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Unregulated Craft of 5-Axis Waterjet Cutting

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This paper discusses the notion of CNC Craft as influenced by the role of representation in the design and fabrication process, aiming to develop a more agile and adaptive workflow between digital models and contemporary manufacturing techniques. A particularly powerful such technique is waterjet cutting, which is capable of working with a wide variety of materials, but presents different challenges as compared to other digital fabrication technologies. In particular, the CNC craft approach for 5-axis waterjet machining can explore the potential of a machine that has not been investigated to the same extent as CNC milling.

Keywords: craft, fabrication, workflow, waterjet

Introduction: The Need for CNC Craft

CNC machines are incredibly powerful and general machines. They are usually controlled through extensive CAM software that can optimize and precisely control many specific tasks. Too often, however, this software acts as a barrier to innovation and development as it creates a disconnect between the designer and the making process. Yet at the heart of digital tools lie two ideas that have an ancient connection to craft and making: the notion of the drawing and the notion of the tool [1]. The connection between these two ideas can be seen as some of the earliest models of algorithmic construction, for example the use of a pattern in knitting and weaving [2], in basket weaving [3], or in architecture [4]. The key addition to the process is the automation of the relationship, allowing the abstract world of the drawing to directly impact the physical world, rather than through human mediation. This addition has great potential, but also presents the challenge described above. Automation can too often make the link between drawing and process illegible.

In architecture this challenge has led to a robust debate over the nature, opportunities and challenges of computational design on the drawing side [for example 5,6]. Yet much of this debate focuses primarily on the design of form. This is challenged for example by Achim Menges:

"From a methodological point of view, this deeply entrenched prioritization of the generation of geometric shape over the processes of material formation imbues most digital design approaches with a deeply conventional touch, even when well camouflaged in exotic form and exuberant articulation.

If, in contrast, we begin to view the computational realm not as separate from the physical domain, but instead as inherently related, we can overcome one of the greatest yet most popular misconceptions about the computer in architectural circles, namely that it is just another tool."[7]

Yet the focus of Menges and others is still in the design process, though with a model of more complex behaviors of material and optimization of geometry, with tools like Kangaroo Physics [8]. The question of the geometry of the machine used to bring these designs into reality is rarely addressed. For example the generally encyclopedic Architectural Geometry [9], while it does describe manufacturing techniques, does not develop the details of their differing geometry. The greatest exception to this comes in with the use of robotic fabrication, though this often requires dedicated programming teams. In contrast, simpler, more common machines are often neglected in the discussion. This neglect, is at least in part due to the age and sophistication of the technology to control such machines. Numerical control is an old technology and proved to be one of the first applications of computers beyond computation in the 1950s and 1960s. [10] The standard workflow for CNC is to start from a model that fits certain criteria and pass this through a black box process in the hope that an object approximating the model comes out of the far end.

When this process works, it is incredibly efficient and effective but is limited in two ways. Firstly, it can be hard to troubleshoot when a problem occurs, as there are several steps between the actively controlled process (the initial model) and the final result. Secondly it acts as a barrier to innovation, both because the effects of the intermediate steps might not be clear and even when changes can be identified, they are hard to implement.

Breaking Down the Machine Control Process

To break down the control process, we begin not by desired output, but simply by controlling the machine movement. The first level has a lot of complexity, with both the electrical engineering of machine control and the physics of the interaction between tool and material. Yet above this is a simpler abstract level that is usually used for input, the structure of languages like GCode. This provides a first step from the machine movement in the physical world into a geometric space.

The core of such abstract languages are the numbers that give CNC its name. At the simplest level, a line of code gives a position for each of the axes of the machine, plus some additional information like the speed of the spindle and how to interpolate from one position to the next. For a five axis machine for example there are three coordinate directions and two rotational axes. These numbers pull the machine into an abstract geometric space, yet a list of five numbers is hard for most, if not all, people to truly see. The next step, therefore, is to convert into a more visible geometry without losing any information. The three coordinate directions convert to a point in space, and the two rotations give a direction away from that point. A single line of code can therefore be represented by a point and direction, in CAD software this can be drawn as a short line with one of the end points marked[1].

At this stage we have moved from the machine to a visual representation of the machine position in such a way that there is a legible connection between the representation and the actual behavior of the machine. Using this representation on the computer as our finishing point we can develop many different techniques to convert geometry into this model of machine action. We are left with a four step process:

The legibility of this process means that observations made during the machine movement can be linked directly to the design behind them. As this process is observed therefore the loop is closed and the machine movement and output object can inspire new strategies and geometric constructions.

