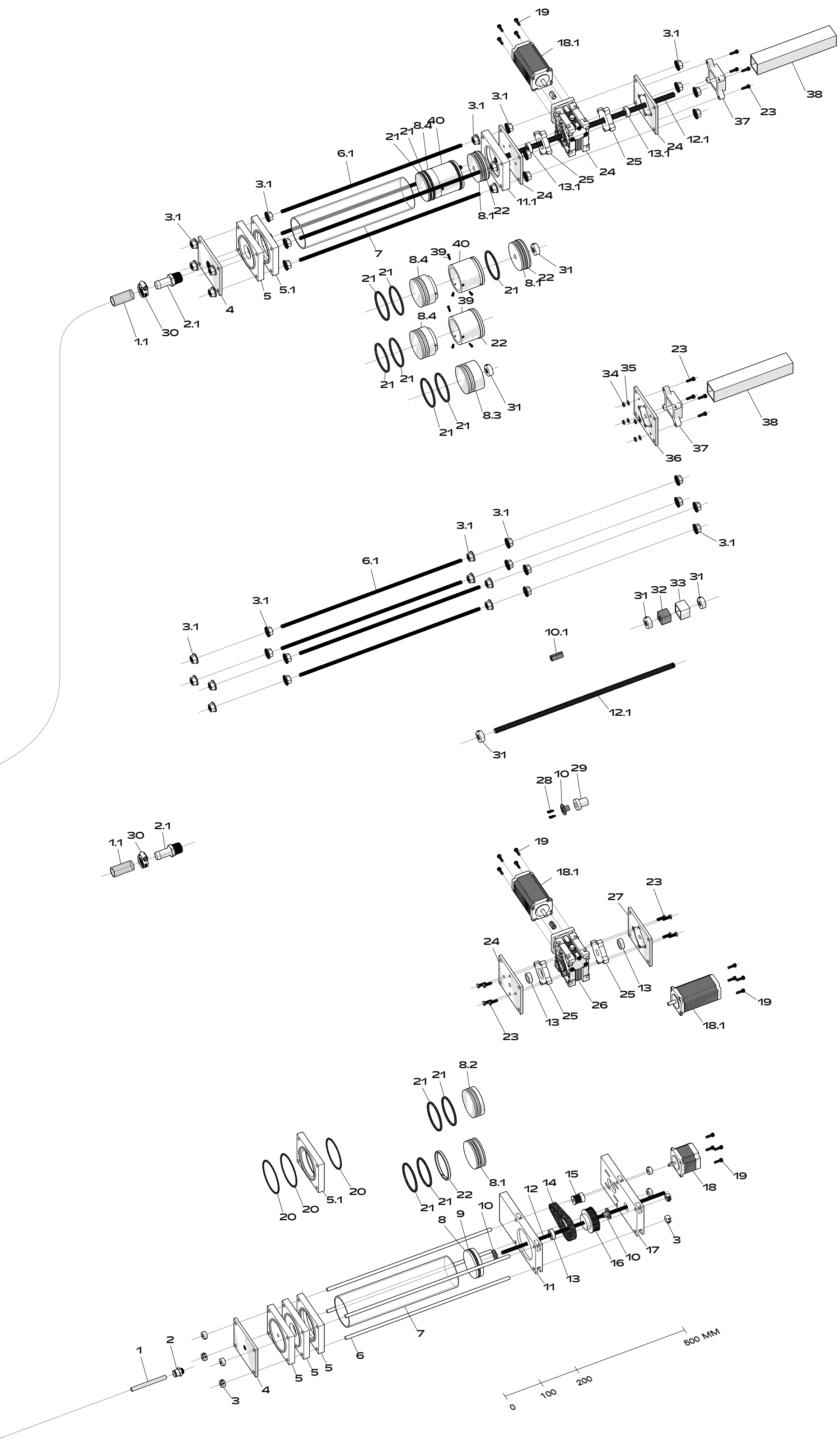


Figure 12. Final extruder design

1 8MM ID HOSE
1.1 .75" ID HOSE REINFORCED HIGH PRESSURE
2 8MM ID PUSH-TO-CONNECT HOSE ADAPTER
2.1 .75" ID HOSE ADAPTER
3 8MM SHAFT COLLAR
3.1 8MM LOCK NUT
4 FRONT CAP PLATE*
5 FRONT REDUCTION PLATE*
5.1 FRONT REDUCTION PLATE W/ LIPPED SEAL*
6 8MM X 400MM STAINLESS STEEL SHAFT
6.1 8MM THREADED ROD, HIGH STR STEEL
7 3" ID / 3.25" OD X 12" CLEAR PETG TUBE
8 HDPE PISTON*
8.1 HDPE PISTON, DOUBLE O-RING*
8.2 ALUMINIUM PISTON, DOUBLE O-RING*
8.3 ALUMINIUM PISTON, WEAR RING*
8.4 MODIFIED ALUMINIUM PISTON*
9 HEAD SEAL, 3" BORE
10 M8 ACME LEAD NUT
10.1 M12 ACME LEAD NUT - NMRV-030 GEARBOX*
11 HDPE BACK PLATE #1*
12 M8 X 3MM ACME LEAD SCREW
12.1 M12 X 3MM ACME LEAD SCREW
13 BALL BEARING, 8MM BORE
14 TIMING BELT, 120MM
15 TIMING BELT GEAR, 20 TEETH
16 TIMING BELT GEAR, 60 TEETH
17 BACK PLATE #2*
18 NEMA 23 STEPPER MOTOR, 2.6 N/M
18.1 NEMA 24 STEPPER MOTOR, 4 N/M
19 SOCKET HEAD SCREW, M5
20 1/16" RUBBER GASKET*
21 X-PROFILE BUNA-O-RING, 3" BORE
22 GLASS-FILLED NYLON WEAR RING, 3" B
23 12-24 X .75" FLAT HEAD SCREW
24 BACK PLATE #3 FOR GEARBOX*
25 HDPE GEARBOX TO PLATE CONNECTOR*
26 NMRV-030 SPEED REDUCER 80:1 RATIO
27 BACK PLATE #4 FOR GEARBOX*
28 M3 X 50MM SOCKET SCREW
29 LEAD NUT TO GEARBOX COUPLER*
30 1.25 - 1.5" TUBE CLAMP
31 SHAFT COLLAR - M12 / 3MM LEAD SCREW
32 SQUARE NUT - M12 / 3MM LEAD SCREW
33 1" X 1", 1.25" X 1.25" SQUARE ALU SECTION
34 M5 LOCK NUT
35 M5 WASHER
36 BACK PLATE #4 FOR GEARBOX**
37 BACK PLATE #4 / SQUARE COUPLER*
38 1.5" X 1.5" SQUARE SECTION, 24"
39 M3 X 10MM LOW SOCKET HEAD SCREW
40 PISTON EXTENDER*





41	6MM PLA CIRCLE NOZZLE, 1/4” NPT*
41.1	2MM PLA CIRCLE NOZZLE, 1/4” NPT*
41.2	4MM PLA CIRCLE NOZZLE, 1/4” NPT*
41.3	8MM PLA CIRCLE NOZZLE, 1/4” NPT*
41.4	4MM PLA ANGLE NOZZLE, 1/4” NPT*
41.5	2 X 12 PLA LIN. NOZZLE, 1/4” NPT*
42	AUGER HOUSING / RECEIVER*
43	AUGER SCREW, 8MM DIA
44	TWIST-TO-LOCK COUPLING*
45	KUKA END EFFECTOR MOUNT
46	BRACKET TO CONNET NOZZLE, ARM*
47	M3 X 30MM ALUMINIUM STANDOFF
48	6MM X 8MM FLEX. SHAFT COUPLING
49	NEMA 17 STEPPER MOTOR
50	1/16” GASKET FOR AUGER*
51	1/16” GASKET FOR ENCLOSURE*
52	3/4” PLA NUT*
53	2MM PLA CIRCLE NOZZLE, 3/4” NPT*
53.1	4MM PLA SQ. NOZZLE, 3/4” NPT*
53.2	6MM PLA CIRCLE NOZZLE, 3/4” NPT*
54	40MM HOLLOW NOZZLE, 3/4” NPT*
54.1	60MM HOLLOW NOZZLE, 3/4” NPT*
55	PLA CARVING TOOL MOUNT
56	6-32 LOCK NUT
57	6-32 WASHER
58	6-32 X 1” SOCKET HEAD SCREW
59.1	CARVING TOOL #1
59.2	CARVING TOOL #2
59.3	CARVING TOOL #3
59.4	CARVING TOOL #4

