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Cyclopean Cannibalism

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A Method for Recycling Rubble

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1 *Cyclopean Cannibalism* wall prototype, Matter Design, Seoul, Korea, 2017.

ABSTRACT

Each year, the United States discards 375 million tons of concrete construction debris to landfills (U.S. EPA 2016), but this is a new paradigm. Past civilizations cannibalized their constructions to produce new architectures (Hopkins 2005). This paper interrogates one cannibalistic methodology from the past known as cyclopean masonry in order to translate this valuable method into a contemporary digital procedure. The work contextualizes the techniques of this method and situates them into procedural recipes which can be applied in contemporary construction. A full-scale prototype is produced utilizing the described method: demolition debris is gathered, scanned, and processed through an algorithmic workflow. Each rubble unit is then minimally carved by a robotic arm and set to compose a new architecture from discarded rubble debris. The prototype merges ancient construction thinking with digital design and fabrication methodologies. It poses material cannibalism as a means of combating excessive construction waste generation.

INTRODUCTION

The majority of the world's population is moving to urban centers. "By 2050, this percentage will increase to 86% in advanced countries, and 64% in developing nations." (UN.org 2014) In preparation for this influx, our cities are growing, and concrete is being poured at an unprecedented rate (Harvey 2014), pushing us into a crisis of debris. The United States produces about 254 million tons of municipal waste each year (U.S. EPA 2015). A recent report in the *Journal of Nature* attempted to put such vast numbers into perspective, stating, "[t]he average person in the United States throws away their body weight in rubbish every month" (Hoornweg et al. 2013). Meanwhile, construction demolition produces about 534 million tons of debris per year (U.S. EPA 2016). For each of these monthly body weights of trash, the construction industry produces two more for every person in the United States.

Of this construction and demolition debris, the majority is concrete. Seventy percent, or 375 million tons, is generated per year (U.S. EPA 2016). In other words, every year there are 1.17 tons of concrete being taken to landfill per person in America. The principal source of this concrete is the demolition of roads and bridges (150 million tons), followed by buildings (84 million tons) (U.S. EPA 2016).

Strategies for recycling concrete exist, but the energy and labor involved in this recycling is suspect, and the quality of the aggregate is low, limiting subsequent applications (Tam 2009). Papers on the recycling of concrete make no reference to the idea that one could take a block of concrete from the construction site and use it as a load-bearing brick. The reality is that today the majority of concrete is landfilled because a solution to re-insert randomly sized rubble back into the material stream has yet to be provided. But this crisis has been solved before. For instance, Saint Peter's Basilica in the Vatican cannibalized stones from Rome's Colosseum. "For most of the Middle Ages and early Renaissance the Colosseum was not so much a monument as a quarry" (Hopkins 2005). Past civilizations were adroit in readapting previous built structures. By leveraging contemporary methods such as scanning and robotic machining, this work reinserts the abandoned method of cyclopean masonry into an apt solution for our future.

ON CONTEMPORARY CANNIBALISM

Cyclopean Cannibalism argues for the ingestion of waste materials to generate new structures. This postulation links two islands of knowledge—ancient stone-fitting techniques and contemporary computational tools. It poses cyclopean masonry as a living system that ingests urban debris to generate new, flexible building systems. Technique is prioritized over final form, with mass-customized units robotically carved to generate a single system.

While this concept of cannibalization is not standard practice today, the groundwork has been laid to tackle these motivations in the contemporary context. Lebbeus Woods positions this concept in his text *Radical Reconstruction*, . His drawings operate under the premise of "reincarnation out of willful destruction" (Woods 1997). Material debris is readapted to become entire buildings or armatures on existing structures. This act of reconsuming becomes a character trait in the resultant architectures. The appropriated debris embedded in his drawings—rubble left over from warfare, economic stagnation, and earthquakes—raise questions on the entrenched, past experiences of readapted materials. It questions what these memories carry into the reassembled structure.