CAMel

The discussion above is only practical with tools to translate geometry into the machine control. This is the goal of CAMel, a Rhino/Grasshopper plugin to write GCode (and other text based languages) for machines to use. Its core is the basic jig that takes a list of points, or points and directions, plus some additional information about the machine and produces the control file. The set up for the machine only needs to be done once and all the settings are then set up in the Grasshopper environment, so that the toolpath details can be played with. In addition many basic features that might be added to a path are also available, for example inserting and retracting the tool, moving safely from the end of one path to the start of the next and for routers creating a step-down path so the tool is never removing too much material.

Sitting on top of this basic structure (that can be used on its own) are tools to work on higher level operations such as creating drill operations or surfacing. These act to achieve the first step described above, converting a geometric object (such as a mesh or brep) into a toolpath. The environment of Grasshopper, with simple visual programming, the ability to create more advanced new components in C# or Python and many plugins means that it is easy to create new tools to convert geometry into toolpaths described geometrically. The underlying (robust and tested) code writing system can then convert that reliably into the machine movement. In addition, this path is read back and displayed to allow a preview to ensure that it will run safely on the machine.

This workflow has several benefits, once a setup is complete small changes can be made to the geometry and these will flow automatically through the CAM process to provide an updated cut file. This provides a strong link between the design space possible with Rhino/Grasshopper and the construction process. As the system can easily be set up to create many files at once the opportunities to have a robust workflow between design and manufacturing are significant.

Applying the Design Concept to Waterjet Cutting

Abrasive waterjet cutting uses a high-pressure stream of water mixed with garnet abrasive to erode material, producing a thin kerf cut. It is a flexible process, able to cut a wide variety of materials at impressive thicknesses. Although 3-axis abrasive waterjet machines are common, multi-axis machines are more specialized but particularly powerful and capable of handling a wider range of general tasks. While there are several manufacturers of 5-axis CNC waterjet cutting machines, their use remains specialized due to their high cost and programming complexity. More advanced uses of 5-axis waterjet machines reside within the aerospace industry where they are used for trimming composite parts [11]. Typical uses of these machines allow fabricators to get parts further downstream in the manufacturing process by incorporating the otherwise manual labor of beveling, chamfering, and contour cutting metal parts for weld preparation. Many 5-axis machines provide taper control to produce much cleaner and precise angled cuts in thin and thick materials, reducing the overall handling and fabrication time by eliminating the need for further grinding or machining.

The possibility to cut a wide range of materials and thicknesses requires careful consideration for how each material reacts to the high pressure. While the kerf of the cutting path of a CNC waterjet machine is very thin (approximately 0.03”-0.06” in thin materials), the interaction between the speed of the cut and the raw material is directly related to edge quality, producing cuts that range from entirely smooth with all edge taper compensated within the scrap cut to heavily serrated with a large amount of taper registered in both the scrap and final cut faces. Depending on the application, these material effects could produce a desirable aesthetic as an expression of the high pressure erosion process, evoking David Pye’s notion of deliberate approximation [1]. More typically however, advanced multi-axis CNC waterjet machines have the ability to compensate for tapering with proprietary algorithms to help control the speed and tilt of the nozzle based on the cut angle. The CAMel scripts written for the OMAX machine incorporate this into the workflow and allow the user as much freedom as OMAX software itself allows, integrating the powerful internal OMAX software algorithms.

Proprietary software used to program the cutting operations are optimized for standard industry utilization, and are in many cases quite proficient. However, research oriented and creative uses (or misuses) of the machine and the accurate cutting of complex geometry are more difficult to program, and in some cases, impossible to achieve given the limitations of software functionality. Addressing those challenges, several researchers have begun developing custom interfaces with multi-axis waterjet machines in order to unlock the full range of motion for different purposes. This research intends to contribute to those efforts by demonstrating the benefits of an agile workflow to control industrial machines through the prototyping of a large-scale demonstrator, which similarly would require a strict adherence to desirable dimensions and cut angles to ensure neighboring parts connect accurately. This is meant to demonstrate the potential repeatability of the 5-axis waterjet cutting process, the successful communication between CAMel and the OMAX machine, and the benefits of a customizable parametric workflow that is able to rapidly produce machine instructions for each of the parts.

