“Lucid” Foam

Multi-Axis Robotic Hot-Wire Cutting for Translucency

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Hotwire cutting of Styrofoam or Polystyrene has been a popular tool for developing fast prototypes by the architectural community. The introduction of multi-axis industrial robots in the architectural curriculum, and the enhancement of the design to fabrication process by software bridging the gap, provided an alternative meaning to the traditional mostly representational process of hotwire cutting.This paper sets out to document and assess the procedural methodology and the results of a series of integrated design to fabrication experiments that took place in the Institut für Experimentelle Architektur-Hochbau. By channelling design intention towards a component assembly for a translucent effect, students were asked to utilise industrial robots to fabricate and prototype via hotwire cutting, designs that refer to architectural elements. These elements, mainly due to their scale and the commercial availability of bulk Styrofoam panels, can lead to functional or ornamental representations of discrete elements, which can be assembled together as part of a greater design.

Keywords: *Robotic Fabrication, Design Research, Hotwire-Cutting, Polystyrene, CAD-curriculum, translucency*

INTRODUCTION

Numerically controlled prototyping methodologies, not only affect the way we fabricate things, but in several cases they extend the design process itself and become the cohesive medium for design. Hotwire cutting of Styrofoam or Polystyrene, either extruded(XPS) or expanded(EPS), has been a popular tool for developing fast prototypes by the architectural community. The introduction of multi-axis industrial robots in the architectural curriculum, and the enhancement of the design to fabrication process by software bridging the gap, between the commercially available CAD packages and the numerically controlled programming language of the machine apparatus, (Braumann; Brell-Cokcan 2011), have provided an alternative meaning to the traditional, mostly representational process of hotwire cutting.

This paper sets out to document and assess the procedural methodology and the results of a series of integrated design to fabrication experiments. These took place at the Institut für Experimentelle Architektur-Hochbau at Universität Innsbruck during the period of the Vertiefung Hochbau course. By channelling the design intention towards a component assembly for a either a translucent effect or an

Figure 1
One of the design projects as a suspended light element

ornamental / texturized result, whilst pre-defining the material (Polystyrene foam), students were asked to utilise the ABB industrial robots of REXLab to fabricate and prototype designs that refer to architectural elements (Fig. 1). A Hot-Wire cutter operating as an extension to the robotic arm was also a pre-requisite. The architectural elements produced, mainly due to their scale and the commercial availability of bulk Styrofoam panels, was speculated whether they can lead to functional or ornamental representations of discrete elements, which can be assembled as part of a greater design.

The research intention, is to comprehend whether a non-conventional fabrication process and in extend design methodology can be developed through these experiments, by targeting the material properties of Polystyrene Foam and its inherent capacity of enabling light penetrating its composite mass. An assessment of the results both on aesthetic and practical criteria (i.e. economy of material, structural integrity, prototyping time, mass customisation) may potentially render the process as universal, since the fabrication constraints are incorporated directly into the form-finding process and the data transfer from the CAD medium to the robots is automated.

BACKGROUND

Polystyrene due to its inherent characteristics has been used extensively as the formwork for generating moulds for casting construction materials. In the instances where the design is morphologically complex, polystyrene has provided accurate formwork process, but at the same time generated the necessity for equally rapid mass production of these moulds. Constraints as economy of time and material were established, which lead to a transition from the traditional CNC milling to a faster process, that of the numerically controlled hotwire cutting utilising multi-axis industrial robots as the mass customisation medium (Feringa; Søndergaard, 2012, p. 495). In the latter, the designer is called to disengage from "visualising design through an abstract medium" (Evans, 1997), hence moving towards to an integrated approach where design, material and fabrication constraints have to work together as a seamless non-linear creative process.

