Fig. 1: RDM vault.
FABRICATING ARCHITECTURAL VOLUME
STEREOTOMIC INVESTIGATIONS
IN ROBOTIC CRAFT

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The 2011 edition of Fabricate inspired a number of collaborations, this article seeks to highlight three of these. There is a common thread amongst the projects presented: sharing the ambition to close the rift between design and fabrication while incorporating structural design aspects early on. The development of fabrication techniques in the work presented is considered an inherent part of architectural design and shares the aspiration of developing approaches to manufacturing architecture that are scalable to architectural proportions and of practical relevance.

RDM VAULT

The RDM vault presents a collaboration between Matthias Rippmann and Silvan Oesterle, initiated by Jelle Feringa. Earlier work suggested the necessity of dealing with structural design aspects early on in the design phase. An important constraint to building with expanded polystyrene (EPS) elements is their limited capacity to deal with tensile forces, while the material can cope with considerable compression forces. The project therefore sought to deal with both structural and fabrication constraints as the driving parameters of the design phase. RhinoVault, developed by the Block Research Group provides powerful and intuitive design tools for the design of compression-only structures. Earlier work was built with a custom-built and fairly improvised machine specifically for hot-wire cutting. While that resulted in precise elements, both the software and design of the machine had a restrictive platform. Robotic hot-wire cutting (RHWC) coupled with the development of the PyRAPID CAM software dedicated to RHWC, allows the application of a truly voluminous approach to the production of the trait. The RDM vault is comprised of (fig. 1). At the time of construction, deploying RHWC for the first time at Hyperbody’s Robotics Lab for the production of very large and geometrically challenging elements, the tolerance of the cut elements was unknown and therefore the design’s shingles were accommodated for the eventual tolerances. As such, fabrication constraints become design drivers. In hindsight, margins for assembly were greater than the cutting tolerances (ranging from 1 – 2 mm). The project was designed and executed in the course of a month, emphasising the importance of experts having the opportunity to collaborate. The EPS elements were rendered with Acrylic One, a gypsum/acrylic composite material, and glass fibre. Resulting in a structural shell, a rendered finish and a fireproofing layer were applied to the EPS structure, increasingly the longevity of the fragile foam components. Though the approach has many practical merits, in the end, the project suffered from an architectural ambivalence that could be traced back to its materialisation. There is a precarious unease present whether one observes a 1:1 mock-up of an architectural intent (a representation) or the artefact as conceived. That apprehension extends to the inconclusiveness of whether the vault is an assembly of individual traits, or a monocoque glass fibre reinforced shell (fig. 2). While efficient, practical and economical, the materialisation of the RDM Vault lacked a tactile and tectonic quality.
STONECUTTING

The concern of tectonics pushed the volumetric approach to fabrication further towards stereotomic tradition and towards a more permanent materialisation, fuelled by the development of a diamond wire saw. The powerful abrasive wire saw is powered by a 40 Kw hydromotor and allows the processing of stone at a very high speed. While stonecutting is a mechanically and time-intensive process, the effectiveness of abrasive diamond wire cutting, traditionally a demolition method, is easily proportionate to the speed up (an order of two) achieved by RHWC.

This research has precedents in the work of (Shutao Li, et al)\(^8\), machining AAC slabs from BIM data and (Bard 2012),\(^9\) where a spiral cutting wire was applied to process cured plaster, while the work presented here is focused on the lost art of stereotomy and processing hard mineral materials.

Elements shown in (fig. 3) were fabricated in 20 minutes per piece. These initial experiments were conducted with an inexpensive material, engineered limestone. This experiment was conducted at Hyperbody’s workshop for the first edition of the Robots-in-Architecture conference, taught by Wes McGee, Jelle Feringa and Lauren Vasey. The diamond wire saw was engineered and built by Jelle Feringa and Frank van Brunschot with the support of the industry partner Husqvarna. Further research took place in the summer of 2013 at the marble quarry of Carrara, in cooperation with industry partner Marmi e Graniti d’Italia, one of Italy’s largest quarries (fig. 4).

The work on robotic diamond wire sawing (RDWS) research is taking place right at the intersection between revisiting a long-lost ancient craft while employing state-of-the-art industry tools and bespoke software development. As such, the work is pleasantly equivocal; rooted in many centuries of a progressive architectural tradition while empowered by recent advances in industry and custom CAD software.

Stereotomy is resurfacing as a contemporary technique since Robin Evans formative book *Projective Cast: Architecture and its Three Geometries*\(^10\) appeared in the early 1990s along with Bernard Cache’s seminal work and writings in the late nineties.\(^11\) Many recent projects, such as the MLK Jr. Park Stone Vault\(^12\) in Austin, Texas, by the Block Research Group, Brandon Clifford’s recent publication, *Volume – Bringing Surface into Question*, and Matterdesign’s *Voûte de LeFevre* as well as Giuseppe Fallacara’s many publications and projects emphasise the relevance of the line of inquiry.
During the Fabricate 2011 conference, the authors of this paper presented projects that dealt with topology optimisation (TO) and hot-wire cutting. It was instantly clear that while topology optimisation motivated the need for sophisticated formwork, hot-wire cutting could provide these in architectural proportions, at a modest cost, and, as such, offer substantial complementary advantages. With forces joined, the Opticut project launched to explore the architectural and performative potential for large-scale realisation of optimised spatial structures through the use of RHWC and casting concrete. A research partnership between Aarhus School of Architecture, TU Delft’s Hyperbody’s Robotics Lab, Odico Formwork Robotics and HiCon was mobilised.