Architects have recently taken up Woods's assertions, operating within the framework of digital fabrication. Greg Lynn and the team of Gramazio Kohler Research have expanded our vocabulary of design uncertainty through advances in scanning and robotics. Greg Lynn's "Blob Wall" (2005) employed reinvented hollow plastic as robotically trimmed, rotationally molded bricks, with individual components assembled to form a "blob" wall. This inventive project reconsidered the potentials of selectively carving complex intersections via the flexibility of robotic machining. This process relies on apriori knowledge of the geometries prior to the digital boolean operation, illuminating the problematics of compacting the units to ensure that collisions occur. Gramazio Kohler's "Endless Wall" (Helm 2012) also utilizes robotics in the construction process to assemble individualized components into a single wall. While this project contributes to resolving unknown conditions through scanning, it maintains stacking without carving. Another recent project explores the stacking of found rubble stone in a fully closed loop process, using a rigorous physics simulation to analyze the stability of the resulting structure, as well as fully autonomous path planning for the assembly of the structure (Furrer et al. 2017). These explorations underscore the burgeoning confluence between construction processes, robotics, and masonry.

Recent advances in robotics and scanning allow for the dislodging of this technique from its roots within the contemporary context of economy of labor. The incorporation of sensor feedback into a production process can occur at multiple levels. A typical sensing system might include a one- or two-dimensional laser, or a three-dimensional time-of-flight camera such as the Microsoft Kinect (Dal Mutto 2012).

Industrial manufacturing processes often use a variety of sensing and gauging techniques to insure part accuracy, especially in processes where tool wear or variability in work holding could compromise the desired tolerances. By integrating the sensing process tightly within the production workflow, this can be extended to the concept of "adaptive part variation" (Vasey 2014), whereby sensors are utilized to provide real-time feedback to robotic fabrication and assembly processes. This feedback can be used to make online corrections to the geometry of future components to adapt to deviations between a master digital model and a constantly updated as-built condition. Within the context of mobile robotics, sensors can be used to provide feature-based localization, for example in-situ assembly processes utilizing mobile robot manipulators (Dörfler 2016).

CYCLOPEAN MASONRY – A DIFFERENT APPROACH

Cyclopean masonry (Figure 2) refers to masonry structures so massive, precise, cryptic, and irrational that the only conceivable builder was a primordial race of giants we know of as Cyclops from Hesoid's *Theogony* (1953). But while the term cyclopean is anchored in Mediterranean history, this particular practice of dry-stone construction emerged across the globe. Though civilizations had not communicated with each other, a striking similarity between their constructions emerged (Figures 3 and 4). Stones were sourced, selected, templated, and minimally carved in-situ to respond to site constraints. This living procedural method ensured precision architecture, but it also allowed for the recycling and cannibalizing of architecture. The results are apparently cryptic, but they mirror the contemporary potentials offered by digital production. The repeated ingenuity produced by these early civilizations is predicated on a few shared resources.

Hammerstones

Each of these cultures share the same resource of dense stone, but do not have the technology of metal tooling, resulting in a shared technology—the hammerstone. It is more akin to sanding than cutting. In fact, the Inka didn't call this carving. As Carolyn Dean explains, "the Inka referred to the working of finely joined masonry as *canincakuchini*, which is derived from the verb *kanini (canini)*, meaning to bite or nibble" (2010). Blows from a hammerstone at angle close to an edge can rapidly draft away large chunks of material. This method is now called "pitching." When hit perpendicular to a face, they peck and dress the stone. This act of pecking is tedious, but as a result extremely precise.

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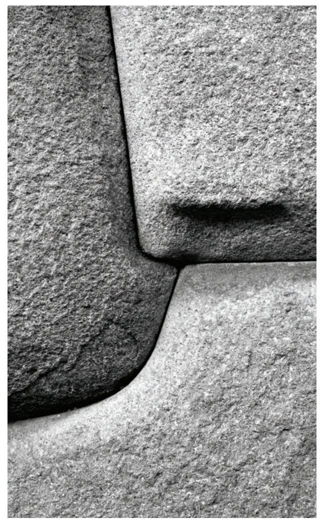

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Quarrying and Selecting

The restriction of the hammerstone also forces these cultures to look at stone sourcing in a different way. It reconsiders the role of prefabrication vs. in-situ carving. The Inka (and other cyclopean constructors) dressed their stones instead of carving them. Jean-Pierre Protzen describes: "In the quarries of Kachiqhata, the In[k]as did not practice quarrying in the technical sense … The quarrymen simply went through gigantic rockfalls, carefully selecting raw blocks that met their specification" (1993). Because their subtractive method was so slow, it made more sense to devote time to properly selecting the appropriate shape to fill a hole and only work on that stone minimally to fit.