Figure 13.
Tool chronology, showing the evolution of the design


1


2


3


1


2


3


4


5


6

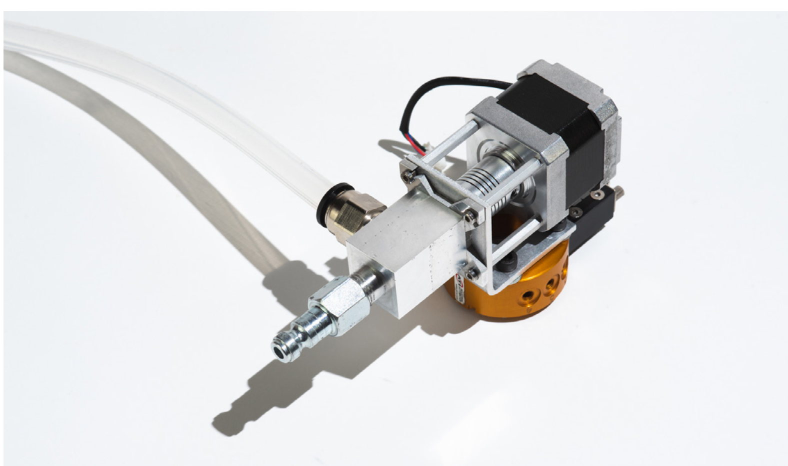

7


8


9


10


11


12

1
Carving tool #4, flat tip

2
Carving tool #1, tapered tip

3
Carving tool #2, open-loop tip

4
Carving tool #3, rigid scoop tip on a variable angle mount

5
Spring-loaded pen mount

6
Nozzle, 3 mm

7
Nozzle, 6 mm

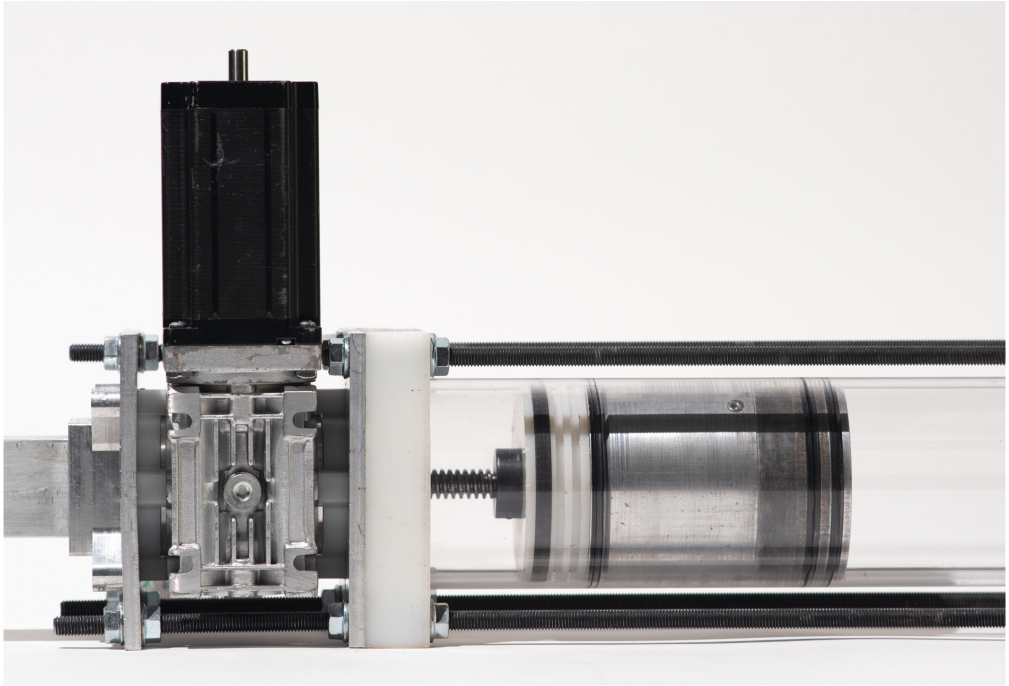
8
Elongated nozzle, 4 mm

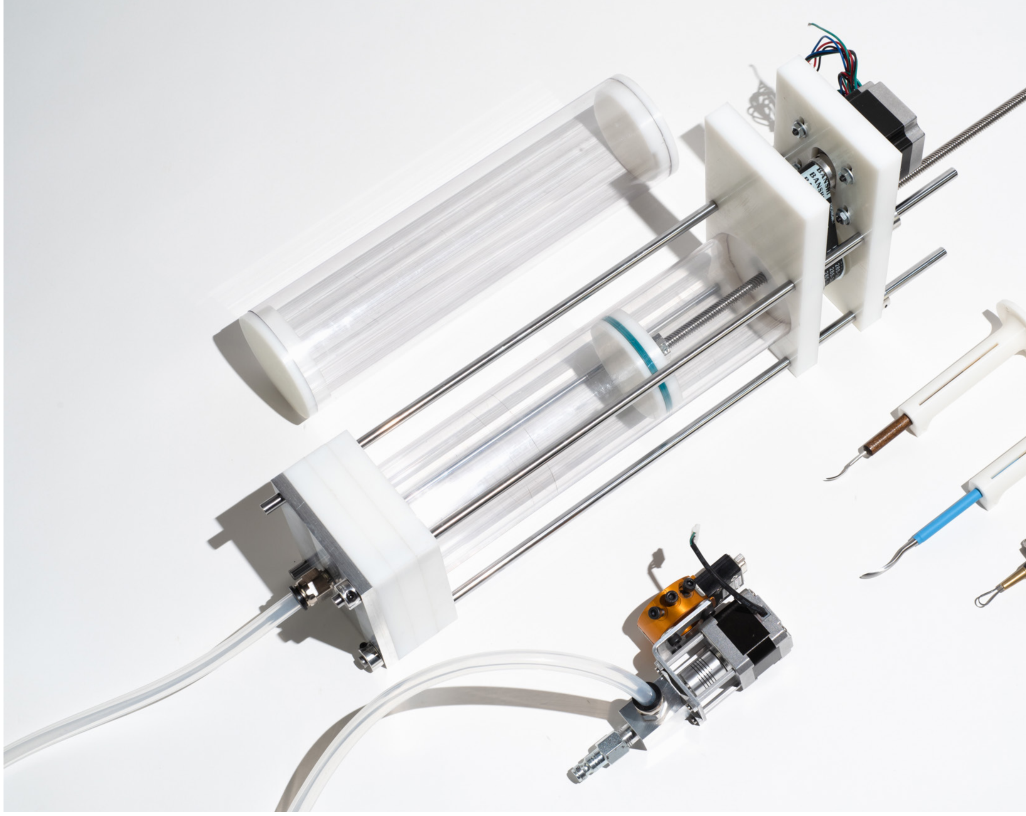
9
Elongated nozzle, 6 mm

10
Nozzle with extension, 4 mm

11
Hollow tube nozzle, 60 mm

12
Auger extruder nozzle





EXPERIMENTS

Figure 14. Manual intervention on 04–02–01

Figure 15. Modulating toolpath speed on 02–03–02

The experiments populate the edges as well as the middle of the diagram—some objects are on the verge of collapse, some pile up formlessly, some approximate the formal-numeric geometry almost perfectly. The experiments isolate specific actions to study the results with and without intervention. We kept all but one parameter constant to study the different outcomes produced by changing each parameter. In all subsequent studies, we restricted the definition of material control to modulating extrusion speed, KUKA toolpath speed, layer height, and angle of action. In general, the higher the density of actions, the higher the geometric fidelity, and the more suppressed the material behavior. Conversely, the lower the density of actions, the lower the geometric fidelity, allowing the material to perform. We define intervention as an improvised change of course—a deviation from the encoded toolpath or another change of material behavior by hand, or by any extension of the hand (through real-time speed control, for example). This intervention can be later encoded in a modified process. Although beyond the scope of this project, many future research opportunities abide in the further exploration and more complex implementation of this feedback loop.

The following pages document each of these studies. First, we test each action with no intervention. Then, some actions are repeated with intervention. Following this intervention, we encode the modifications to make the process repeatable. For example, in the case of study 02–03–01, the layer height was 3 mm, the nozzle size was 2 mm, the extruder speed was 0.1 mm/s, and the toolpath speed was 0.15 m/s. In this initial experiment, all of these parameters were kept constant to only compare with previous studies of different layer heights. However, in 02–03–02, with layer height, nozzle size, and extruder speed kept constant and identical to the parameters in 02–03–01, we started modulating the toolpath speed in an inverse gradient: as the layers started leaving behind the deposited clay and we noticed rope-coiling, we incrementally decreased speed from the initial 0.15 m/s to 0.02 m/s. For all initial experiments in coiling, stacking, and carving, material control was set at a constant. For all interventions and following studies, material control was modulated and usually followed a gradient. In the compressing section, this encoded behavior was studied as an experiment in itself, laying out layer heights according to different distributions.

Coiling performs a simple layer-by-layer deposition following the long-practiced hand-building technique of the same name. In the experiments with different degrees of material control, coiling can produce liquid rope-coiling due to insufficient layer density—or in our terms, a lower fidelity of material control—an otherwise much-studied non-Newtonian behavior.[44] Rather than treating this as an error, the experiments begin to work with this property, and the strategies section begins to design with it.

Stacking performs a similar action to coiling, this time with pauses between each step.This temporal play is nothing new—as has been demonstrated by designers and artists alike.[45] We use stacking to create a high fidelity object in terms of material control, producing more stable (yet less geometrically exact) geometries than simple coiling would.

While the experiments isolate actions and only incrementally change parameters, some of them also layer operations in hybrid processes. Carving exemplifies this best. Starting out with the same initial operation, in many cases, a very stable 04–02–01, another action is performed on the wet, malleable surface that we keep at a higher moisture level in-between operations.

44
George Barnes, and Richard Woodcock, "Liquid Rope-Coil Effect." American Journal of Physics 26, 205; doi: 10.1119/1.1996110, 1958.

45
See Zach Cohen, "Hold Up: Machine Delay in Architectural Design," Willmann, J., Block, P., Hutter, M., Byrne, K., Schork, T., *Robotic Fabrication in Architecture, Art and Design 2018* (2019): 126-138. 10.1007/978-3-319-92294-2_10.and Anish Kapoor, Adam Lowe, Michael Perry, and Piers Wardle, *Anish Kapoor: Unconformity and Entropy: Greyman Cries, Shaman Dies, Billowing Smoke, Beauty Evoked.* Madrid: Turner, 2009.

Figure 16A. Stacking and carving on 04–02–01S/C2–02

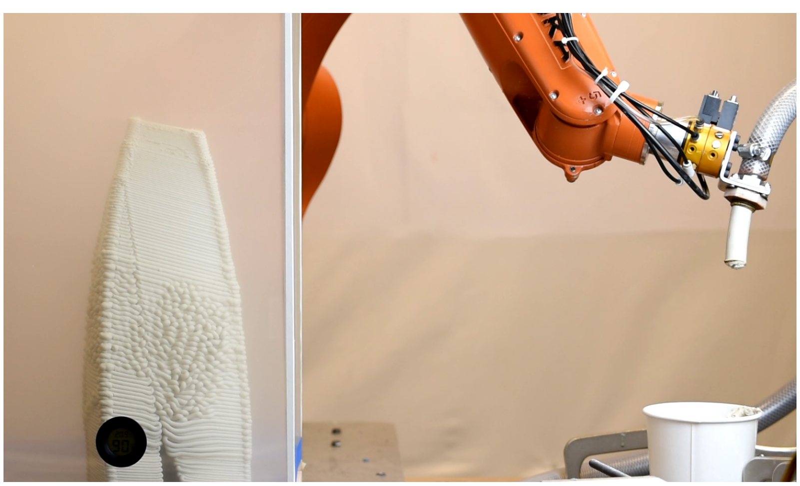
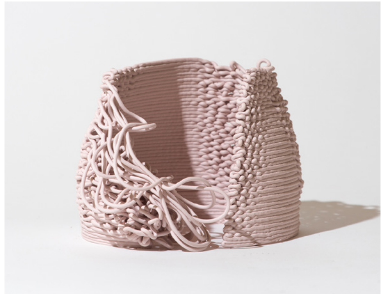


Figure 16B. Condensation chamber keeps clay moist between actions


02-01-01

02-02-01

02-03-01

03-01-01

03-02-01

03-03-01

04-01-01

04-02-01

04-03-01

04-04-01

04-02-01S

04-03-01S

04-02-01/C1-01

04-02-01/C2-01

04-02-01/C1-02

04-02-01/C2-02

02-03-02

04-*-02

04-*-03

Left side of the dotted line represents constant actions. To the right, the actions were intervened on either manually or by adjusting KUKA speed.

COILING

ID

CLAY TYPE

02—01—01

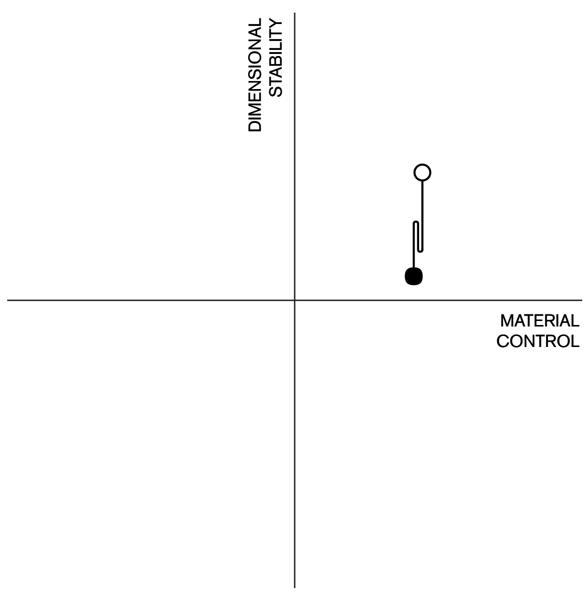
20266 PORCELAIN
MOIST CLAY

LAYER HEIGHT	1 MM
NOZZLE SIZE	2 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	20%
MOISTURE	N/A
SHRINKAGE	14.5%

COMMENTS

CLAY REFILLED DURING EXTRUSION.



ID

02—02—01

CLAY TYPE

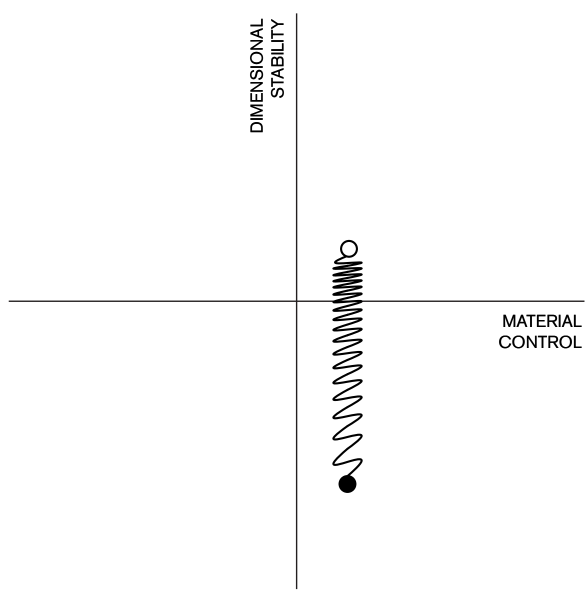
20266 PORCELAIN
MOIST CLAY

LAYER HEIGHT	2 MM
NOZZLE SIZE	2 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	19%
MOISTURE	N/A
SHRINKAGE	14.5%

COMMENTS

INCONSISTENT SPEED INTERPOLATION BY THE KUKA SOFTWARE.



