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Processes for an Architecture of Volume

Robotic Wire Cutting

Abstract This paper addresses both the architectural, conceptual motivations and the tools and techniques necessary for the digital production of an architecture of volume. The robotic manufacturing techniques of shaping volumetric materials by hot wire and abrasive wire cutting are discussed through a number of recent projects. A comparative analysis between milling and hotwire cutting is presented and a number of case studies and tool development studies are considered. Finally, the specifics of toolpath generation for robotic wire cutting are introduced.

Keywords: Hotwire Cutting; Abrasive Wire Cutting; Volume; Traite.

Introduction

There has been a growing interest in material processes that can support an architecture of volume, investigating materials which are unconstrained by the limitations of sheet based materials. Our initial investigations in processes for an architecture of volume explored the lightest and least expensive volumetric material available, EPS foam. This material has seen many applications in the mold making, highway and construction industry, as it is cheap, recyclable, extremely light and easy to shape. This material is typically carved using large CNC routers, and for double curved geometries this is still a requirement. The material can also be cut with a hotwire, which provides a method whose historical precedent can be associated with stereotomy and the developed surface of traditional stone masonry (de la Rue, 1782) (Fig. 1).

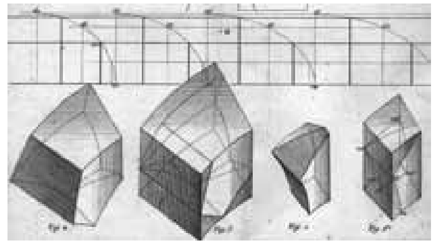

Figure 1 De la Rue, Traite de la Coupe des Pierres.

Architectural production has been systematically compressed into ever thinner layers by the constraints of industrially processed materials. CNC fabrication processes, initially heralded as liberating the designer from the disconnect between drawing and making, have accelerated the process, packaging components into the discrete 4' x 8' work envelope of the typical 3 axis router. In addition, streamlining the workflow from design software to fabrication processes (while this has many positive benefits), has in some ways allowed this "flattening", slicing, slivering and wafering of building construction methods to go unquestioned. Openly available scripts allow 3D surfaces to be ribbed, unrolled and nested into common sheet sizes, ready for production. Contemporary digital fabrication techniques continue to proliferate this limitation, producing a stream of contoured, folded, notched and otherwise surface-driven projects.

This scope - that of a representational model - is sufficiently nebulous in terms of scale to abstract architecture from its realization. The irony of the proliferation of CNC methods such as 3D printing, 2D laser cutting, and routing is that its obscures the industrial potential of the

Figure 2 Subdivided columns, M. Hansmeyer (left) Metropol Parasol, J. Mayer (right)

close coupling of design and manufacturing methods. This becomes problematic when these false or self-imposed constraints become the aesthetic of the building, where the approach of building a representational model has been projected to its full size, as observed in the "Metropol Parasol" project by Jürgen Mayer (Fig. 2 right). An interesting example that simultaneously illustrates the merits and limits of this approach is the work of Michael Hansmeyer. His "subdivided columns", a series of 2.7m high columns, built from 1mm layer grey cardboard (Fig. 2 left). While the intricacy and elegance of the work is not questioned, the project is antithetical in terms of fabrication; columns are load bearing structures that aren't made of cardboard, and the intricacy can be subscribed to the strong will of architectural students, rather than architectural engineering. A consequence of exploring methods of construction that have little or no manifestation in building practice can be construed as a form of technological self-censorship. With the mechanics, tooling and technology available, it is paramount to focus research on those modes of production that do scale, hence are of value to the construction industry.

Figure 3 Production of the RDM Vault at Hyperbody's robotics workshop in Rotterdam

While advanced manufacturing methods have traditionally been associated with costly manufacturing methods, robotic hotwire cutting (RHWC) breaks with this trend given that complex formwork can be delivered for the approximate cost of normative formwork. As such RHWC is both an enabler, technically, in terms of forms that can be produced, and economically since this can be achieved at little or no additional expense. With the many ongoing predicaments in the construction industry, and the modest cost of delving into robotics, this is an important aspect that is open to further exploration.

Hyperbody's robotics lab is equipped with two second hand ABB S4 robots, that were both acquired for less than what a makerbot costs (Fig. 3). Brand new robotic manipulators typically cost less than half the price of a typically capable dedicated CNC machine. Robotic fabrication presents a development platform for such considerations, given the trade-off of precision, ease of integration and programming, robustness, and market availability. As the technology has begun to gain acceptance in the building fabrication industry (admittedly it remains a very small fraction), these methods have started to challenge what type of construction can be delivered within a given budget.