Out of the many precedents of Robotic Hotwire Cutting, the methodology used in the conducted experiments follows a similar approach "Linking Robotic Hotwire-cutting and Assembly" (Brell-Cokcan; Braumann 2013) and the "Large Scale Hotwire and Diamond-wire Cutting" workshop (McGee; Feringa 2012) both in the context of the "Robots in Architecture" Conferences. In the latter, as well as in the case of "Robotically Fabricated Thin-shell Vaulting" (Kaczynski et al 2011, p 115) more robust, tectonic materials such as sandstone are employed, hence the original hotwire concept transforms into diamond water-jet cutting. The examined approach differs from these three precedents in terms of the design context. All of the above refer to a discretised assembly of complex geometrically building elements, whereas in the presented research the properties of the material and the fine-tuning of the robotic medium, are put into action, for designs that might not necessarily be complex morphologically, but are focusing on the attribute of translucency or ornament, both in the way they are produced and in the way they are conglomerated. Translucency in robotic fabrication has been addressed in other occasions such as in the "Graded Light in Aggregate Structures" study (Angelova et al 2015, p. 400) where robotically assemble discrete standardised elements are articulated in favour of sensing of light as a design initiative. Yet again this approach is different from the research presented, where the material is mostly subtracted to permit light emission.

INTEGRATED ASSOCIATIVE MODELING FOR ROBOTIC FABRICATION

Four separate design experiments were conducted, each exploring a distinct design scenario based on the given material's properties and the constraints of hotwire cutting as a fabrication methodology. Fig. 2, fig.3 and fig.4 display a panelling system design where dark and light colours are produced solely by material thickness providing different levels of translucency. A gradient translucent effect was the project's requirement, with cross-direction cuts and under-cuts being of varying height or depth from the centre towards the edges of the design, producing the required effect.

Each project dealt with a different geometrical challenge, whether working on flat foam panels or blocks of foam, produced through linear cutting paths varying in height, ruled surfaces or custom-shaped wire for subtraction (fig. 5). Most difficult tasks, demanding high robotic accuracy. were required by the projects with shared edges by two or more components which where also cut by the hotwire cutter (e.g. fig. 4), compared to the ones that

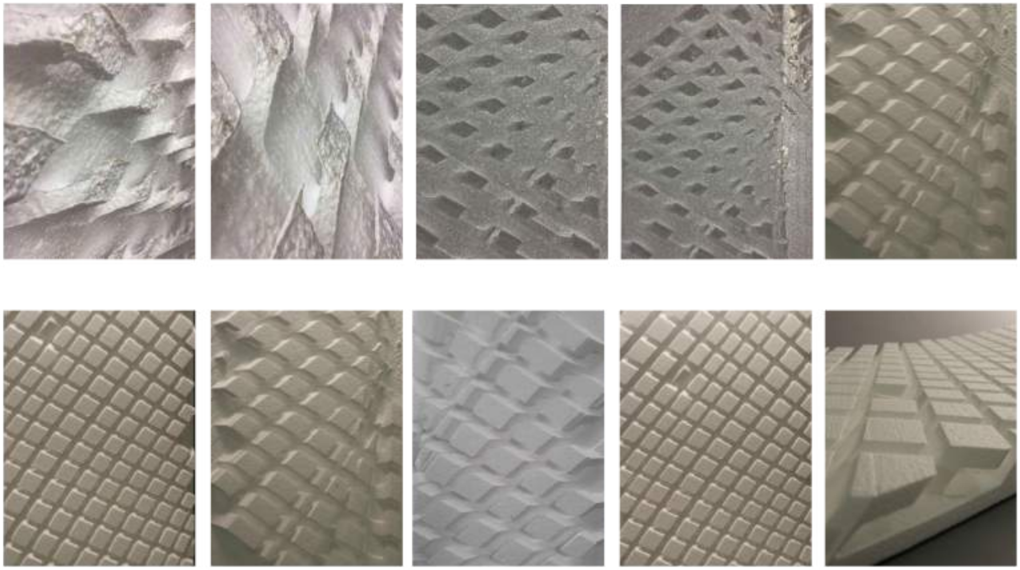

Figure 2
Difficulties with 'perlin noise' effect required lots of test-cuts to evaluate speed, temperature and object placing