ID

CLAY TYPE

02—03—01

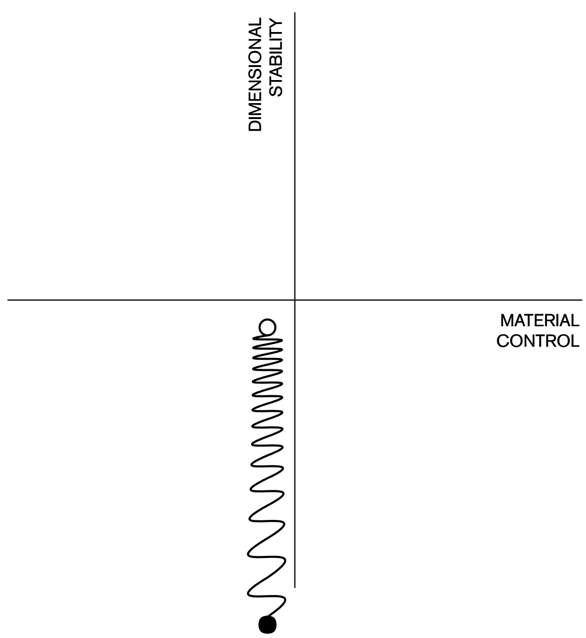
20266 PORCELAIN
MOIST CLAY

LAYER HEIGHT	3 MM
NOZZLE SIZE	2 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.1) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	19%
MOISTURE	N/A
SHRINKAGE	14.5%

COMMENTS

CLAY REFILLED DURING EXTRUSION.



02—03—01 DETAIL

02—03—01 DETAIL

ID

02—03—02

CLAY TYPE

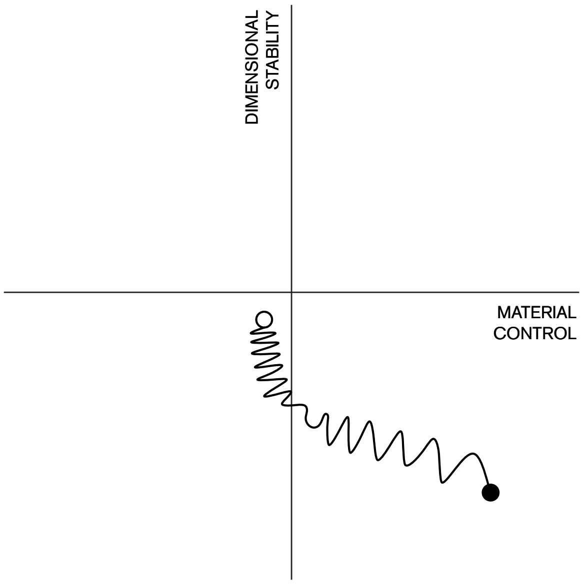
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	3 MM
NOZZLE SIZE	2 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.1*0.2) 0.02 M/S

TEMPERATURE	22C
HUMIDITY	19%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

CLAY REFILLED DURING EXTRUSION.




02—03—02 DETAIL

ID

CLAY TYPE

03—01—01

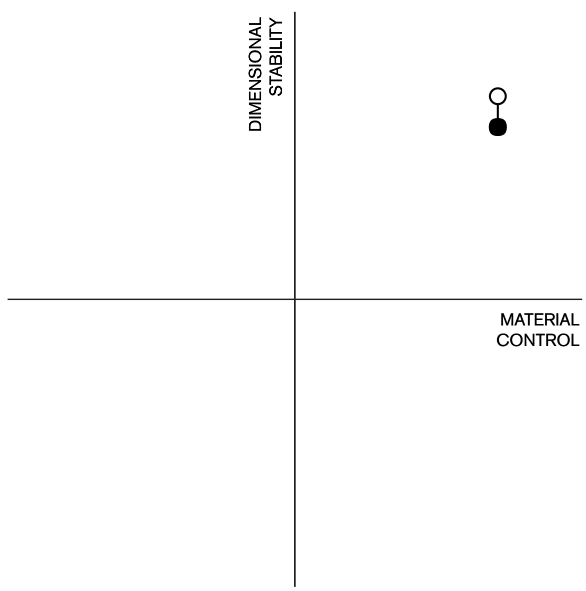
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	1 MM
NOZZLE SIZE	3 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	22C
HUMIDITY	19%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—



ID

CLAY TYPE

03—02—01

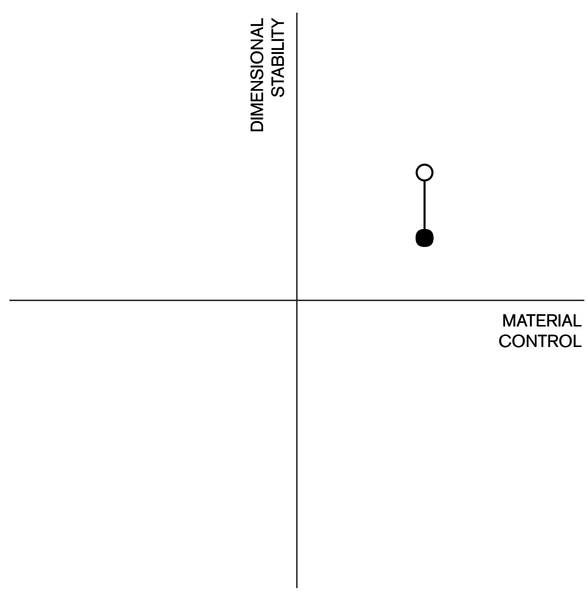
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	2 MM
NOZZLE SIZE	3 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	19%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—



ID

CLAY TYPE

03—03—01

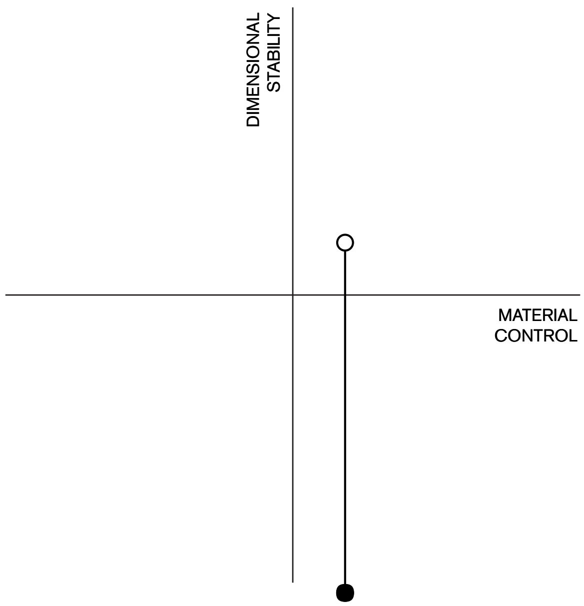
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

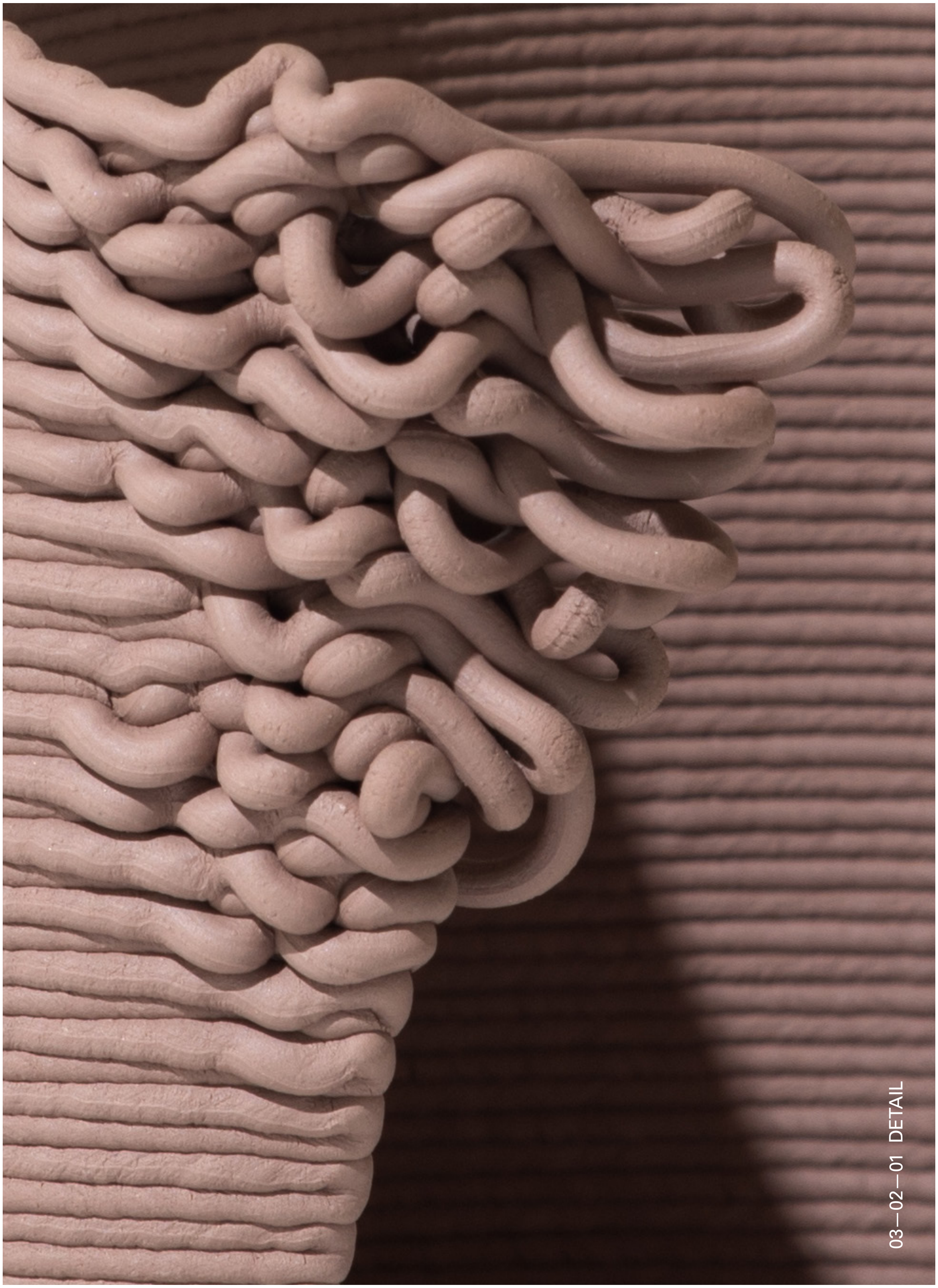
LAYER HEIGHT	3 MM
NOZZLE SIZE	3 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	19%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—




03—02—01 DETAIL

02—03—01 DETAIL

03—01—01 DETAIL

ID

04—01—01

CLAY TYPE

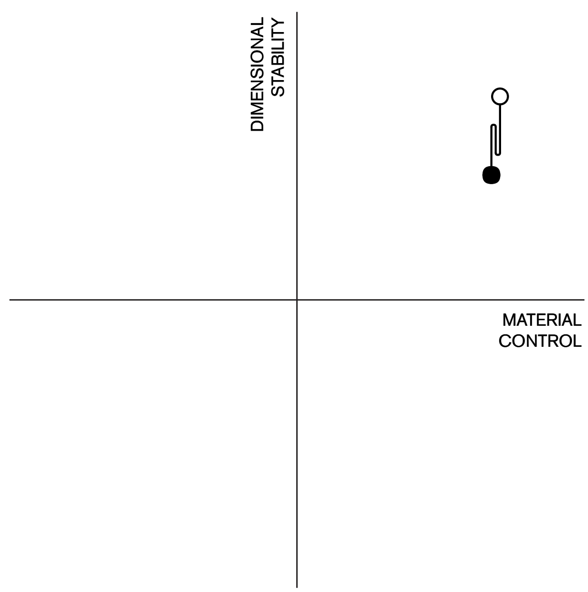
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	1 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	22%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

CLAY REFILLED DURING EXTRUSION.