Search and Set – Massive Stones

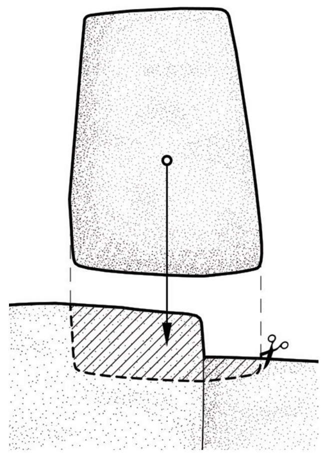
As a byproduct of their use of hammerstones and selection of random rubble to assemble architectures, the cyclopean mason was up against a friction the contemporary mason rarely faces. Confronted with a unique gap in a wall that needed to be filled, the cyclopean mason would then template the gap and search their pantry for the stone that required the least amount of carving. It is worth taking the time to search for the ideal stone because carving with hammerstones is slow and tedious. Once selected, the stone needs to be transported and pre-set in order to dress and fit. This search algorithm in combination with the templating and custom dressing of stones to fit each other is time intensive, but it is ideal for contemporary computation to offset; however, it is understandable that these masons would search for the largest possible stones to fit the holes in order to reduce their searches and sets. Thus, megalithic stones emerge commonly in cyclopean masonry.

ANALYSIS AND SHAPE GRAMMARS

Cyclopean masonry walls are created through generative design processes with procedural methods and rule-sets. If analyzed stylistically, they are seen as cryptic and illogical, but when viewed through the lens of computation, they tell a different story. Computational analysis was employed to find trends and statistics in the shape grammars of these walls. These include the ranges of sizes and shapes of stones in a single wall. For instance, some walls are composed of large but similarly sized stones, while others are made of massive stones filled in with much smaller ones. These metrics help to identify which wall algorithm is the best approach for your stock of rubble. Another metric tested was orientation, whether a stone was more vertical, horizontal, or square in proportion. Similar metrics were applied to test draft angles and the number of neighbors one stone touches. The results of this analysis focus on three primary details that unpack the recipe employed in this wall prototype. These details include bed joints, draft angles, and coursing sequence as seen in Figure 3.

Bed Joints and Utah Details

In conventional masonry, a bed joint is the horizontal joint. While this makes a great deal of sense with orthogonal masonry, polygonal masonry also contains bed joints, resisting gravity, even if they are off horizontal. The Inka would carve the bottoms of the stone intended to be placed and leave the tops uncarved. This is because they know which stones are under a placing stone, but don't yet know the condition above. The result of this directional form is a top profile that is stepped. This stepped profile then becomes an uneven bed joint for the next course. Once set, those tops would be carved in-situ to correspond and receive the bed joint of the stones above them. This sequence results in a phenomenon called a Utah-shaped stone as seen in Figure 5. Locating Utahs is helpful in deciphering a wall because they clearly define sequential intention.



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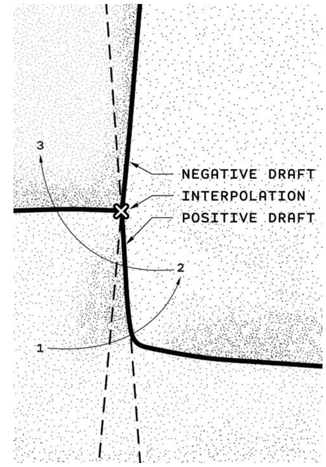

