SPATIAL WIRE CUTTING

Cooperative robotic cutting of non-ruled surface geometries for bespoke building components

Abstract. The research project Spatial Wire Cutting (SWC) investigates a multi-robotic cutting technique that allows for an efficient production of geometrically complex architectural components. Being pursued by the group of Gramazio Kohler Research at ETH Zurich, this approach involves a spatially coordinated movement of two six-axis robotic arms that control the curvature of a hot-wire, which adopts itself against the resistance of the processed material (e.g. polystyrene). In contrast to standard CNC hot-wire cutting processes, in which the cutting medium remains linear, it facilitates the automated fabrication of non-ruled, doubly curved surfaces. This pursuit includes the development of a custom digital design and robotic control framework that combines computational simulation and manufacturing feedback information. Ultimately, SWC enables a considerably expanded design and fabrication space for complex architectural geometries and their construction through automated robotic technology. This paper addresses the applied workflow and technology 1) such as computational design and simulation, robotic control and adaptive fabrication, 2) results of application within a two-week design and building workshop, and 3) will conclude with further steps of future research.

Keywords. Computational design and digital fabrication; feedback-based automated manufacturing; multi-robot control; digital simulation; hot-wire cutting.

1. Introduction

Since the beginning of the 1990s advanced computing technologies have led to a substantial architectural design revolution facilitating the graphical representation of complex geometries and shapes (Pottmann, et al., 2007). In order to convert these digital data sets into physical reality, digital fabrication technology has become crucial and marked the advent of a “Second Digital Age” (Gramazio, et al., 2014). In turn, multiple constraints that come along with computer-controlled manufacturing have also substantially fertilised the field of architectural design and geometry exploration, posing challenging construction-related problems and, ultimately, opening up new architectural research directions for the physical production of complex geometries (Eigensatz, et al., 2010). However, a number of commonly used fabrication techniques, such as, for example CNC-milling or 3D printing, are still inefficient and time-consuming (Schipper, et al., 2014) when it comes to the manufacturing of bespoke double-curved surfaces. Here, the simplification and post-rationalization of a specific design proposition is often the consequence. In this context particularly digitally-controlled wire-cutting techniques have become very common in the larger fields of architecture,
design and construction. However, due to the used linear cutting medium, the range of applicable geometries is narrowed to ruled surfaces (Flöry and Pottmann, 2010).

The research presented in this paper explores a Spatial Wire Cutting (SWC) technique, which is performed by two six-axis lightweight robotic arms that are connected through a single hot-wire, which is attached to their end-effectors (see Figure 1). Their coordinated spatial movement allows for cutting configurations in which the hot-wire takes the form of a curve being shaped by the friction of the wire against the processed material (e.g. expanded polystyrene). By escaping in this way from the conventional linearity of the cutting medium, the automated fabrication of non-ruled surfaces, in particular sweep surfaces, which can be geometrically defined by the motion of a changing profile curve along two trajectory curves, becomes possible. However, in order to precisely control the curvature of the wire throughout the multi-robotic cutting process, all relevant material properties and forces that occur during the physical manufacturing process have to be monitored and, if applicable, to be reacted upon, for instance the overall temperature of the wire, the forces acting on the wire, etc. In SWC, these are all crucial factors that constantly change throughout the cutting process and directly influence the absolute geometry of the evolving object.

![Figure 1. Illustration of the experimental set-up, featuring two Universal Robots UR5 robotic arms moving on different path curves with a curved wire which is shaped by material resistance.](image)

Authoring this complex manufacturing process requires an enhanced robotic control approach that enables feedback-based fabrication, and which adapts dynamically to the physical material manipulation by constantly being fed by sensor data and seamlessly adjusting the velocity of the cooperating robotic arms. Furthermore, these fabrication process-inherent geometrical formulations and constraints have to be integrated in the overall design approach. This clearly fosters a fabrication-informed computational design method, where geometry is directly interlinked with material and manufacturing characteristics. This aligns with the idea of perceiving design and fabrication as a system of recursion, as a dynamic computational composition (Fuller and Matos, 2011), which will affect the way complex architectural artefacts can be designed, fabricated and constructed.
2. State of the art