RHWC

Hotwire cutting holds a number of advantages when used to create formwork for

casting. At an architectural scale, traditional approaches such as CNC milling become prohibitively time consuming. At the sheer volume demanded for full scale architectural in situ casts, such as bridges and commercial buildings, the incremental removal of material offered by the milling technology necessitates considerable machining time and results in production fees unacceptable to most building budgets (McGee 2011, Feringa 2011). Machining hours may be reduced by tolerating a rougher surface, however, production times remains prohibitively high, and the rough tooling paths simultaneously frustrate the demoulding process. This limits the application prospect for CNC-milling technology primarily to detailing tasks, exclusive high-end building budgets and repetitive casts, where formwork may be reused. RHWC offers a number of advantages. The removal of material in this process is essentially volumic; the cutting process processes a surface in a single sweeping motion, whereas in milling the volume is removed layer-by-layer, constrained by the limited depth of the milling bit. Per surface, the length of the tooling path is parameterized over the radius of the milling bit, where often a roughening milling bit is used with a large diameter to approximate the shape quickly, while a milling bit of a smaller diameter is required to achieve a smooth surface. In addition, the RHWC leaves a surface considerable smoother than that of the milling process, producing a better surface finish on the cast product, while reducing demoulding adhesion. For extremely finished surfaces the mold can still be coated with polyurea, requiring less coats than a typical milled finish. The difference in production speed is easily understood geometrically; whereas milling essentially removes a sphere, RHWC removes a cylinder of material at an instance in time (Fig. 4) That amounts to a difference of 1 to 2 orders of magnitude, as the following comparative study shows, approximating the differences in production time for either production technique (Table 1).

It is important to mention that, while the increase in production speed is dramatic, the additional effort of rationaliz-

Figure 4 Comparative scheme of sample geometries

	ex. a	ex. b	ex. c	ex. d	ex. E
CNC rough.	3h 34m	5h 5m	3h 44m	4h 22m	6h 31m
CNC finishing	6h44m	7h 42m	7h 01m	h 31m	12h 14m
RHWC	0h 01,8m	0h 02,4m	0h 02,3m	0h 02,7m	0h 03,1m
Area cut	2,66 m2	2.95 m2	2.86 m2	4,01 m2	3,49 m2
Removed vol	1,44 m3	2.06 m3	1,44 m3	1,72 m3	2,41 m3

Table 1 Machining metrics comparing the CNC milling with RHWC

ing geometry to ruled surfaces – a key topic of architectural geometry – is not factored into this comparison. While RHWC is remarkably efficient, the geometric grammar that can be produced is a subset of what can be produced by milling. However, it is important to realize that architectural scale works in favor of RHWC. First of all, in the sense that forms which traditionally would not be manufactured by CNC methods can now be produced. Secondly, due to scale, the limitation to ruled surfaces becomes less of an issue, since a greater surface area makes constructing a satisfactory approximation less problematic.

Projects

A number of case study projects have been performed to validate the capabilities of RHWC. In "Periscope", by Matter Design Studio, the hotwire process provided the means for the rapid production of a 50 foot tower of foam (Fig. 5). The economy of time and material was of paramount importance, due to the pressures of a two week construction window and limited budget. The RHWC process was used to generate a large array of mass customized masonry units, which were assembled in a running bond to approximate the original, doubly curved column. In an effort to establish a characterization of the various approaches to working with volumetric materials, one could consider this a "slab based" process, whereby components are cut from a slab of material, preserving some portion of the slab surface on the top and bottom of the part (Fig. 6). In this case the preservation of the parallel top and bottom surface is important to support the assembly technique.

A more recent project by students at the University of Michigan uses the slab cutting process to shape AAC sheets into voussoir units to form a thick-shell compressive vault. In this case the prototype uses abrasive waterjet cutting to cut the 4" thick AAC block. Previous work at the University of Michigan saw the application of this technique to process 2" thick sandstone (in slab form), uniquely cut to form thin-shell vault components. Wire cutting becomes more efficient and precise at larger material thicknesses, and opens

Figure 5 Periscope completed

Figure 6 Slab cutting EPS

up the possibility of structural systems that respond to additional factors beyond the material efficiency of the thin shell vault (Clifford, 2012). Clifford describes this as a shift from form-finding to form-responding, and uses it as an approach to develop structurally viable forms requiring relatively thick sections. The ability to work with volumetric materials is critical to the success of the process (Fig. 7).