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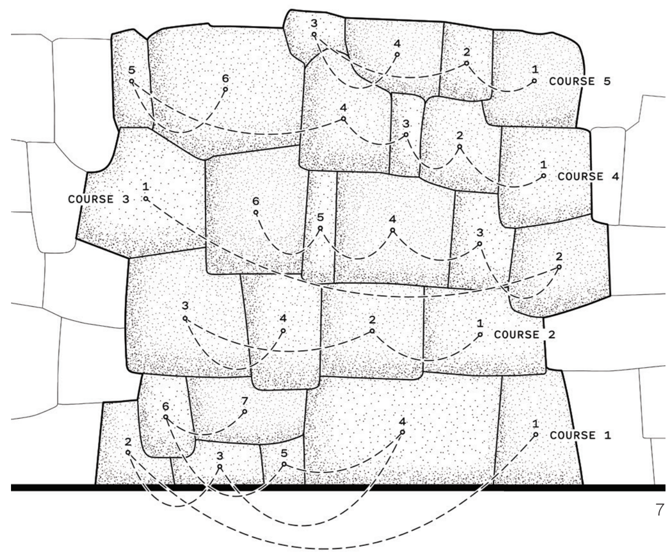

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2 Cyclopean Masonry: *Inka Roca*, Cusco Perú, c. 1350 CE.

3 A detail of cyclopean masonry at Inka Roca containing draft redirection, a Utah, and a nub detail.

4 A comparison image of Inka (left) and Rapanui (right) cyclopean masonry. While these cultures had not communicated with each other, their resultant architectures are strikingly similar.

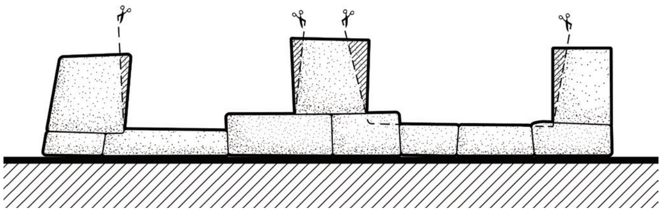
5 A diagram of the bed joint setting sequence for roughly coursed polygonal masonry, which results in a Utah detail.

6 A diagram of draft redirection.

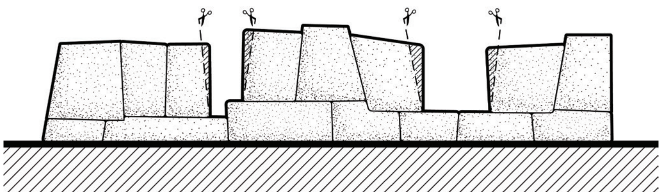
7 A coursing sequence diagram deciphered from Inka Roca in Cusco Perú.

Draft Angles

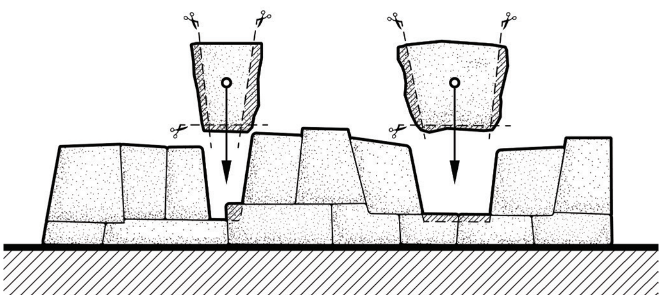
If bed joints are about the horizontal condition, draft is about the vertical. It is in this difference from true vertical that a wall can further tell its story of assembly. This simple orientation of the side joint can describe the sequence of a wall, but the degree of that angle can also determine whether something is set from above, slid in from the side, or even tilted in. Draft can describe all of the possible assembly directions, often suggesting a narrow range that



8 Recipe Diagram for Step 2: Set type A stones (trapezoids)



9 Recipe Diagram for Step 3: Set type B stones (parallelograms)



is most helpful. Draft and bed joints commingle in a particular topic we call draft redirection. This telling detail occurs at a vertex between three stones. A vertical edge might shift its angle from positive to negative when engaging a different stone (Figure 6), suggesting that a positive draft was helpful to set this stone, but the stone above cannot be slid in from the side, requiring a vertical draft.