Prior Research

Outside of standard machining operations, multi-axis waterjet cutting holds much potential for design research, architectural fabrication, and artistic expression. Several non-standard applications have demonstrated this by utilizing a range of materials that are not easily machined using other means, and by creating material effects that only high pressure erosion could produce. For example the precedents below include the swarf-cutting of hyperbolic edges of thick stone structural components, reducing the thickness of marble slabs for light diffusion, and creating the appearance of natural erosion in masonry materials have taken advantage of the customization of waterjet workflows and have begun to define the craft of the waterjet beyond its industrial capacity.

Research conducted by Kaczynski, McGee, & Pigram explored multi-axis robotic waterjet cutting to produce unreinforced stone vaults. The fabrication process was based upon the use of an abrasive waterjet to cut unique panels from Berea sandstone. The multi-axis functionality of an industrial robot arm was used to cut each edge of the stone panel into twisted ruled surfaces by tilting the waterjet cutting stream at a different angle along the length of the cut [11]. The resultant twisting edge-to-edge panel connection self-aligns each panel to their appropriate orientation, minimizes the need for additional formwork, and eliminates the need for mortar to hold the panels together since they would be unable to rotate out of position [11]. Here, the increase in the cost and complexity of the fabrication process is offset by the minimized formwork and assembly costs, advantages that necessitate 5-axis water jet cutting. The multi-axis approach made possible by an industrial robot arm cannot match the rigidity and potential accuracy of gantry CNC systems [11]. Combined with kerf and stream lag errors, it was noted by the authors that deviations were found on the order of 2mm and +/- 2 degrees of taper, while advanced 5-axis CNC waterjet machines may hold much tighter tolerances.

Research by Bechthold, Ponce de Leon, & McGee have attempted to produce partial depth cuts using abrasive waterjet milling, sidestepping a known limitation of waterjet cutting which is the lack of control over the cut depth. However, while the researchers noted that it was possible to remove part of the stone thickness (allowing light to penetrate), the lack of control in shaping the stone without cutting through the material was a slow and inefficient process [12]. In contrast, more recent research by De Micoli, Rinderspacher, & Menges explores the potential of erosion-based processes by instrumentalizing erosion as a fabrication methodology [13]. The research takes both a technical and craft-based approach, resulting in a series of successful prototypes and the development of a custom digital workflow with a CNC plasma cutter gantry modified for waterjet eroding. Interestingly, the results were expected to be indeterminate, with nuance and variation that are influenced primarily by the composition of the stone. The material effect is intended to be more natural and varied than the predetermined surface geometry explored by Bechthold et.al. Gradients in the peaks and valleys left behind in the stone are controlled by changing the water pressure and distance of the nozzle from the material as well as the speed of nozzle movement across the surface. This level of control is not available in standard waterjet machining software platforms, but is easily handled by the CAMel OMAX component scripts. As noted by the authors, the ability to control a 5-axis waterjet in the same way would allow the three-dimensionality of the erosion-based fabrication method to be explored with larger limestone blocks [13].

Machine Movement as Design Space

To date, our work has resulted in a series of small prototypes that may be similarly analyzed as objects whose creation is made possible only through 5-axis waterjet machining as instructed by the customizable workflow. The prototypes are geometrically difficult to program using standard waterjet CAM software, but can be quickly modeled and programmed by using the plug-in. This is because the standard use of 5-axis waterjet machining does not typically require the full range of movement that the machine has been designed to accommodate. The proposed workflow opens up a new design space within the fabrication process and is able to produce precise detailing, complex surface geometry, and at times unexpected aesthetic effects in a wide range of materials. Depending on the approach, the workflow may produce specific results that are discovered through machining, since the plug-in does not require the object to be fully modeled prior to the operation. This allows for a more direct, intuitive, communication between user and machine, encouraging a new way of thinking about advanced fabrication processes. The selected prototypes discussed below have been purposefully designed to test the CAMel to OMAX communication and to gain further experience with 5-axis waterjet cutting operations.