An alternative approach to "slab cutting", which adds an additional level of geometric freedom, is the "solid" based cutting process as explored in recent projects by Hyperbody (Figure 8). A recent collaboration between Hyperbody and ROK-Rippmann Oesterle Knauss / ETH Zurich, the RDM Vault, explores a joint approach to the design and fabrication of vaulting structures, as evoked in Rippmann and P. Block (Rippman and Block, 2011). RhinoVault (Rippman, Lachauer and Block, 2012) provided intuitive tools for the design of a vaulting structure, while PyRAPID enabled the transliteration of the resulting geometry to robotic motion, cutting the "traites" out of EPS foam. The pavilion was erected at Hyperbody's robot lab which will host the RobArch workshop in Rotterdam (Fig. 9).

In this case the components are nested completely within a volumetric block of material. All faces of a component are wire cut, as opposed to the slab cutting process, which relies on a parallel top and bottom face. While the cut surfaces are still limited to ruled geometries, by shaping the entire exterior of the component the aggregation can more accurately approximate a freeform surface, while producing joint faces which are normal to the thrust vec-

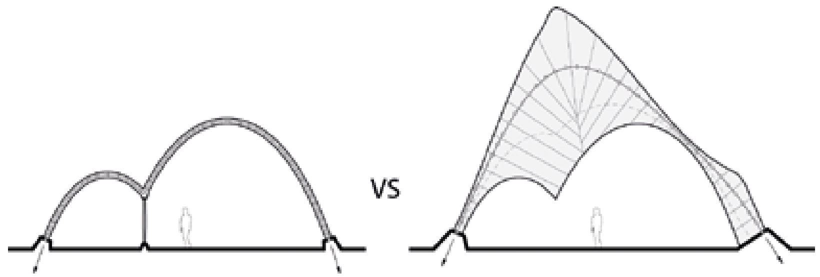

Figure 7 Thick funicular solver

Figure 8 Solid based cutting process, as explored in the RDM Vault.

tors. Component sizes and shapes will still be governed by their ability to fit within an available volume of material.

From Hotwire to Abrasive wire

Building upon the work with EPS, there have been a number of investigations using more permanent volumetric materials, such as AAC (autoclave aerated concrete) and natural stone. It is against this background that several projects were undertaken using robotically manipulated abrasive wire cutting equipment. While numerous projects have investigated the geometric potential of hotwire cutting EPS, considerably fewer have dealt with developing the end of arm tooling to mount abrasive wire saws to robotic equipment for the purpose of cutting more rigid materials. While wire cutting harder stone materials remains a very slow process, there are several advantages when compared with CNC milling or multi-axis bridge saw cutting. The capital cost of the equipment is considerably less (one third to one half), with the generic robotic manipulator costing far less than a stone capable CNC, even after factoring in the cost of integration and tooling. In addition, the implication of the process as a semi-finishing operation makes it more appropriate to the tolerances possible using robotic manipulators, as opposed to more precise CNC equipment. There are also potential material efficiencies that can develop, given the much smaller kerf of the segmented wire compared to milling and sawing, although these will be highly geometry dependant.

Segmented diamond wires are well known for their ability to cut harder

Figure 9 RDM Vault

materials like natural stone (marble, granite) and reinforced concrete. Typically, the wire sawing process is used for either semi-finished flat slab cutting applications, or large scale demolition. There are exceptions, of course, such as this large 6 axis CNC wire profiling system by Pellegrini Meccanica Spa (Fig. 10 left). The machine clearly illustrates the possibilities for multi-axis wire cutting, but it also presents opportunities for a more flexible, portable approach to fabrication. Dedicated CNC approaches are likely to always possess an advantage in terms of accuracy and overall capacity, but there are potential applications where the flexibility and portability offered by industrial robotic manipulators can fill a unique role in fabrication. Several researchers have tested applications for robotic wire sawing, but the capabilities of a robotically guided wire cutting operation to yield complex units in a finished/semi-finished state has not been studied extensively. It is worth pointing out that just over a decade ago "nearly eight hundred full-size DIN A0 templates were required to guide the stonemason's hand" in completing the translation from model to ;workshop (Burry, 2001).

Shutao Li, et al. developed a proof of concept production line to machine AAC slabs directly from BIM data. The tooling developed utilized a segmented diamond wire circulating in a rectangular frame (Li, 2007). This approach has also been used in combination with a spiral cutting steel wire, cutting ruled geometries out of cured plaster (Bard, 2012) (Fig. 10 right).

The authors are currently engaged in developing end of arm tooling for robotic diamond wire cutting (RDWC), with a number of areas targeted for study. Robotic applications will require the tooling to be considerably lighter than the CNC applications highlighted above. This is not a trivial task, as even a typical manual profiling diamond wire saw can weigh 500 lbs [3]. In a typical wire cutting operation, as in band sawing, there are guides which support the blade opposite the travel direction. In the case of 3D wire cutting, the wire is capable of moving in any direction. The guide system needs to support this, and potentially will require a servo driven solution for positioning relative to the cut direction, similar to the CNC equipment described previously.