Rough Coursing

The details above help to determine the scale of the stone-to-stone process and method of assembly. A larger scale of analysis is also helpful to consider the macro logic. These cyclopean constructions range from prefabricated, coursed constructions to rough coursing, and ultimately to fully polygonal (meaning no coursing can be seen). They also occasionally transition from non-coursed to coursed in an attempt to tame the system. In these conditions, the non-coursed stones are considerably larger, so a correlation between the size of a stone with the logic of its global assembly also aligns. In order to better decipher these mythical walls, a layer of analysis looks at the walls at this scale. This includes coursing, the range of stone sizes, the number of neighbors each stone has, and "connection" details (Utahs, carved moments edges for custom fit, etc.). Figure 7 demonstrates the results of this analysis.

RECIPE

The following recipe describes one of the most recognizable typologies of cyclopean masonry. It describes the manual sequence of assembly that took place in order to explicitly outline the recipe for the computational design prototype to follow (Clifford 2017, 144–149).

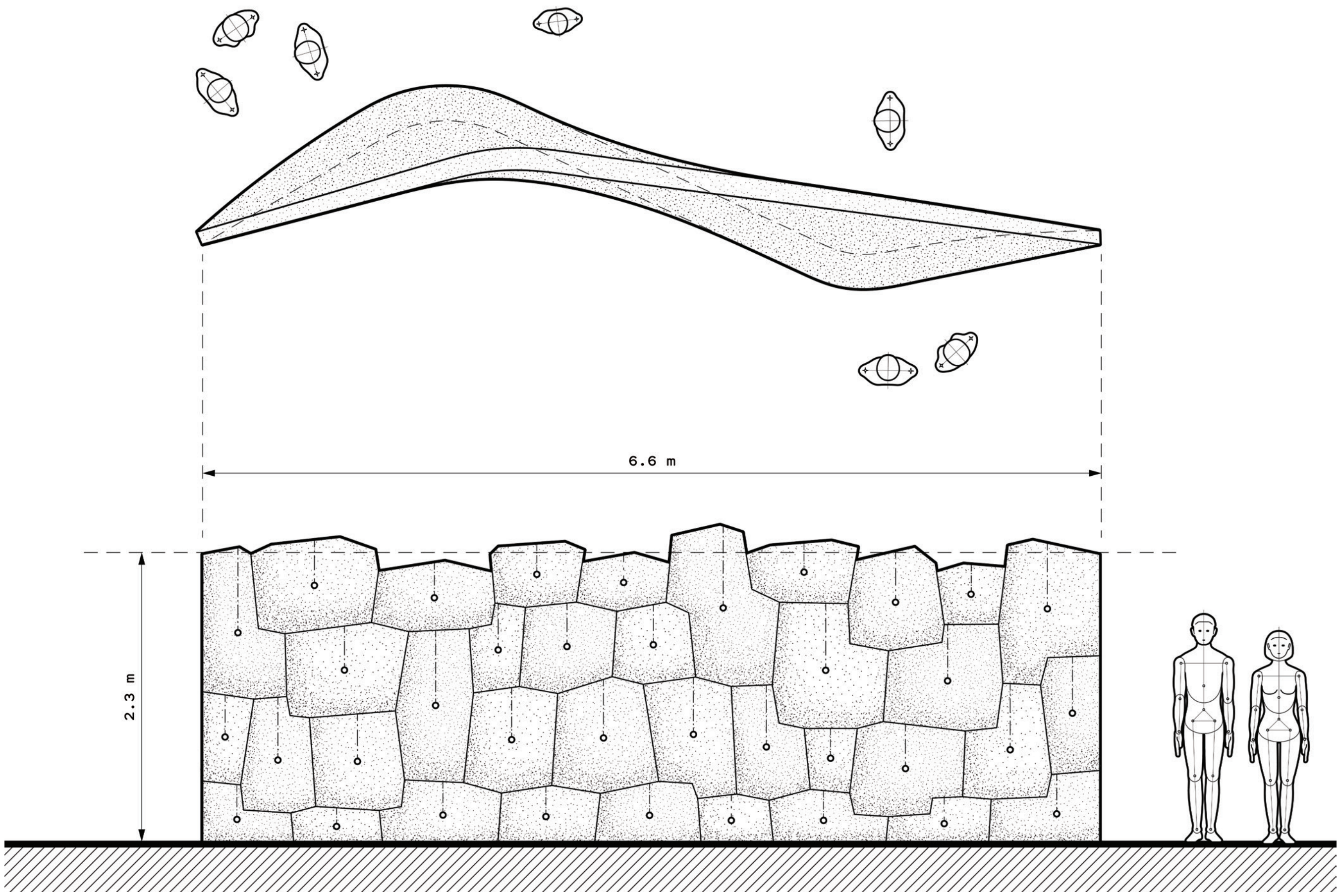
This recipe consists of large to massive stones that are of roughly the same proportion to each other. 1) Sort the rubble stones into two piles—trapezoids and parallelograms. 2) Set a series of trapezoid stones in the stable orientation. Make sure to evenly space these stones so that they are along the wall, but not adjacent to each other (Figure 8). 3) Seek and select a parallelogram stone that fits nicely in the space adjacent to the previously set stones. Nest that parallelogram into place so that it leans against the stable trapezoid (Figure 9). 4) Continue step 3 until there is space for only one stone in each void. 5) Select a trapezoid stone and set it upside down into the gap left in step 4. This upside-down trapezoid will appear like a keystone (Figure 10). 6) Continue the process from steps 2–5 on the next rough coursing, making sure to select stones that always straddle over a vertical joint below. 7) Set the selected stone above the previous course on a stand-off and scribe the geometry of the setting stone onto the bed joint of the course below. Lower this geometry until it gains contact on all surfaces and carve the scribed geometry onto the previously set stones. This will result in a Utah-shaped stone below. 8) Lower the offset setting stone down onto the custom-carved bed joint below and continue the recipe until the desired wall is met.