Brick and Timber Hyperboloids (Cutting Double Curvature)

Ruled surfaces have a long history in architectural design and construction, perhaps due to the relationship between their structural capacity, aesthetic beauty, and rationality. Perhaps the most well-known example is Antoni Gaudi's use of a family of ruled surfaces in the design of the Sagrada Familia; hyperboloids of revolution, hyperbolic paraboloids and helicoids. While these surfaces are doubly curved, they can be formed manually in wet plaster by sweeping a straight edge along guides or from stone by cutting straight lines between corresponding endpoints on 2D templates [14]. This translates well to 5-axis waterjet cutting operations and other contemporary cutting equipment that works in a similar fashion. One could quite easily intersect two or more of these surface types opening up the possibility to create extensively complex surfaces and forms from a highly rational process [14].

Figure 1. Hyperboloids waterjet cut from standard masonry brick. Images by the authors.

Taking advantage of the waterjet's ability to cut thick masonry materials, we've used the hyperboloid of revolution as the base geometry from which to calibrate the CAMel to OMAX workflow against the accuracy (or 'cleanliness') of the cut. By simply increasing the angle of the revolved ruling line as it connects between two endpoints, we can quickly prototype the maximum cut angle that the machine provides, the resultant rippling in the cut as a factor of cut speed relative to angle, and various techniques to finish the cut and remove the waste material. These single hyperboloid tests were cut from standard masonry brick (~2" thick) and from 4" thick basswood to test the geometry against settings for both hard and soft materials. Further testing included an array of intersecting hyperbolic ruling vectors that were scaled using a Mobius transformation and cut from 4" thick basswood. Since CAMel instructs the machine's movement from point and vector data, modeling the hyperboloid surfaces is not necessary thereby avoiding the time required to fully model the result of the intersecting geometry. While this could be done as a visual safeguard before cutting, it's enjoyable to discover the complex intersections that form between the hyperboloids when both the top and bottom surface of the material stock is cut away in the process.

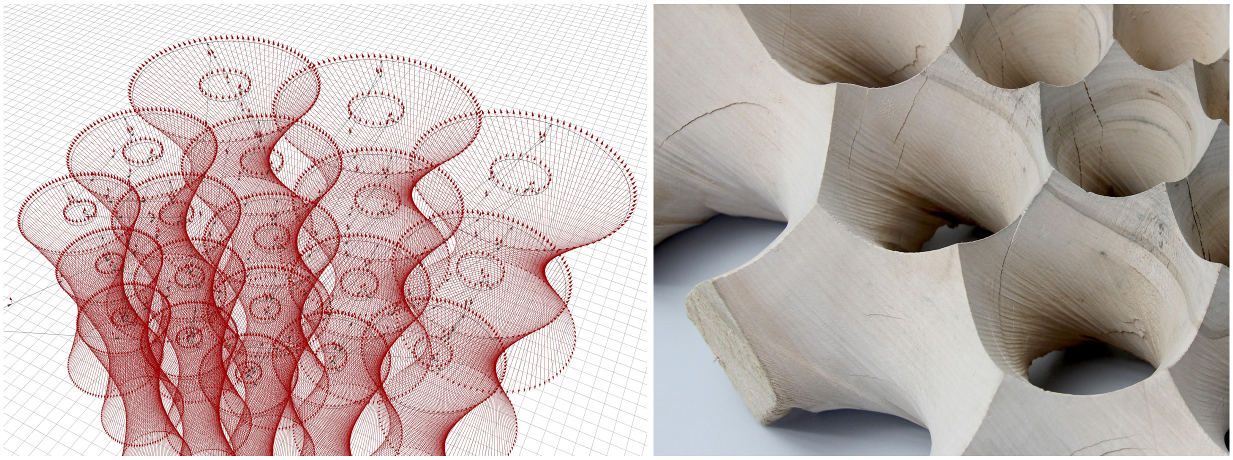

Figure 2. Left: Screenshot of CAMel toolpaths. Right: Intersecting hyperboloids waterjet cut from 4" basswood blocks, revealing forms that were not explicitly drawn. Images by the authors.