Figure 10 6 axis CNC diamond wire saw (left); Wire sawing end effector developed at the University of Michigan Taubman College (right)

Software

It can be argued the generic robotic manipulator utilized in this research is only incrementally different to it ancestors which were in continuous use in mass production for decades. Without a doubt, one of the driving factors behind its growing adoption in the architectural fabrication industry is the use of open source and bespoken software applications. While robotic manipulators provide incredible flexibility, this comes at the price of developing tools which suit both the designer and fabricator. Compared to CNC equipment, which has clearly also benefited from the developing culture around scripting and algorithmic design methodologies, robotics has the added benefit of compatibility with an open framework for fabrication. Closed-loop process feedback and the "ease" of integration into a multifaceted production process are relatively complex to perform using traditional CNC equipment; with robotic manipulators these capabilities are integral to the design. Such open frameworks are superMatterTools, developed by Wes McGee and Dave Pigram, Daniel Piker's lobster, Robots-in-Architecture's KUKA|prc, PyRAPID by Jelle Feringa and HAL by Thibault Schwartz.

A key motivation for the development of open frameworks is how existing approaches such as contour cutting can be adapted to the solid cutting process (Fig. 9), which are considerable more demanding in terms of toolpath generation, motion planning and collision avoidance. An interesting aspect is how the software developed for the exploration of RHWC maps with modest adaption to RDWC. Hotwire cutting is a comparatively safe production method compared to the brutality of the diamond wire sawing process, so the evolution of RHWC naturally paved the way for RDWC. Whereas the development of RHWC was demanding in terms of software development and trivial in terms of the required tooling, these roles are reversed in the continued development of RDWC, where building a practical wiresaw is demanding.

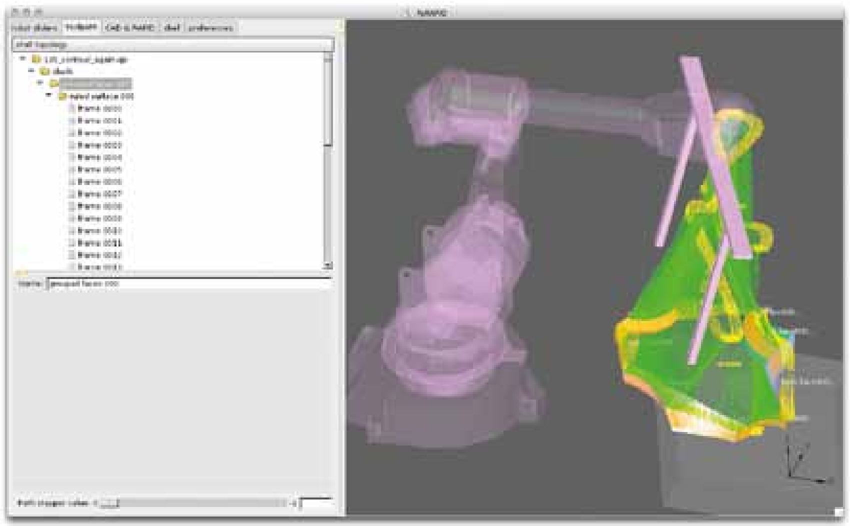

Figure 11 PyRAPID, custom RHWC software develop on top of PythonOCC

The potential of RHWC and RHWD was explored with PyRAPID a software application was developed in Python with PythonOCC, a wrapper of the OpenCasCade CAD kernel as it main dependency (Fig. 11). The application automatically clusters the faces so that they can be cut in a single sweeping motion, and generates a toolpath optimized for extending the reachability of the end-effector, and computes the inverse kinematics from that pose. As the tool orientation has a degree of freedom over the axis of the wire, the key is to exploit this, as it allows for considerable optimization of the reachability of the robot.

After clustering the faces the software tests whether an additional roughening step is required. The roughening step is specific to robotic hotwire cutting, while with a traditional hotwire cutting machine no clashes between the tool and workpiece occur. The downside, however, is that to cut large blocks, a considerably larger machine is required, while a robot is a fairly compact machine, certainly in view of its reachability.

Ongoing efforts include logistics, such as the integration of picking and placing, in order to facilitate a production workflow that minimizes operator attendance. The added flexibility and process integration of this setup is a topic of further research. An important argument why robotic hotwire cutting has considerable merits over a classic CNC hotwire machine is specifically the issue of process integration.

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