ID

CLAY TYPE

04—02—01

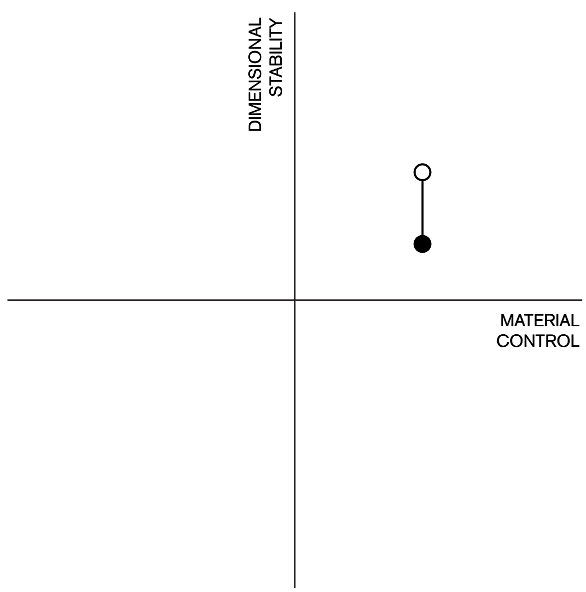
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	2 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	22%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—



ID

CLAY TYPE

04—03—01

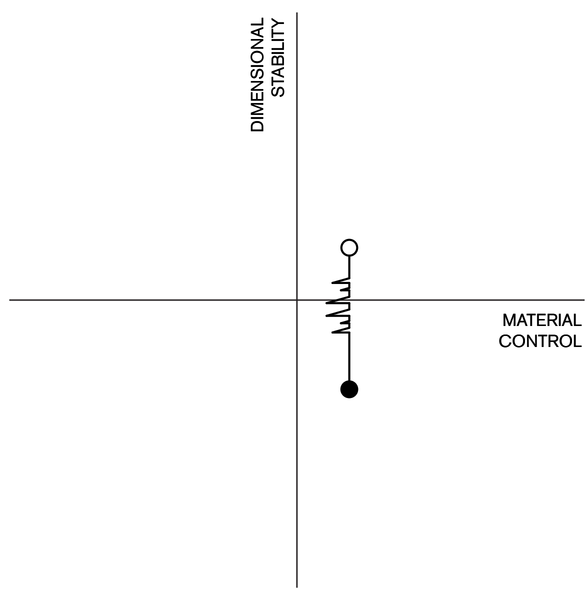
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	3 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	22%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

MANUAL SPEED ADJUSTMENTS TO PRODUCE LAYER VARIATION.



ID

CLAY TYPE

04—04—01

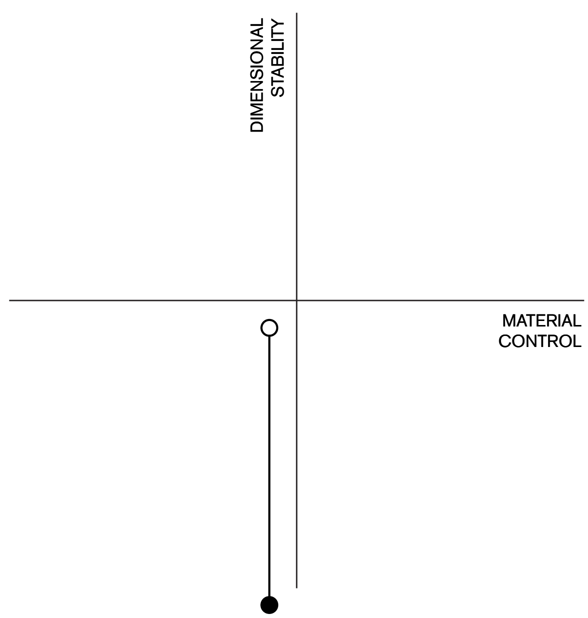
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	4 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	22%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—



04—03—01 DETAIL

04—03—01 DETAIL

STACKING

ID

CLAY TYPE

04—02—01S

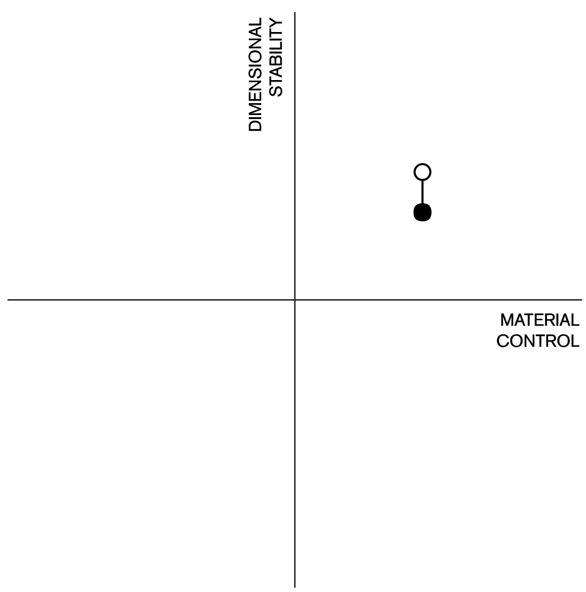
#266 DARK BROWN CLAY
STANDARD CERAMIC

LAYER HEIGHT	2 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S
WAIT TIME	1.5S

TEMPERATURE	23C
HUMIDITY	20%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—



04—02—01S DETAIL

04—02—01S DETAIL

ID

CLAY TYPE

04—03—01S

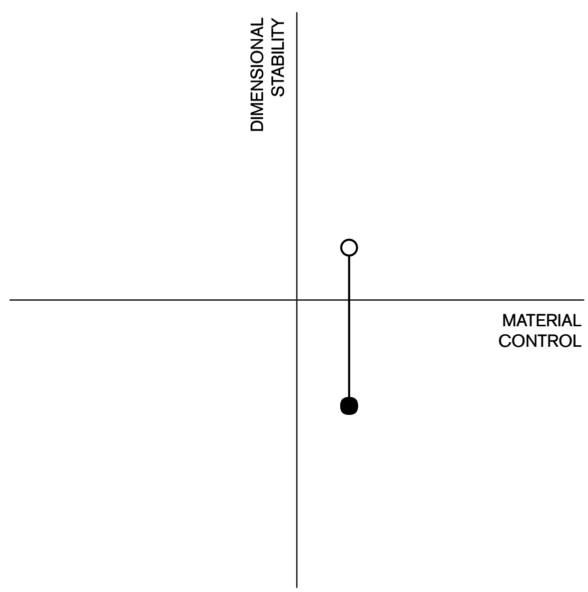
#266 DARK BROWN CLAY
STANDARD CERAMIC

LAYER HEIGHT	3 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	75%
WAIT TIME	1.5S

TEMPERATURE	23C
HUMIDITY	N/A
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—



04—03—01S DETAIL

CARVING

ID

CLAY TYPE

04—02—01/C1—01

4D3B CONE 5 DARK STONEWARE
MOIST CLAY

OPERATION #1

LAYER HEIGHT	2 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

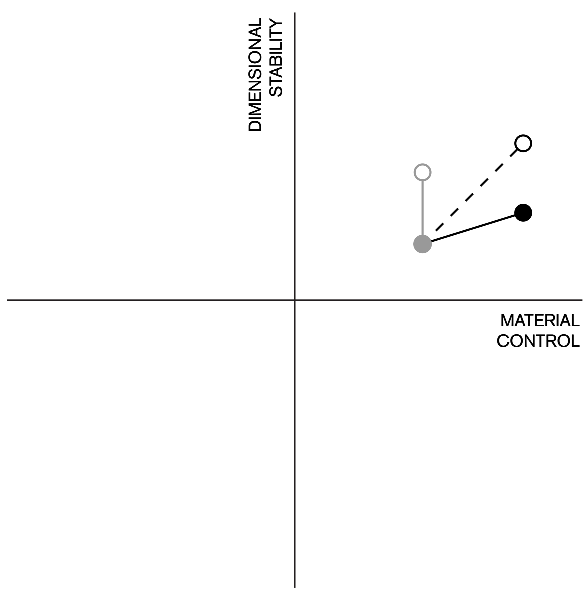
TEMPERATURE	23C
HUMIDITY	20%
MOISTURE	N/A
SHRINKAGE	12%

OPERATION #2

CARVING TOOL	NO.1
STEPOVER	4 MM
CUT DEPTH	2 MM
CARVING PATH SPEED	(0.5*0.2) 0.1 M/S

COMMENTS

EXTRUSION NOZZLE MISALIGNMENT.



ID

04—02—01/C2—01

CLAY TYPE

4D3B CONE 5 DARK STONEWARE
MOIST CLAY

OPERATION #1

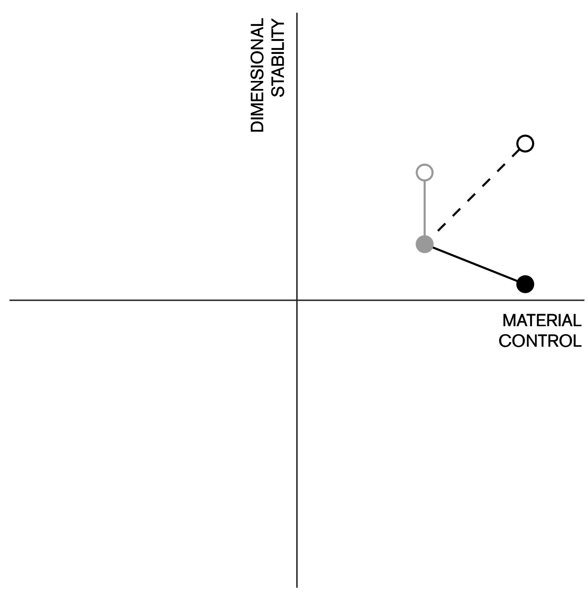
LAYER HEIGHT	2 MM	TEMPERATURE	23C
NOZZLE SIZE	4 MM	HUMIDITY	20%
EXTRUDER SPEED	0.1 MM/S	MOISTURE	N/A
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S	SHRINKAGE	12%