PROTOTYPE

The following prototype experiments with the recipe from above and translates that code into a digital procedure capable of recycling abandoned construction rubble. This prototype wall consists of demolition concrete and offcut stone from a variety of construction sites. The design process of this prototype wall begins with a global surface geometry. Rubble is then scanned and sorted, then digitally placed, carved, and set.

Global Form

The wall is 6.6 m long and 2.3 m tall and weighs 6,896 kg (Figure 11). The stones range in thickness from 100 mm on the ends to 312 mm in the middle for stability. This variation in thickness helped not only in managing the stability of the wall, but also in utilizing the range of rubble units' stock dimensions. In order to facilitate this varying thickness, a second surface is variably offset to inform the thickness and orientation of each stone. This global form is book-ended by two vertical edges, and an undulating



11 Plan and Elevation of the *Cyclopean Cannibalism* prototype wall.

lower curve is adjusted in correspondence with a stability calculation. This undulation produces a compound curvature surface, which would have been difficult to conceive of for the Inka and other cyclopean masons because of their bottom-up approach. While their walls were generally vertical (or canted), this digital procedure allows *Cyclopean Cannibalism* to be virtually set on more complex global forms, a process that shifts many of the cyclopean masonry walls into new geometric territory.

Rubble Scanning and Searching

A selection of demolition rubble is digitally scanned to capture the random geometries. Each stone is set on the chosen back side and the remaining five sides are captured by the scanner. While only five of six sides are received, the flat back is irrelevant to this calculation. This scanning produces a highly detailed pointcloud geometry. However, this is thought of as a stock geometry that will be carved from. A recursive algorithm (Clifford 2017, 118–120) determines the largest four-sided polygon that fits within this digital scan. It is this polygon that is utilized by the virtual set algorithm. The scanning only facilitates the dimensioning of this maximum polygon search.

Virtual Set

Once the "pantry" is stocked with virtual polygonal stones, a parametric rig allows a designer to virtually set each stone along the wall following the recipe. This virtual set is driven by the centroid of the polygon that can be moved along the primary global geometry surface. This point is used to find the closest point on the variable offset surface to establish a planar back in a method similar to one described in "La Voûte de LeFevre" (Clifford and McGee 2014) and demonstrated in Figures 13 and 14. Because this back face is not carved, the virtual set established that the bounding stock polygon is justified to this back planar face. The thickness therefore needs to extend entirely through the primary global geometry surface in order to fully engage the wall thickness.