Recent developments in topology optimisation of concrete structures has shown significant potential for form-finding and design of material-efficient structures, in which up to 70% of material consumption may be reduced in comparison to massive equivalents, while respecting normative performance requirements. This material economy is achieved through the development of advanced structural morphologies, which minimise the required material volume to achieve structural performance through the densification of material in the trajectories of minimal deformation energy while maximising structural stiffness. As a consequence, new architectural shapes emerge, rendering the trajectories of structural force visible.

Topology optimisation induces a significant moment of morphological unpredictability, as topologies emerge freely within an unconstrained solution space.

The architectural specificity of these circumstances were initially investigated in the Unikabeton project, resulting in the realisation of a 12 x 6 x 3.3 m concrete structure using robotic CNC milling of EPS moulds. The project brought two conclusions:

- Topology optimisation’s resulting structures, though structurally feasible, overstrain challenges in in-situ casting and formwork production.
- CNC milling of EPS formwork is prohibitively time-consuming and therefore costly to scale up to architectural proportions.

Concluding that a coupled design / fabrication process is key to achieving the merits and potential material savings offered by TO, Opticut initiated a dual investigation program to explore the capacity for an economically efficient production of advanced formwork for topology optimised spatial concrete
structures using robotic hot-wire cutting (RHWC) of EPS framework (fig. 8). The first part of the project investigated the geometrical post-rationalisation of the mesh resulting from the topology optimisation process, by composing single- and double-ruled surfaces. In the second part, the necessary production procedures and software were developed. Currently, the construction of an over 20 m full-scale prototype structure on the coast at Aarhus is continuing and is scheduled for completion in February 2014.

The design was formulated as a TO problem subject to wind and dead loads. Anticipating later post-rationalisation by ruled surfaces, the envelope was constructed from ruled-surface geometries, merging three typologies: the corner, the wall and the canopy.

Early experimentation found that translations using compositions of simple hyperbolic paraboloids from circular or ellipsoid starting geometries proved to be inadequate for approximating the TO’s resulting mesh. Consequently, a procedure to create n-sided, irregular, hyperbolic paraboloids from non-parallel, double-ruled construction planes was devised. This approach allows for a parametric interpretation of the perforated topology while achieving surface curvature continuity.
The prototype was designed for subdivision in six primary elements ranging from $10 \times 3.5 \times 1.7$ m to $7 \times 2.5 \times 0.3$ m. Casting the elements is achieved by using EPS plugs (fig. 7) inserted in conventional in-situ shuttering systems, able to resist casting pressures on vibration tables commonly used in the prefabrication industry (figs. 9, 11–12).

The formwork is produced at Odico’s production facility, utilising the world’s largest robotic hot-wire cutting machine, an ABB IRB-6400R industrial robot mounted on a 24-meter long linear axis (fig. 10). While milling and hot-wire cutting cannot be directly compared, since cutting is geometrically a more restricted method, i.e. bound to ruled surfaces, architecturally it’s arguably more liberating. To provide a perspective on how production capacity roughly compares, the cutting process presents a speed-up factor of 25 compared to milling. Given the intricate geometry, some of the efficiency of the process is lost, where in practice two orders of magnitude in speed-up are observed.

Figure 10: Robotic workshop at Odico.

Figure 11: Y-joint sample cast constructed from three intersecting hyperbolic paraboloidal surfaces and six single-ruled extrusions.

Figure 12: 1:1 EPS positive of prototype segment.
**ODICO**

The commercialisation of RHWC technologies was fuelled by the measured increase in production speed in comparison to existing procedures. While most architectural productions can feasibly be described by ruled-surface geometries, the tendering with partners NedCam and Dura-Vermeer for the production of formwork for a bridge spanning over 300 m (designed by Zwarts en Jansma), indicated a need for equivalent efficiency in doubly curved production. Following a grant received from the Danish National Advanced Technology Foundation, Odico now heads the 3-year research project, Bladerunner, which seeks to develop an economically efficient production of freeform doubly curved geometry through the development of robotic flexible-blade cutting with heated blades, in collaboration with the Development Department of 3XN Architects, GXN, the Technical University of Denmark and a number of building industry partners.

Although only founded in April 2012, production by means of RHWC is now in full swing at Odico. The company is providing services for companies such as Siemens Windpower and Spaencom.

**PYRAPID**

The projects described in this article fuelled the development of custom software, dedicated to RHWC and RDWS, PyRAPID. PyRAPID is built on top of PythonOCC, with the open-source OpenCasCade CAD kernel as its main dependency (figs. 13–14). The application automatically clusters the faces so that they can be cut in a single sweeping motion, and generates a tool path optimised for extending the reachability of the end-effector, and computes the inverse kinematics from that pose. As the tool orientation has two degrees of freedom (sliding and rotating) over the axis of the wire, the key is to leverage this freedom, as it allows for considerable optimisation of the reach of the robot.
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NOTES


2 Matthias Rippmann is a member of the BLOCK Research Group, ETH Zurich and a founding partner of ROK Office.

3 Silvan Oesterle is a member of the Architecture and Digital Fabrication Group, ETH Zurich and a founding partner of ROK Office.

4 Jelle Feringa is a PhD candidate at Hyperbody, TU Delft, co-founder of EZCT Architecture and Design Research and founding partner / CTO at Odico Formwork Robotics.


7 The workers call the science of the trait, when cutting the stone, the science that teaches how to cut and separately construct more than one ashlars of stone so that, when they are put together (at the right moment), they create a piece of handwork that can be considered as a single object.” (Philippe de La Hire, “Traité de la coupe des pierres”, (Paris: Bibliothèque de L’Institut de France, 1596)


14 Denmark’s leading supplier of precast concrete elements.