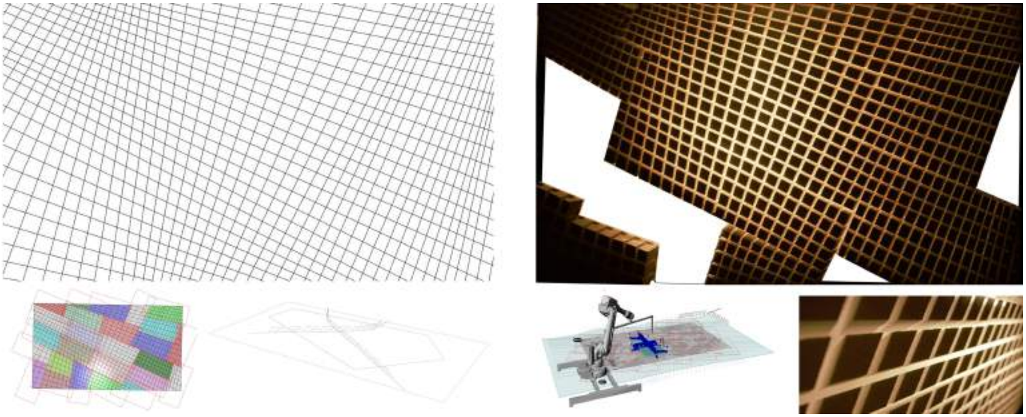

Figure 3
Design to
Fabrication process
for Wall System and
back-lit photo

the cuts were merely on the surface of a pre-cut foam panel (fig. 3)

The procedural steps followed in the research sequence rely heavily on quick decision making as a reciprocal system between the designer and the machine. These steps can be comprised to the following:

1. Design research
2. Rationalisation and parametric modelling
3. Generating the procedural machine language from the CAD software
4. Iterative testing with mock-ups using the robots, evaluating the material properties
5. Design rationalisation according to feedback from the mock-ups
6. Fabrication Process and proof of concept
7. Assembly and introduction of light fixings

The software used for associative modelling was Grasshopper3d for McNeel's Rhinoceros3d. Custom written routines in Python enabled both an iterative control over the design process and the generation of tool paths, primarily handled by Taco in Grasshopper3d(Frank et al 2016).

The fabrication methodology constraints were integrated in the parametric workflow of the designs, as they had to adhere with the size limitations of the Styrofoam block, the dimensions of the hotwire and custom tool tip and the kinematic limitations of the robot, in addition to the geometry rationalisation of the hotwire cuts into ruled surfaces. Ruled are the parametrised surfaces that can be swept out by moving a line in space (Gray et al 1993, p. 431). The hotwire end effector of the industrial ABB robots has inherently to abide to this restriction, as the wire at the end of the tool is a line that follows the kinematic movement of the arm, into space, as displayed in Fig. 4.

There are numerous possibilities for complex geometries generated just by ruled surfaces, however for the purpose of this exercise a supplementary custom tool, Fig. 5, was designed specifically to assist the subtraction of material, one level further than the hotwire end tool one. The need for micro-control and more accurate positioning and cutting has emerged from the nature of the designs, thus a significant amount of mock-ups of different forms and more importantly machine settings, like speed, torsional movement and heating temperature for the custom tool was vital for the success of the final fabrication (McGee; Pigram 2011, p 129).

The design experiments consisted of, two column designs, one wall / panelling infill module and a floating ornamental lighting element. In all of these cases there were a few principles that were rendered as the drives for an integral system of performance design to fabrication:

1. Adaptability and the dynamic associative character of the designs - necessity to evaluate many different results both on the digital and on the physical level
2. Direct connection of parametric design from the CAD software to the tool path of the multi-axis robot, which signifies economy of time
3. Economy of material - the discrete elements were tightly packed within the commercially available blocks of Styrofoam. A standardisation of elements and clustering of self similar elements also contributed significantly towards rapid mass customisation.
4. Implementing smart connections between the discrete cut parts, hence reducing the assembly time and saving material waste. For instance, a finger joint connection was integrated in a few of the designs (Krieg et al 2011, p. 576), diminishing the use of adhesive whilst enabling fewer cuts for the robot, as displayed in Fig. 6.