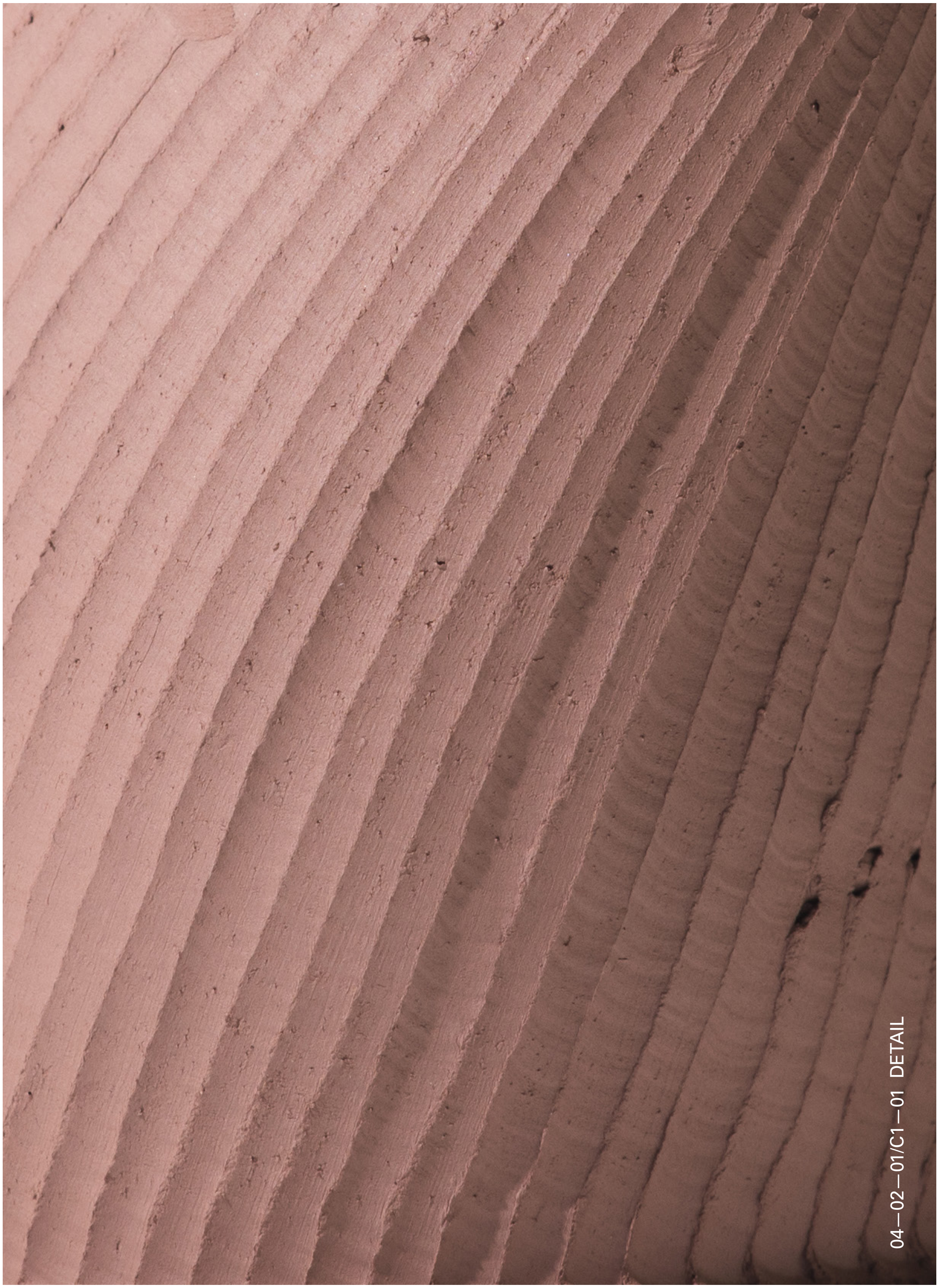
OPERATION #2

CARVING TOOL	NO.2
STEPOVER	4 MM
CUT DEPTH	2 MM
CARVING PATH SPEED	(0.5*0.2) 0.1 M/S

COMMENTS

EXTRUSION NOZZLE MISALIGNMENT.




04—02—01/C1—01 DETAIL

ID

04—02—01/C1—02

CLAY TYPE

4D3B CONE 5 DARK STONEWARE
MOIST CLAY

OPERATION #1

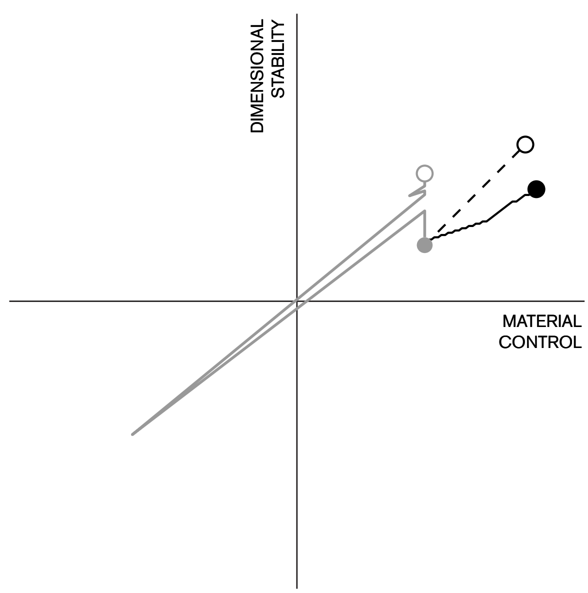
LAYER HEIGHT	2 MM	TEMPERATURE	23C
NOZZLE SIZE	4 MM	HUMIDITY	22%
EXTRUDER SPEED	0.1 MM/S	MOISTURE	N/A
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S	SHRINKAGE	12%

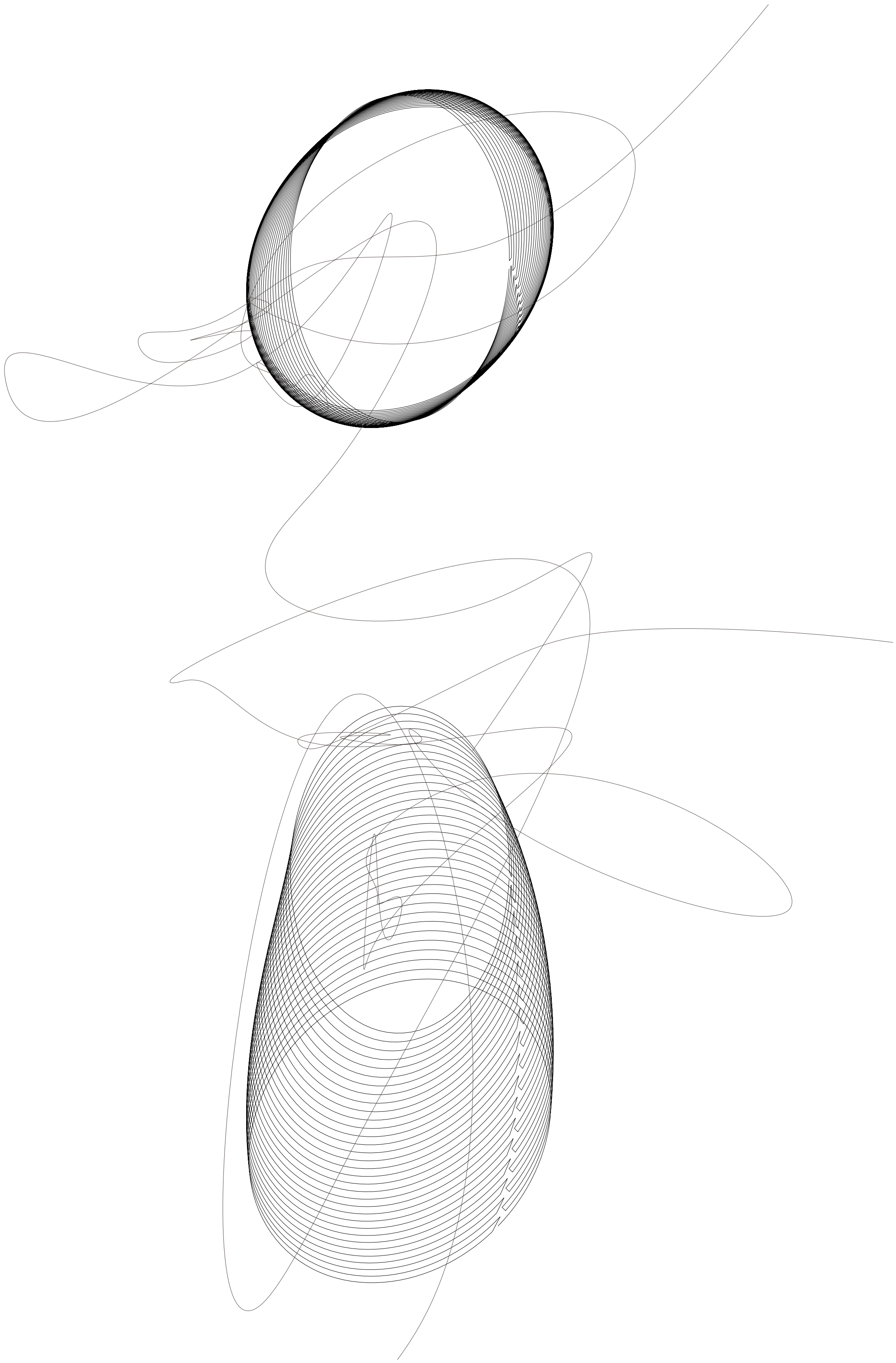
OPERATION #2

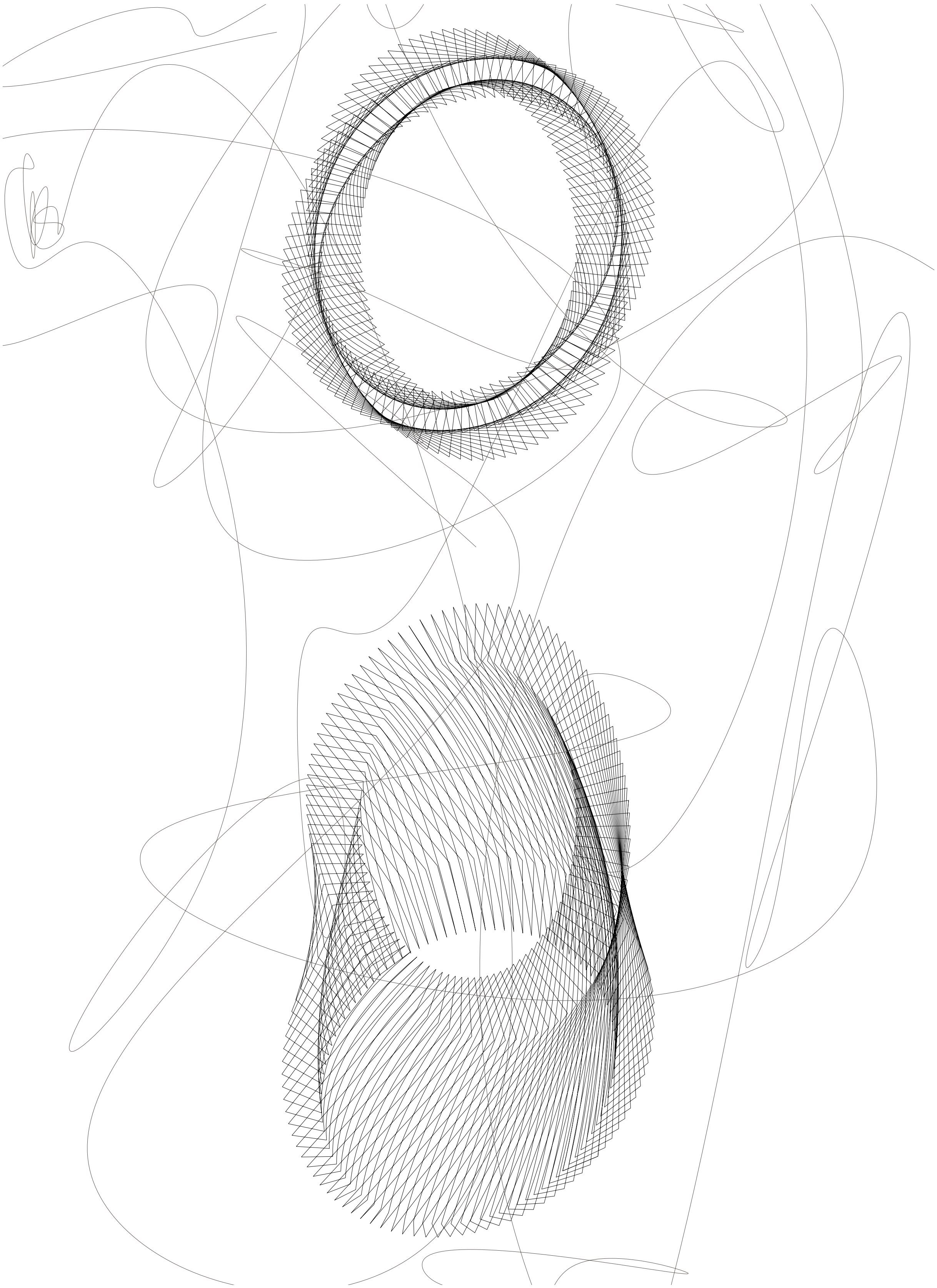
CARVING TOOL	NO.1
STEPOVER	4 MM
CUT DEPTH	2 MM
CARVING PATH SPEED	(0.5*0.2) 0.1 M/S

COMMENTS

EXTRUSION NOZZLE ALIGNED.