Terra Cotta Clover and 5-Point Rotational Symmetry (Rotational Swarf Cutting)

While ruled surface stone cutting has extensive historical precedent, similar methods in fired terra cotta is an area worth exploration. Since terra cotta is hard, brittle, and difficult to manipulate once fired, it lends itself well to waterjet cutting since no heat or vibration is generated in the process and the potential for complex cut edges exceeds the capacity for most industrial saw-cutting techniques. Due to the density and consistency of the clay material, the cut edge is sharp and clean on both sides of the material. Inspired by this, a prototypical geometry was designed to challenge the repeatability of the cut edge, consisting of a series of tapering parts of which the top edge would need to closely align with the bottom edge of the part above. To start, a twisting trefoil was prototyped to initially test how CAMel was instructing the machine to complete a rotational swarf cut with deep undercuts and vast angle transitions. To follow, a tapering column structure was prototyped consisting of a twisting shape with 5 point rotational symmetry with an added sine curve to produce a rippling effect along the exposed cut edge. The prototype served to test the tolerance when matching the edges of tapered and stacked terra cotta layers.

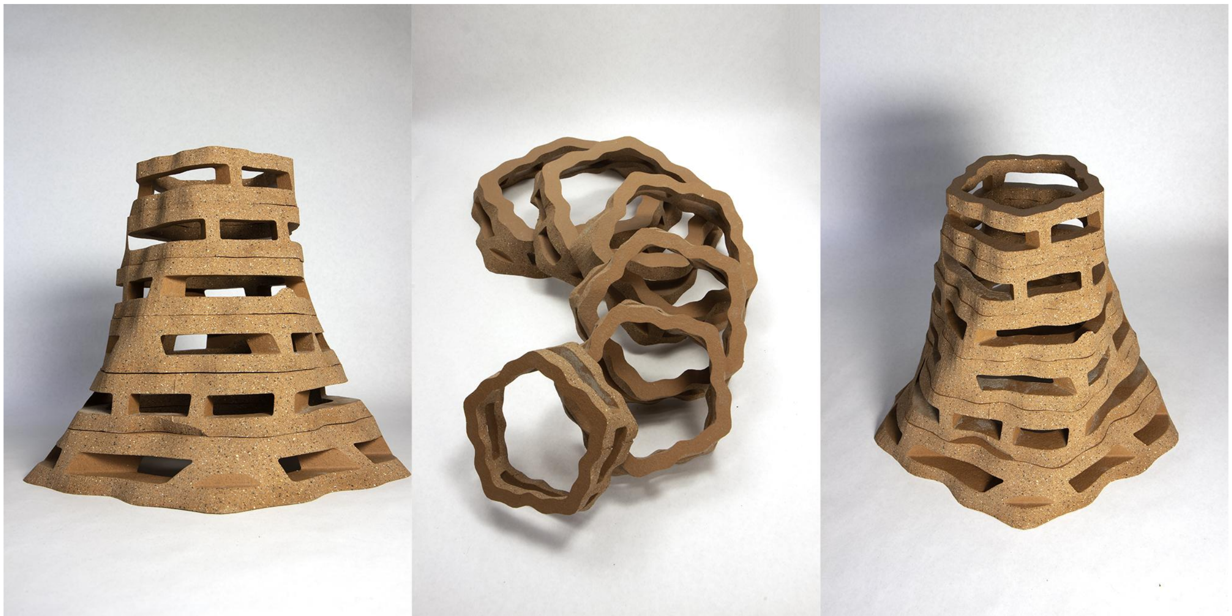

Figure 3. Tapering sections with 5-point rotational symmetry waterjet cut from terra cotta. Images by the authors.

Additionally, each layer may be rotated in 72 degree increments to realign with its neighboring layers, exponentially increasing the overall potential for errors in edge alignment. The success of this prototype inspired a collaborative project that implemented a similar stacking technique at a much larger scale, and was completed as part of the 2019 Architectural Ceramic Assemblies Workshop held annually at the University at Buffalo's Sustainable Manufacturing and Robotic Technologies (SMART) Fabrication Factory. The CAMel to OMAX workflow was used extensively for this project and for an equally ambitious undertaking by Kieran Timberlake Architects which required very precise transitional detailing and minute tolerances in the terra cotta components.

Figure 4. Sequence of rotational swarf cuts. Multi-axis waterjet movements were programmed from the same parametric model. Images by the authors.

Waveform Locking Connections (Linear Swarf Cutting)

Similar in spirit to the multi-axis waterjet cutting of masonry for thin-shell vaulting by Kaczynski, McGee, & Pigram, this series of prototypes experiment with creating locking connections between two or more parts. Substantial work in this area has more recently been done by Fernando, Reinhardt, & Weir, exploring multi-axis abrasive waterjet cutting and robotic hot wire cutting of structural wave joints [15,16]. Alongside the aforementioned hyperboloids, these tests are also being used to calibrate the machine for accuracy within a range of hard and soft materials. However, since the surface geometry doesn't necessarily dictate the angles of ruling lines, CAMel is being used to specify not only the overall movement of the machine needed to finish the part, but also the designed transition between ruling vectors of choice. It is anticipated that this will demonstrate unexpected and aesthetically pleasing visual effects to the exposed cut edge.