CONCLUSIONS AND FURTHER DEVELOPMENT

Numerous potential can arise from the utilisation of integrated multi-axis robotic fabrication. Especially when this is enhanced by fully parametric control of the design scenario and seamless connection of the design genotype which gets then translated to phenotype by the machine grammar. From the assessment of the prototypes, the aesthetic effect of the design intention was communicated in a quite successful manner. Regarding the "by the text book" methodology, this has yet to be perfect, as lot of manual intervention was essential to tackle issues mostly appearing during the fabrication process, such as recalibration of the robot, unstable fixings which resulted to destroyed elements, even in some cases bugs in the code that made the fabrication process erroneous. However, at least 80% of the process was fully automated. This research should be critically evaluated as an integrated design to fabrication methodology which focuses on the light permeability of the fabrication material. This distinct characteristic of light translucency, lead to non-mainstream thinking and to the development of case specific bespoke tools, both digital and physical. As further development a feedback loop in-between the robotic end effectors and the CAD software would be extremely valuable, as it would be an error recognition system, most probably based on a computer vision routine, which would enable the system to run uninterrupted without being under constant human supervision.

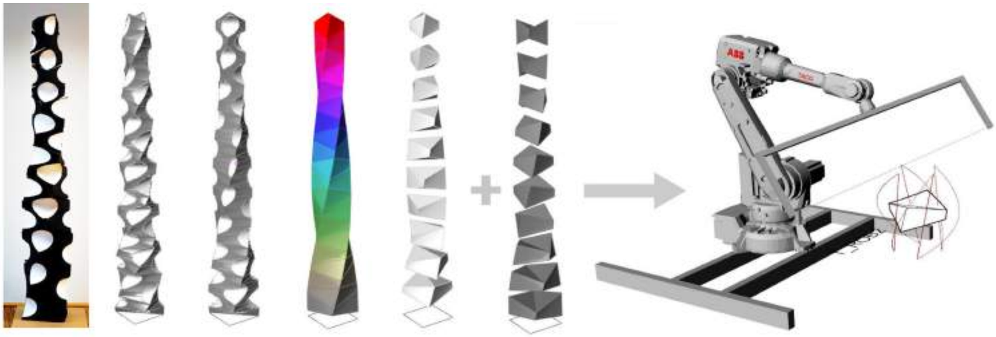

Figure 4
Rationalising a twisted geometry and generating the toolpaths for mass customisation.

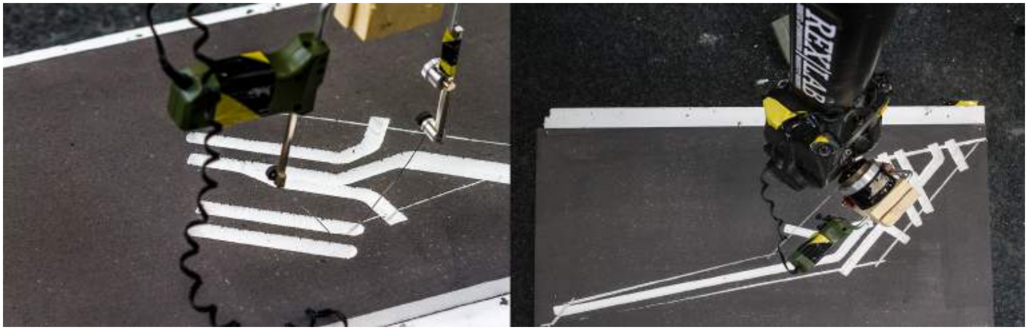

Figure 5
Custom tool subtracting Styrofoam and performing cuts

ACKNOWLEDGEMENTS

The Authors would like to acknowledge the contribution to this research of REXLab tutor Pedja Gavrilovic along with the following students: Baicu Alexandra, Bradenbrink Lea. Contala Jan, Dalpiano Sara, Echeriu Maria Alexandra, Grimm Raffael Julian, Jenewein Benjamin, Kappeler Paul Johannes, Keser Mümün, Kieffer Lynn Hyun, Kugelmann Patrick, Larcher Julian, Luksch Johannes, Moschig Verena, Musavi Seyyed Mohammad, Peters Jeff, Schlusche Johannes, Schramm Anke Kristina, Schreter Anna Elisabeth, Schwaderer Philipp, Sieder-Semlitsch Jakob, Stephan Nicolas Marc, Umhaller Andreas, Zanon Mara Elide, Stieler David Christoph, Weber Thomas Reinhard, Brandtner Markus, Alan Clara.