ID

CLAY TYPE

04—02—01/C2—02

#266 DARK BROWN CLAY
STANDARD CERAMIC

OPERATION #1

LAYER HEIGHT	2 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S
WAIT TIME	1.5S

TEMPERATURE	23C
HUMIDITY	22%
MOISTURE	N/A
SHRINKAGE	12%

OPERATION #2

CARVING TOOL	NO.2
STEPOVER	4 MM
CUT DEPTH	2 MM
CARVING PATH SPEED	(0.5*0.2) 0.1 M/S

COMMENTS

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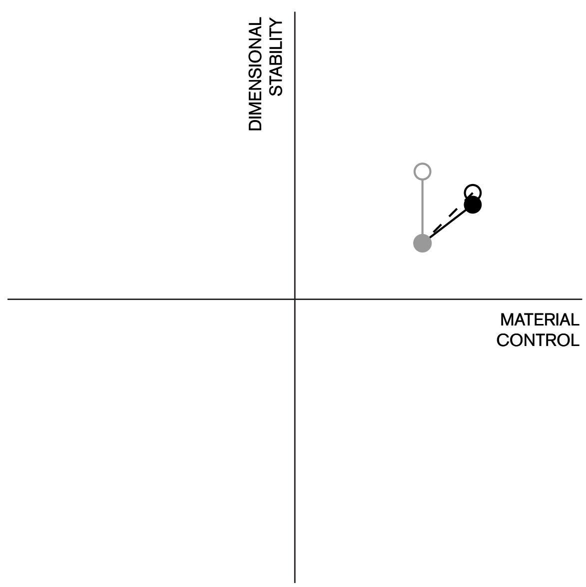


04—02—01S DETAIL

04—02—01S/S2—01 DETAIL

COMPRESSING

ID

04—*—01

CLAY TYPE

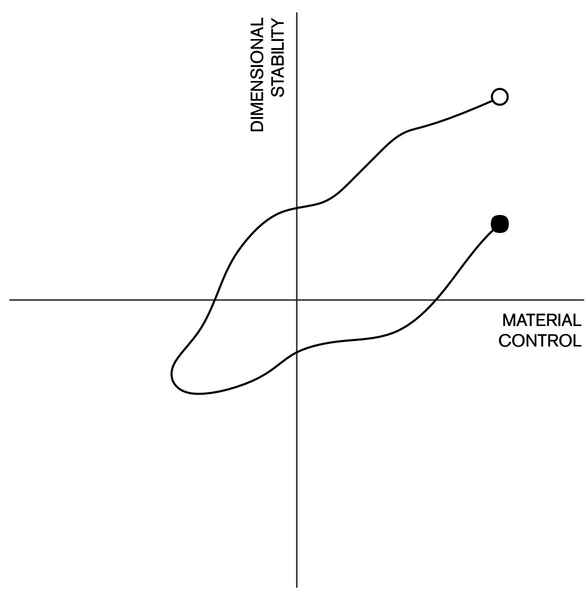
4D3B CONE 6 DARK STONEWARE
MOIST CLAY

LAYER HEIGHT	2 MM
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	20%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

COMPRESSION ACHIEVED BY MANUALLY VARYING SPEED.



04—*—01 DETAIL

ID

CLAY TYPE

04—*—02

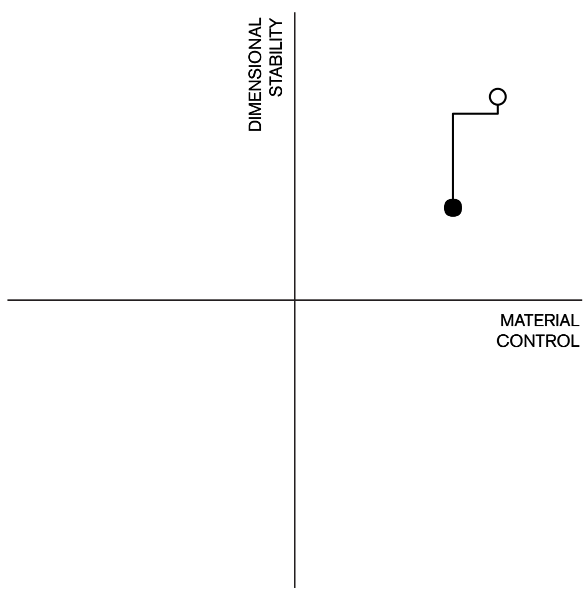
BOB'S PAPER CLAY

LAYER HEIGHT	VARIES
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

TEMPERATURE	23C
HUMIDITY	20%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—



ID

CLAY TYPE

04—*—03

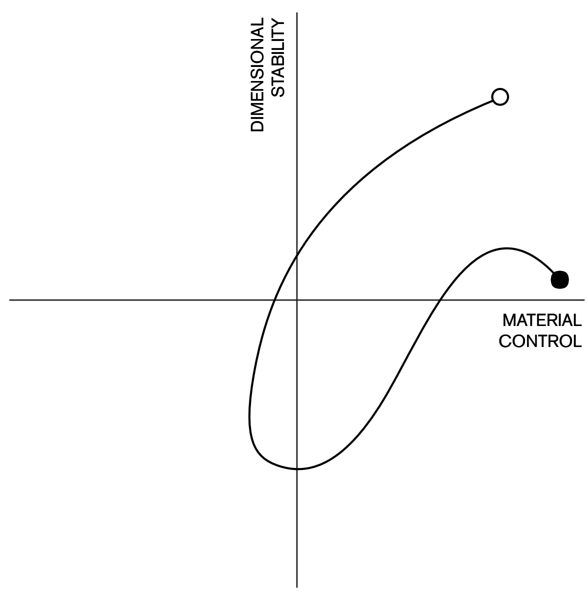
BOB'S PAPER CLAY

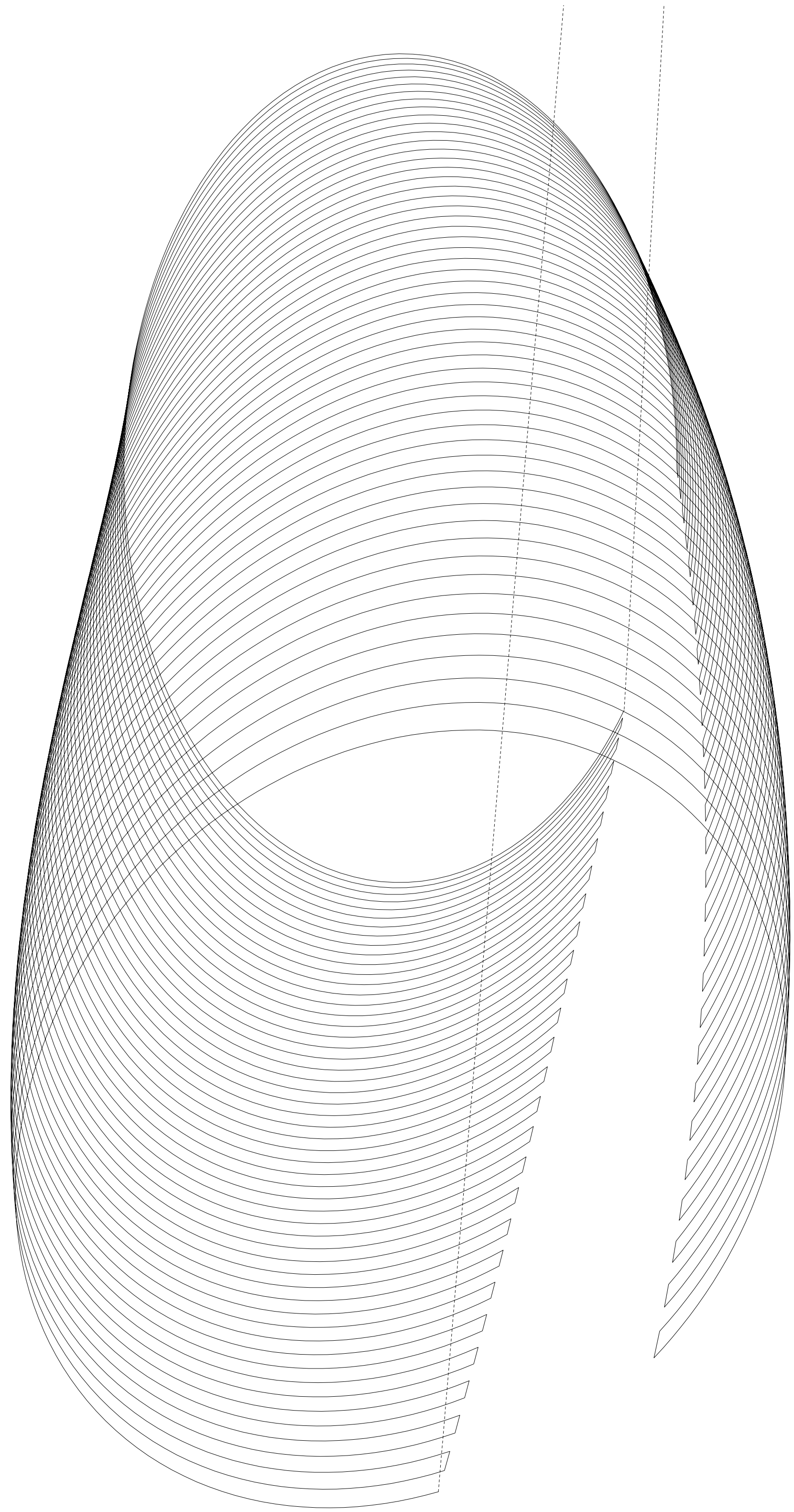
LAYER HEIGHT	VARIES
NOZZLE SIZE	4 MM
EXTRUDER SPEED	0.1 MM/S
TOOLPATH SPEED	(0.75*0.2) 0.15 M/S

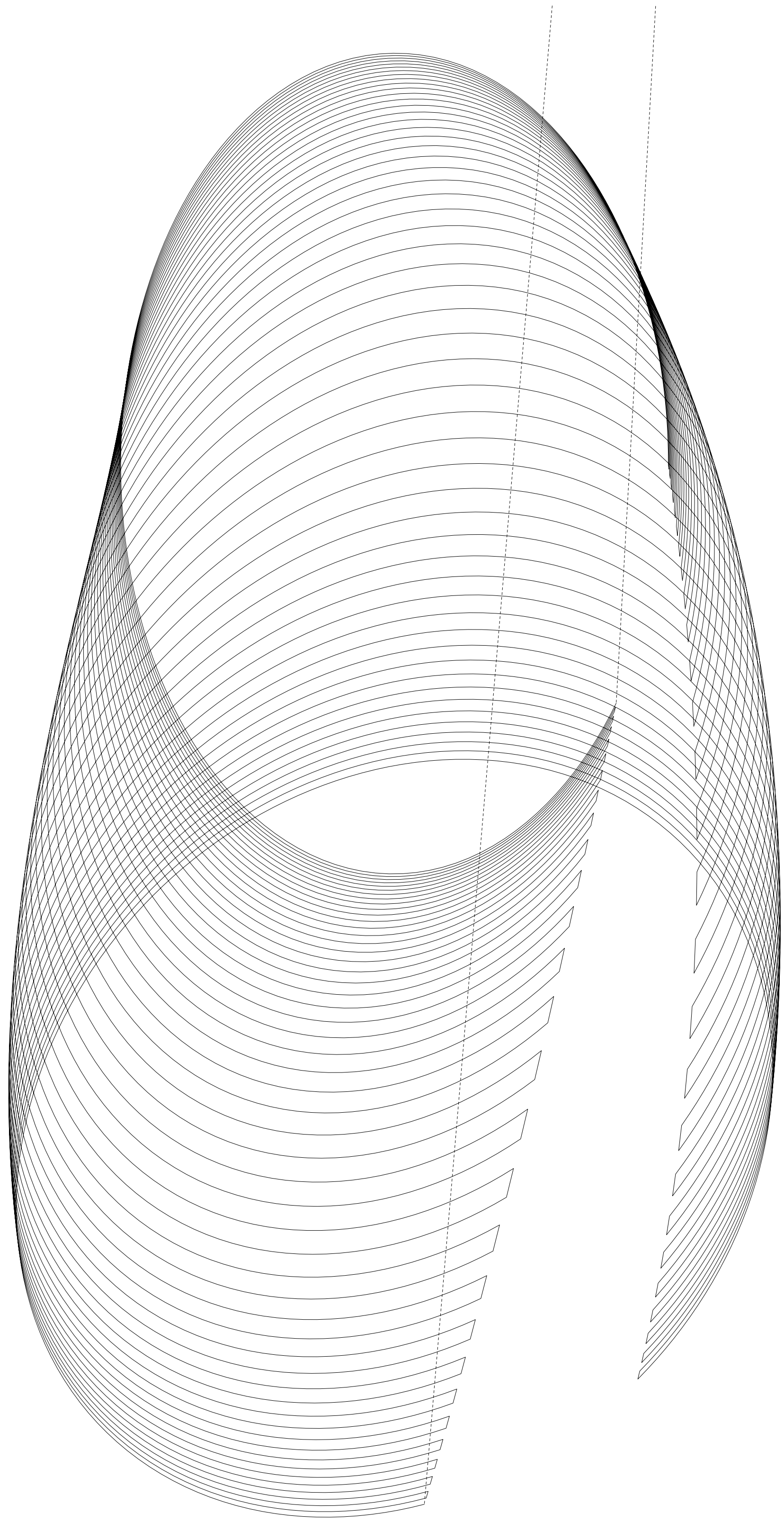
TEMPERATURE	23C
HUMIDITY	20%
MOISTURE	N/A
SHRINKAGE	12%