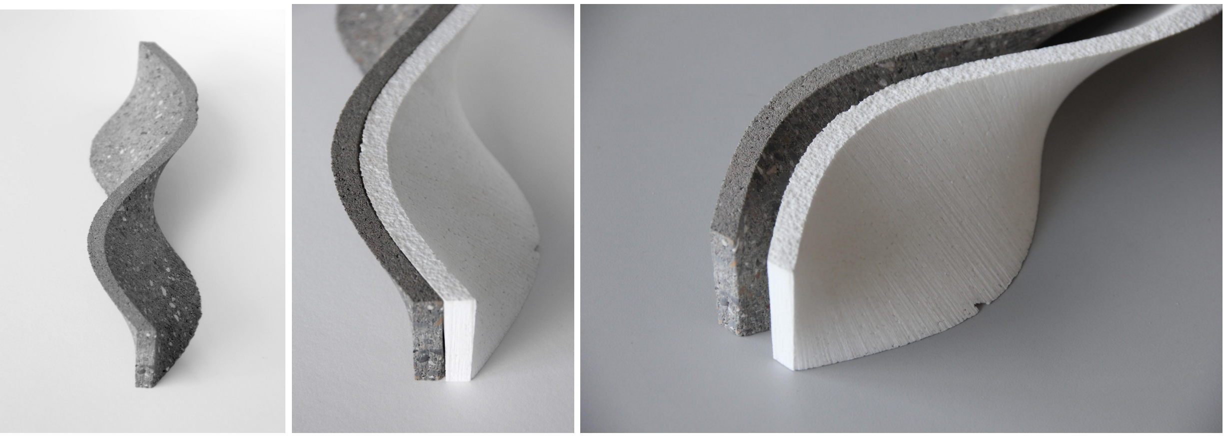

Figure 5. Thin ruled surfaces waterjet cut from standard masonry block and polystyrene foam with a high level of accuracy. Opposing sine curves guide the end points of the ruling lines. Images by the authors.

Conclusion and Future Work

As a contribution to the discussion around CNC craft, the initial phase of this research aims to open up new possibilities with 5-axis abrasive waterjet cutting by providing direct control over the full range of movement and multi-material cutting potential. With more nuanced and designed control, the design space of machine movement becomes more intuitive and flexible. When design work or creative intent (drawing, digital modeling) becomes more directly related to the parameters of manufacturing, new discoveries may result as the role of predetermined visualization is less related to the actual fabricated product. Agile machine control combined with the power of multi-axis waterjet cutting has great potential for further exploration as the precise cutting of complex forms from a wide range of materials is made less specialized. The proposed CAMel to OMAX waterjet workflow may be impactful to several creative disciplines as it is situated within an increasingly ubiquitous digital modeling environment, and once the baseline technical learning curve is surmounted, relies on creative approaches to fabrication as opposed to predetermined sequences within a limited catalog of common machining operations.

As we continue the work, it may be worth revisiting David Pye's distinction between certainty and risk; the former defining a result as an outcome that is predetermined and outside the control of the operative, and the latter defining a result as an outcome that is determined during a process that depends on "judgement and dexterity" [1]. The proposed workflow may exist somewhere between, perhaps as an unregulated[2] craft. The result may or may not correspond exactly with the idea since this depends on the will and the technique of the craftsperson. One may choose to model machine movement whose appearance on-screen does not exactly depict the object created, or they may extract machine movement from a pre-designed form. This is no longer a question of disparity of accuracy or approximation of form, as the workflow may provide a platform to rethink fabrication as a question of design intent as related to the vision of machine movement.

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Notes

1. This analysis does gloss over one aspect, that there will often be more than one position (or stance) of the machine corresponding to a particular coordinate. What is captured here is all possible interactions between the tool and material.
2. This is a reference to Pye's notion of "regulated workmanship", where "the achievement appears to correspond exactly with the idea." He notes that if there is a lack of exact correspondence, then the evident disparity and approximation may be called "free" or "rough" workmanship.