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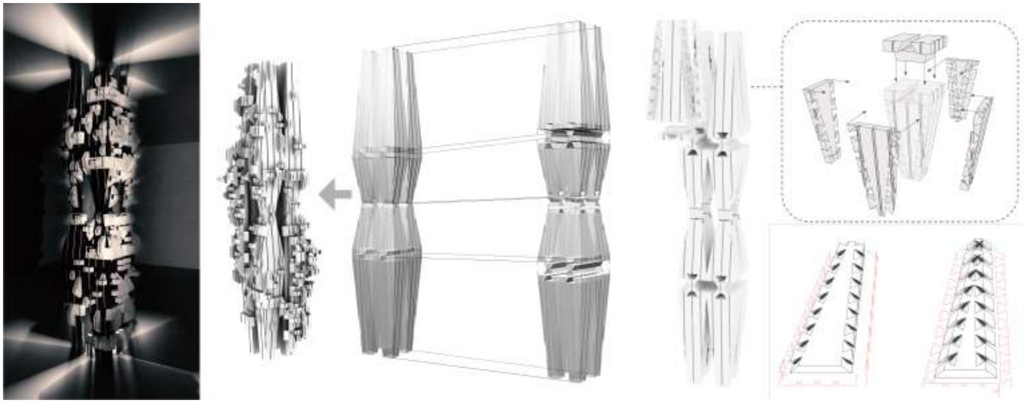
Figure 6
Finger-joint connections and minimising material waste for one of the designs



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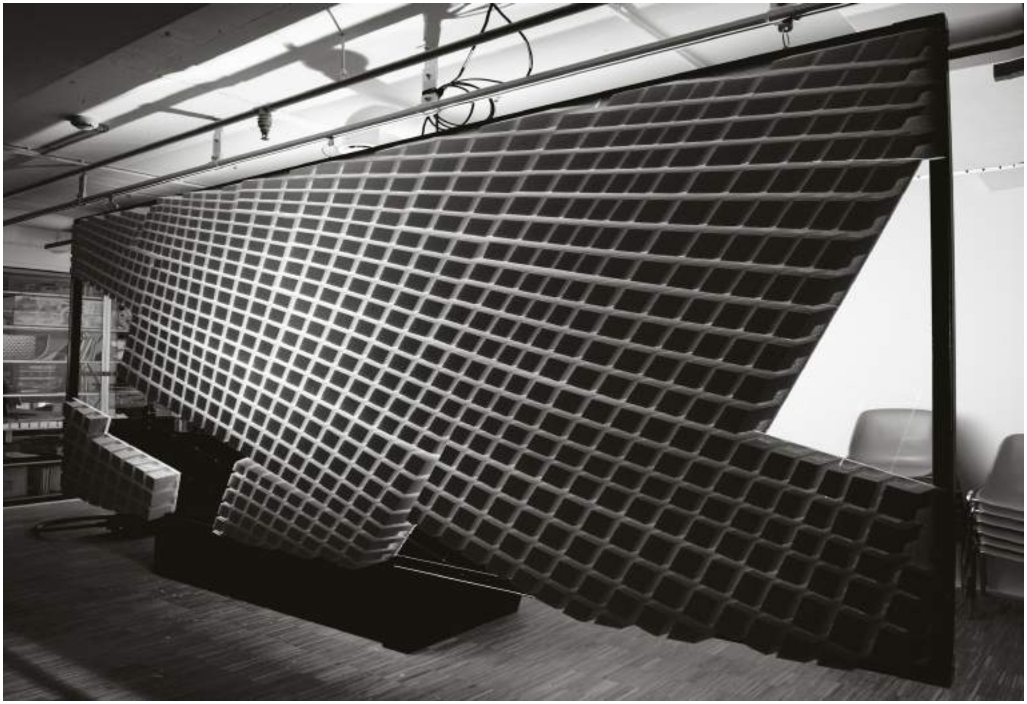
[1] http://www.food4rhino.com/app/taco-abb
[2] http://www.robotsinarchitecture.org/1250/robots-in-architecture-down-under