COMMENTS

—







STRATEGIES

Whereas the experiments isolate actions, verbs in our strategies indicate intentions. While the object's trajectory within the diagram is not overconstrained, in these cases, we wanted to reach certain conditions within the space of the expanded diagram. The hand and its mechanical or numeric extensions constantly negotiate the object's trajectories. Due to this incremental modulation during the experiments, we understood certain material (mis-)behaviors to the point of repeatability, and we deployed these towards specific purposes, such as the creation of openings, enclosures, or covers. Rather than disciplining matter to follow the toolpath exactly, clay could perform its own choreography along the way.

Openings are created through the complex entanglement of carefully calibrated moments of instability, as well as total improvisation by the tool-matter combination (Figure 17). While we encoded points of high stability (especially using pausing and 'beaded' deposition), we also encoded a gradient of layer heights that produced rope-coiling in locations of high instability. Layering another action, carving, to follow deposition, we produced openings at the locations far enough from the stable corners. In this way, clay was free to follow any path in some locations, whereas we increased material control to ensure stability in other places. While we never prescribed, whether numerically or

Figure 17. Three experiments creating openings by modulating layer height and compounding actions

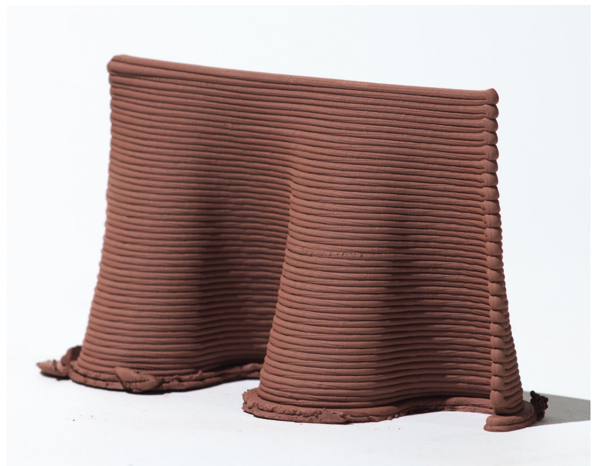
formally, the exact morphology of the openings, the design could accommodate, and even capitalize on this significant precarity due to a careful observation of material behavior.

The three examples of producing complete enclosure demonstrate material control through the angle of action: while all three approximate the same vault, they show different degrees of stability and deformation due to their respective angle alignments (Figure 18). The first example demonstrates the typical "slicer" deposition, where the geometry is discretized in horizontal layers, and the angle of the deposition is vertical. This results in the misalignment of the clay deposition force and the resisting force of the wall, and consequently, slumping. The second example shows the layers that follow the topology of the geometry with vertical deposition. This resulted in the same behavior of the wall caving in, but a better articulation of the distinct openings at the top. The third example uses horizontal layers but the angle of deposition is aligned to the angle of the wall, resulting in the least deformed outcome. While force alignment produced a more stable geometry, the other, less optimal alignments have the riskier, yet more exciting, potential to create enclosures by anticipated slumping.

Figure 18. Vaulted geometries realized with different types of nozzle alignment.

ENCLOSING

1A, 1B



1C, 1D

1D

OPENING

2A

2B

2C

2C

2D

COVERING

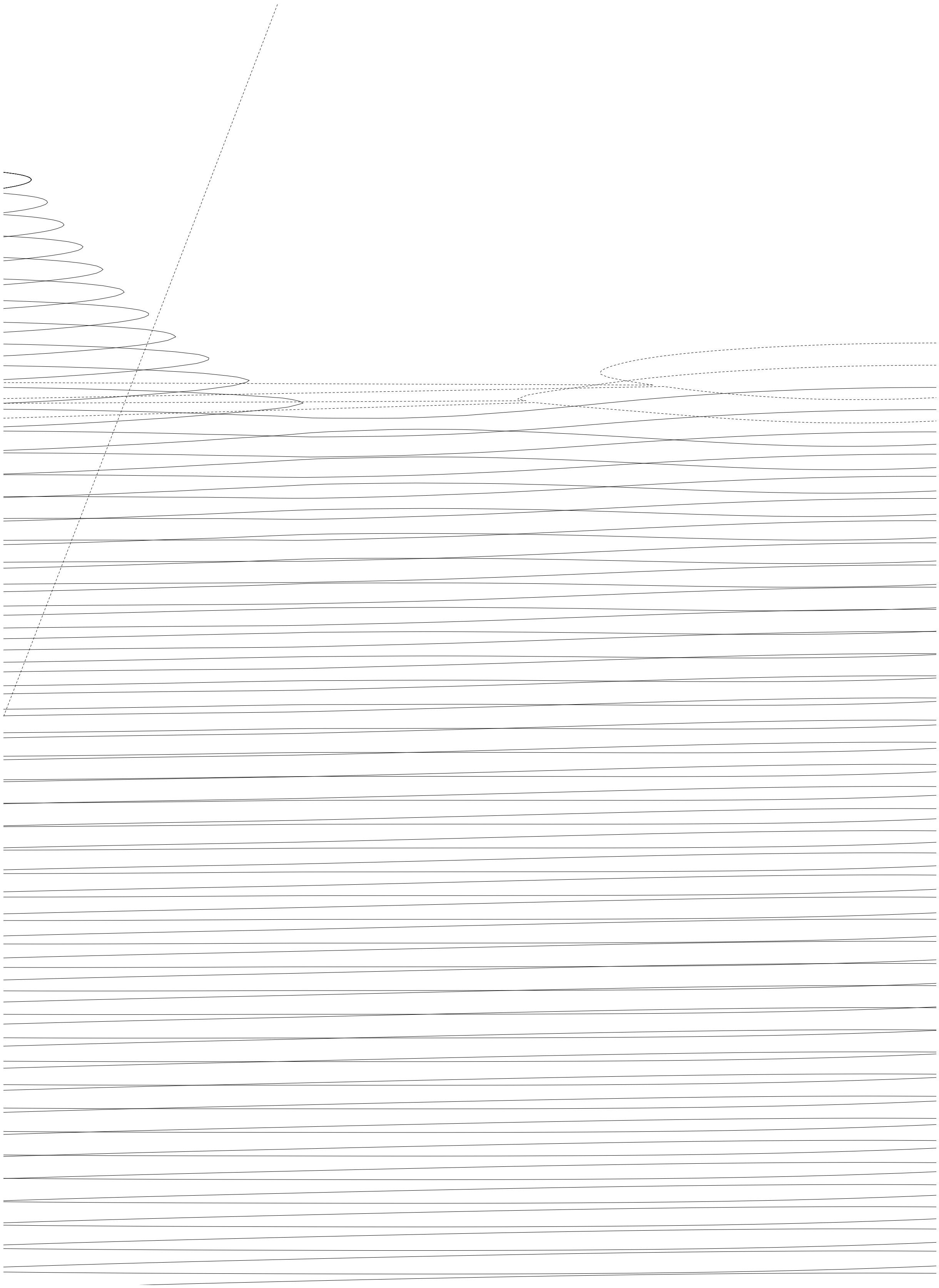
3A

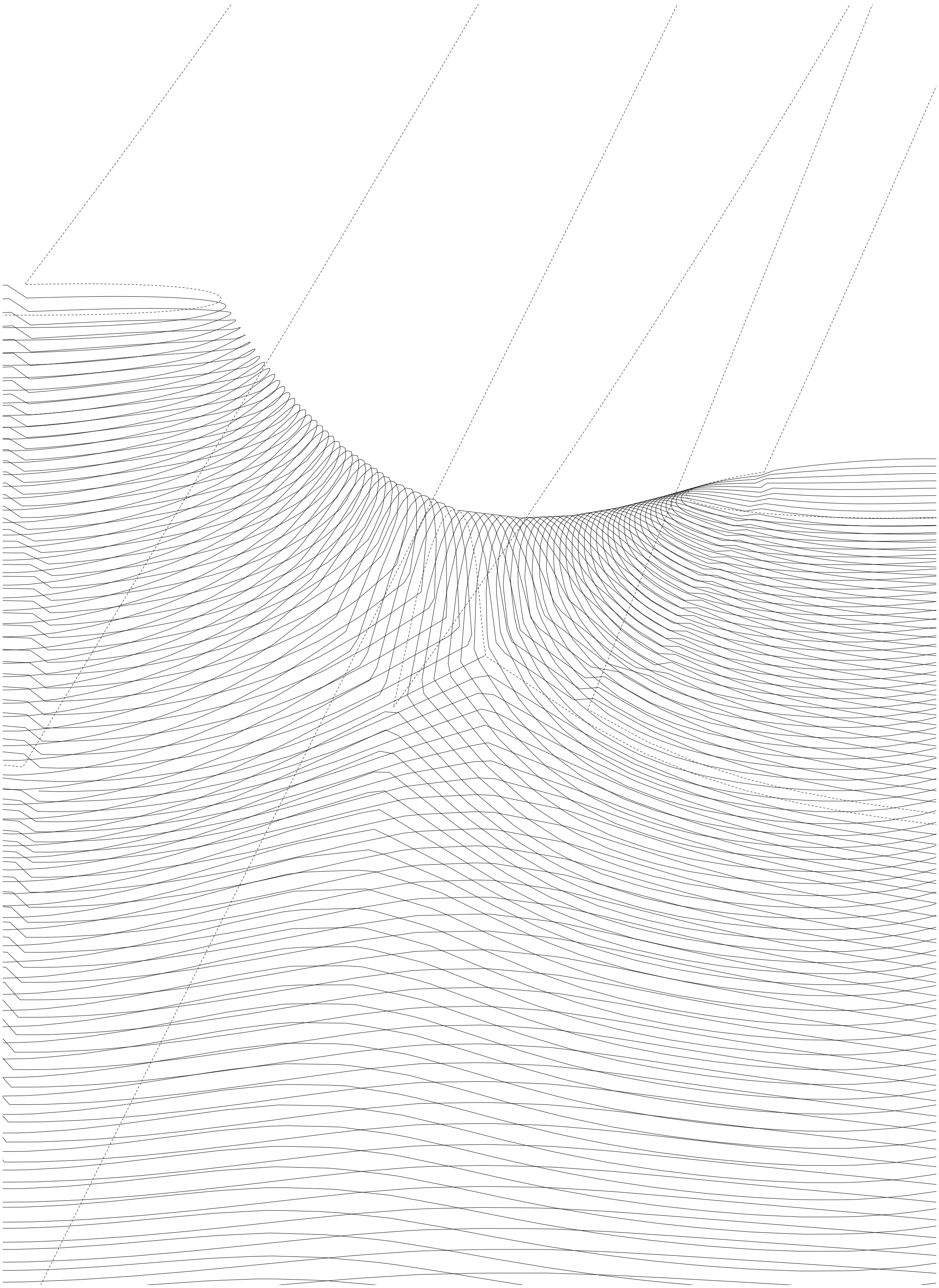
3A

3A

3B

3B





STUDIES

Thinking of building as process, and exactitude as a liminal quality between dimensioning and material control, these studies speculate on the malleability of form—form permanently in transition. The supple body incorporates multiple moments of instability, and one operation does not finish or fix the outcome: it remains available for layering further actions. Ultimately, this projects a different attitude towards building: breaking away from the aesthetic spectrum of a legacy that prioritizes a singular, ideal state, it celebrates the complex trajectories that each object performs in a balancing act between design intention and material improvisation.