The other variable available to the designer is orientation. Each polygon is able to rotate around this depth axis in order to set the stone in the orientation that best suits to conditions. When setting, the designer further carves away from the vertical draft angles of adjacent polygons in order to ensure each stone can be set from above. These virtual stones overlap each other until no gap is left between them, and the stones are then carved back at these intersections. This process of setting is different from nesting algorithms,

12 Detail image of the dressed front face after the manual pitching brings the stock thickness back to the intersected index edge.

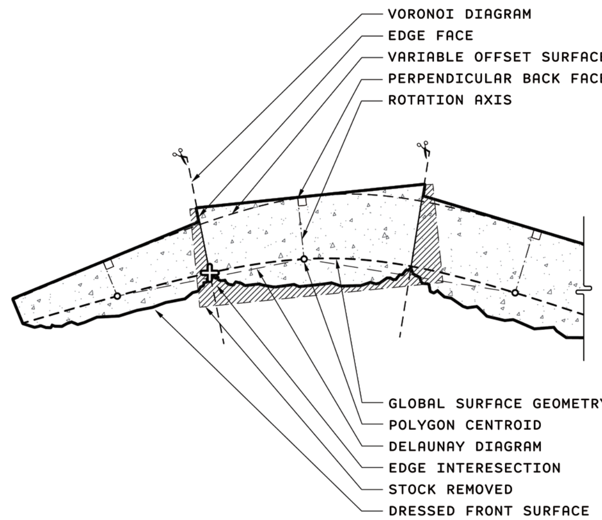
13 Detail of the back planar surface.

which operate under the goal of setting as many geometries into a given bounding condition by minimizing the residual waste, but maintaining the original geometry of each set part. The algorithm employed in this process differs in that it doesn't minimize the space between parts, but has to remove it entirely, therefore displacing the concept of waste to the amount of material carved from each part. These parts do not retain their original scanned geometry but attempt to reduce the amount of material carved away, resulting in new, but approximately similar polygons to their original rubble shapes. Throughout this virtual set process, a stability check is run iteratively to ensure that each part is not only stable on its own, but also that the current assembly sequence is stable. It is for this reason that a particular assembly sequence is important, not only in ensuring draft angles that allow parts to be set, but that the assembly can be stable throughout the construction process. The recipe is linear and progressive, imparting a design process that ensures the assembly process will be both geometrically possible as well as physically stable. Once this virtual set algorithm is complete, the units are ready to be carved.

Carving

These units are carved with a six-axis robotic arm in conjunction with an external rotary table. Each unit is set on the rotary table with the flat back side down. This surface is left planar and not carved. The remaining geometries to be carved include the side faces and the front dressed face. The majority of the side faces are planar and intersect with obtuse angles. These are through-cut rapidly with a saw, which also cuts directly through any steel reinforcement. In the event of a Utah detail, interior corners are produced, requiring a contour milling operation. In order to expedite this process, these faces are carved with "swarf" machining. This process of carving can be seen as a tilted profile cutting a ruled surface and therefore establishes the bounding conditions of each of the units and how these units rest upon each other. Figure 15 describes this process.