Figure 7
Overall view of the wall-panelling installation with the gradient translucent effect



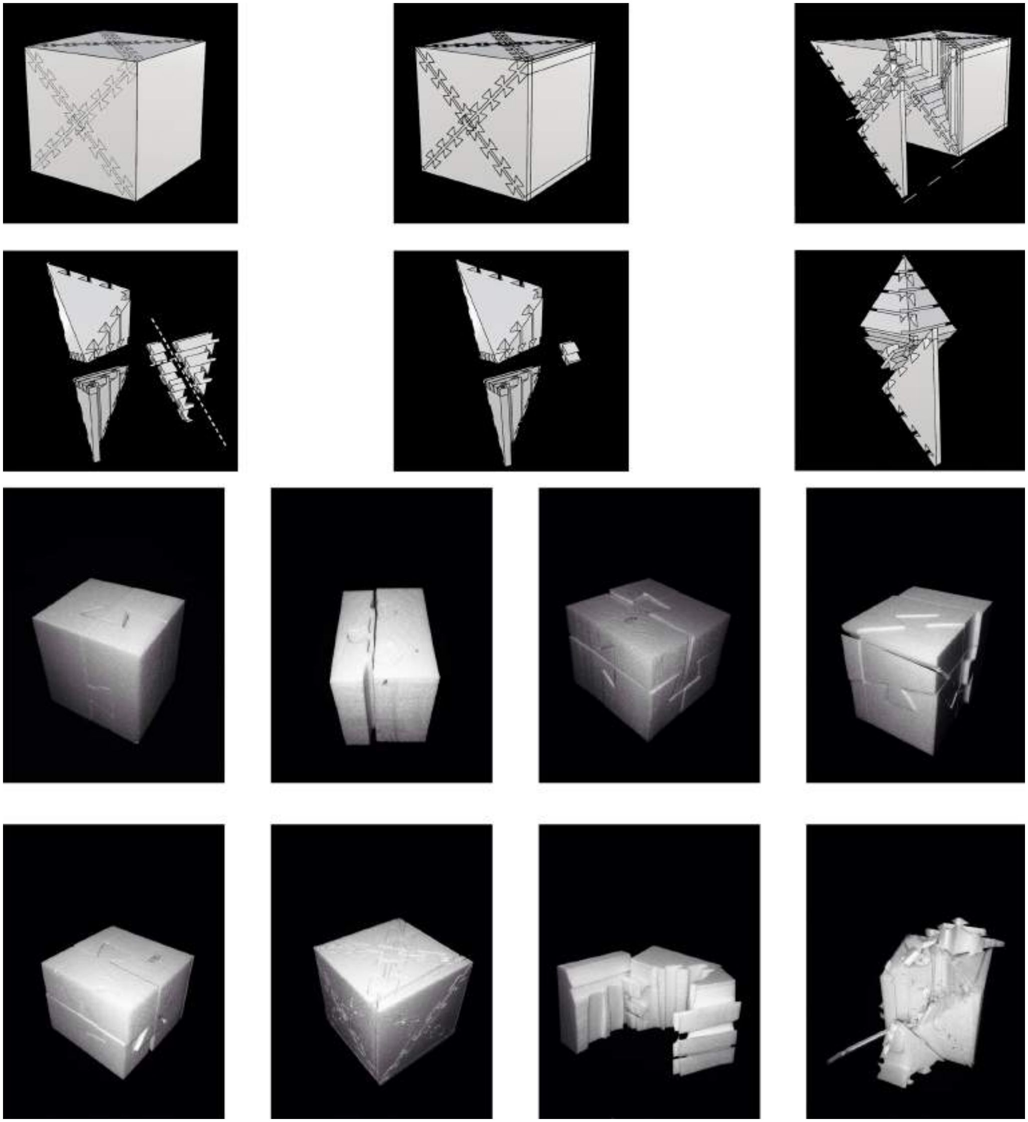


Figure 8
Hot-wire cutting documentation (digital and physical) of process aiming to produce ornamental complexity via single cube cuts and minimum material loss