Figure 19. Intervention to stabilize the extrusion of an addition onto an existing structure

One critical implication of this proposal concerns material use: instead of working with "pure" materials only—ones that fall within the currently acceptable range of tolerances—, it opens up opportunities in chunkier, rougher, less easily manipulable industrial misfits that would otherwise be purged as landfill. Second, this process encourages material hybridity, distancing from the current homogeneity of matter. Material becomes the site, relying less on the global infrastructure of extraction and prefabrication and more on materials readily available either as already shredded grains or as cut-and-fill. This breaks away from the current regime of homogeneity and exactitude to foreground the aesthetic qualities of the rough, the misfit, the heterogeneous, the slump, the sag, the gap, and even the collapse.

Another interpretation approaches the results—especially the coil-rope effect and its subsequent carving or other means of easy removal—as temporary scaffolds. We already experimented with this, and while most structures presented in this paper are created entirely without formwork, we could see the extension of these studies to other forms of enclosure that would benefit from loose scaffolding during construction. Working with similar materials could manifest at different scales: some of the larger studies could be recontextualized as wall sections, where the openings perform a completely different role in drainage or temperature control.

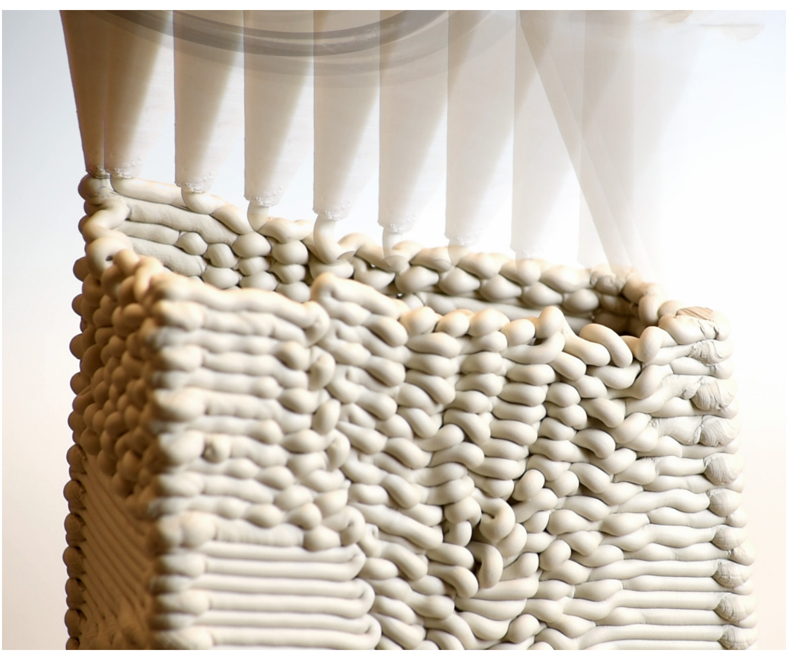
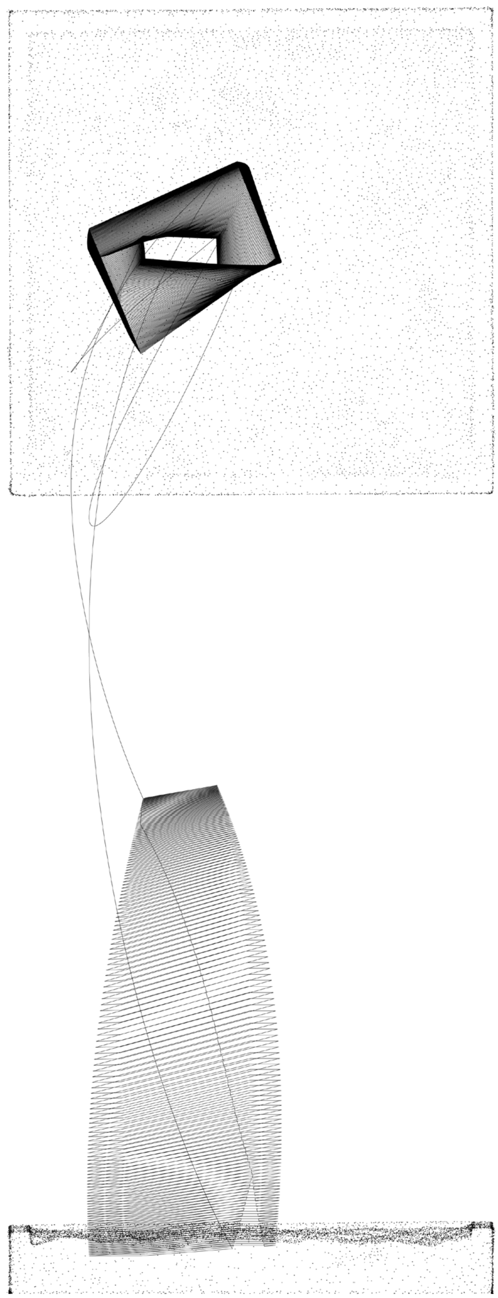
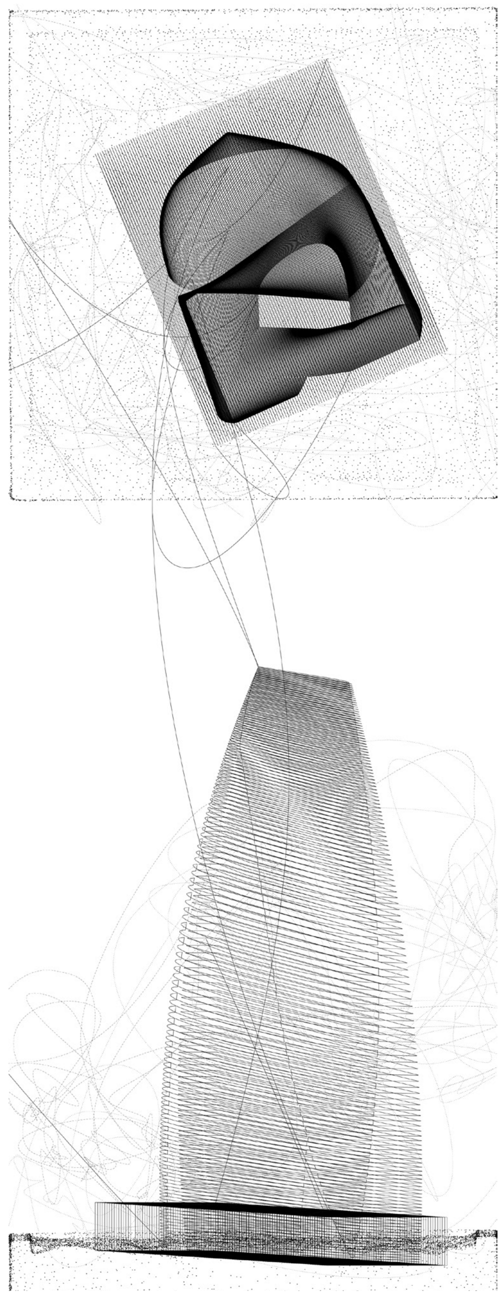


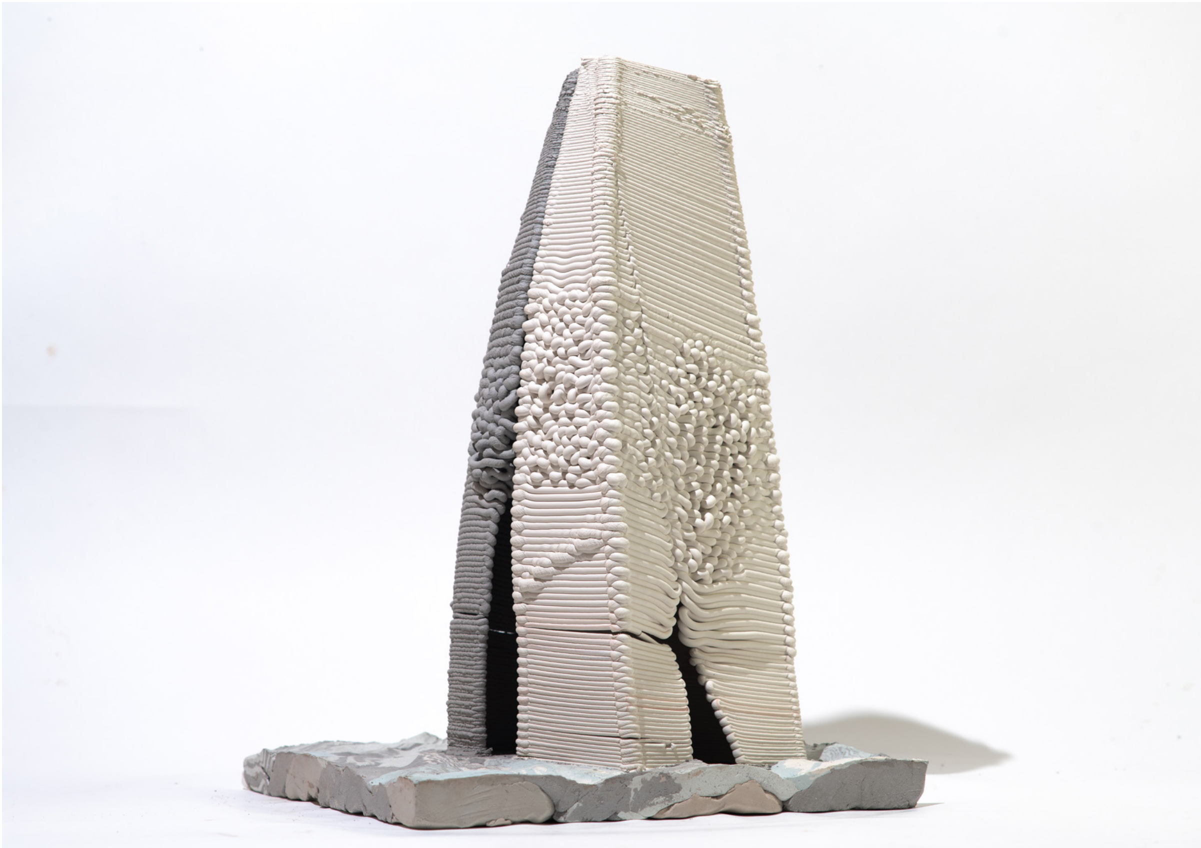
Figure 19. Variable angle of action to stabilize the rope-coiling effect in the middle and reinforce corners



Toolpath representation



Toolpath representation and hand trace



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COLOPHON

All images and text by the authors, produced for the Master of Architecture Thesis at the MIT School of Architecture and Planning, including work from previous courses at the Massachusetts Institute of Technology and at the Harvard Graduate School of Design.