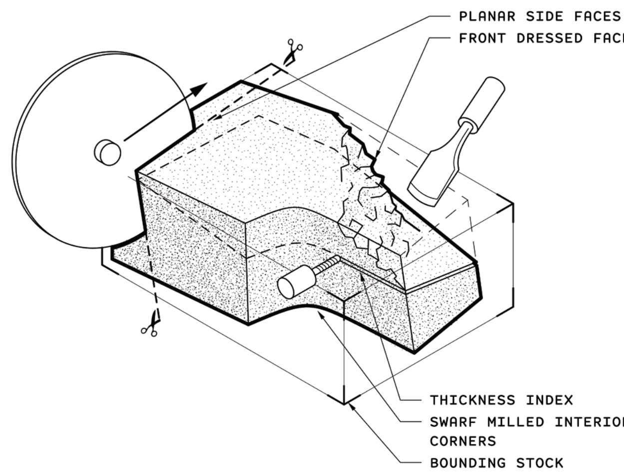
Once these side edges are carved, the units still retain their original stock thickness. The back faces of the assembly are planar, and therefore slip past each other; they do not serve as an index for the placement of stones. The fronts also operate from a variable stock dimension, meaning their depths needs to be carved back to index how each unit can be set relative to its neighbors. In order to index this depth, the primary global geometry is intersected with the edge surfaces to produce a curve that brings the variable thickness of these rubble stones back to the global surface geometry. While on the robotic table, a milling bit traces this curve onto the side faces of the part. The part is then removed from the table and hand worked to rapidly dress this thick volume back to this complex edge geometry. This process of pitching is rapid and large chunks of excess material are removed while this precise edge is maintained. The result is a rough pillowing to this dressed face, which is reminiscent of the original cyclopean masonry walls as seen in Figure 12.



14 Detail Plan Diagram describing the various geometric operations of the virtual set process.

Physical Set

One of the challenges in working with massive stones is the assembly process. The prototype wall was assembled by a team of unskilled laborers, guided by the recipe, which dictates the order of assembly. The wall is designed to be stable once assembled, but the stones must be guided precisely in order to slide vertically into place. In some cases, the orientation of a "lifted stone" did not match its final orientation due to the relationship of the pick points and the center of gravity. This should be considered in future iterations of the process. In the case of the prototype, the stones were dry stacked in order to produce a structure that could be disassembled. This necessitated the use of structural alignment dowels across the joints. The demand for precision in the placement of these holes is critical, and they must be aligned according to the vector along which the massive stones will be lowered into place (Figures 16–18).



15 Diagram of the carving process.

CONCLUSION

The *Cyclopean Cannibalism* wall prototype is the first of many tests to implement the theoretical recipes put forth in *The Cannibal's Cookbook* (Clifford 2017). The intention behind this work is to disseminate the potentials of this way of thinking in the digital context. The technique intends to be accessible for a broad audience to combat the increased generation of building waste. In addition to these contributions, contemporary building practices as they relate to waste production are cast in a new light.

The *Cyclopean Cannibalism* wall prototype yielded 73% of the scanned stock material. While this number could be improved upon with a larger sampling, that percentage constitutes 100% of discarded rubble. This prototype demonstrates the viability of digitizing the cannibalistic process of cyclopean construction, but also raises a number of questions regarding what content should be carried over into the digital era. For instance, while the Inka were operating under a procedural rule-set, their constructions were built from the ground up, stone by stone, without a predetermined composition. On the other hand, *Cyclopean Cannibalism* employed digital procedures to run the same recipes (or codes), but through a virtual set. In this process, the entire wall is established digitally and each stone is custom carved to assemble together. This process does not take into account accretion of tolerance errors, or if a stone might crack in the process of setting. Therefore, further work could integrate this knowledge back into the algorithm.

ACKNOWLEDGEMENTS

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16 *Cyclopean Cannibalism* wall prototype, Matter Design, Seoul, Korea, 2017.

17 *Cyclopean Cannibalism* wall prototype, Matter Design, Seoul, Korea, 2017.

Office, the *MIT HASS Fund*, and the *Marion and Jasper Whiting Foundation*, as well as the *Taubman College of Architecture and Urban Planning*. The prototype is designed by *Matter Design*, realized by *Quarra Stone Company*, and exhibited at the 2017 *Seoul Biennale of Architecture and Urbanism: Imminent Commons*.

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18 Detail of the back side of the wall assembly.

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IMAGE CREDITS

All drawings and images by the authors.

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Wes McGee is an Assistant Professor in Architecture and the Director of the Fabrication Lab at the University of Michigan Taubman College of Architecture and Urban Planning and a Principal at Matter Design. McGee has been recognized with awards such as the Architectural League Prize for Young Architects & Designers and the ACADIA Award for Innovative Research. His work revolves around the interrogation of the means and methods of material production in the digital era, through research focused on developing new connections between design, engineering, materials, and manufacturing processes as they relate to the built environment.