Digital-controlled wire cutting has become a topic in many research groups (Pigram and McGee, 2011; Rippmann and Block, 2011; McGee, et al., 2012; Bonwetsch, et al., 2012). It offers a low-cost and flexible production of non-standard volumetric elements for manifold applications (such as bespoke formwork components, prototype construction, etc.) and is fast becoming a mature technology that is ready for larger industrial applications. Here, three-dimensional objects are fabricated via repeated movements of a cutting medium, for instance hot-wire, steel cutting wire, mechanic cutting, stiff or flexible blades (Broek, et al., 2002), through a solid material, (predominantly non-metallic, synthetic materials like EPS, EPP, EPE, PU or XPS with a density lower than 60 kg/m$^3$). As implemented by a number of architectural research groups, a conventional hot-wire cutting set-up consists of one standard industrial robotic arm with a customised end-effector, where the wire (Nichrome, Kanthal or stainless steel, heated via electrical resistance up to 200$^\circ$C) is tightly fixed at two points. The hot-wire is being moved through the material with a predefined velocity that relates to the temperature and vaporises the material just in advance of contact to prevent occurring resistance forces contrary to the moving direction. The kerf width is directly proportional to the speed, so consistency of motion is extremely important to be kept throughout the cutting procedure to preserve a proper surface quality.

In contrast to these approaches SWC is based on two-robotic arms and operates in transition states between thermal cutting and thermo-mechanical cutting a) to utilize the material resistance contrary to the moving direction and b) to exploit the (individual) robotic velocities at both wire ends to directly manipulate the cutting medium. Most importantly, the resulting curvature of the cutting medium enables the fast and efficient fabrication of non-ruled doubled curved surfaces through single cuts, and therefore significantly expands the set of possible hot-wire cutting geometries.

3. Design and fabrication methodology

The main inputs for the fabrication procedure that are principally guiding the geometry of the evolving surface (along with velocities and the temperature of the wire) are the path curves for the robotic arms, respectively their synchronized positions on that curves (see Figure 2). However, there is a non-transparent relationship between the design of these path curves and the resulting physical cut surface. Therefore, a design and simulation framework has been deployed (and experimentally tested during the Summerschool workshop, see Section 4.), that emulates the wires deformation within the material according to the input curves and the position of the foam block (see Figure 3).

3.1 COMPUTATIONAL WIRE SIMULATION

This simulation framework is written in the programming language python and integrated into the computational design toolkit in Rhinoceros 3D/Grasshopper. Currently, the wire’s shape is simulated through calculating a funicular curve using the non-linear force density method (Malerba, et al.,
The wire is discretized into segments by a number of nodes, whereas the wire’s end points are the fixed nodes on the path curves. While iteratively stepping along the path curves and taking another pair of fixed nodes, the (differing) forces, consisting of vectors with a defined magnitude, are recalculated on basis of the previously calculated shape. The correct calculation of these forces is essential to define the overall shape of the wire.

![Figure 2. Path curves and synchronized positions on that curves](image)

![Figure 3. Simulated hot-wire curves and lofted surface thereof](image)

Concerning material behaviour and relationships between the parameters guiding the process, this research builds upon results that have been achieved in the field of mechanical engineering with hot wire cutting. A property that is commonly used in this field is the area specific heat input $Q_{\text{eff}}$ [J/m²] (Ahn, et al., 2003). It is a means to consider the influence of both the heat input and the cutting velocity and is defined by

$$Q_{\text{eff}} = \frac{Q}{tv_c}$$

(1)

Where $Q$ is the Joule heating effect, appearing when an electric current is passed through a resistive metal specified by $Q = l^2 R$, ($i[A] =$ electrical current, $R[\Omega] =$ resistance), $l[m]$ the length of the wire in the cut and $v_c$ [m/s] the tool velocity.

![Figure 4: Force measurement along the cut, experiencing three different stages: 1. vaporization, 2. transition, 3. steady state.](image)

![Figure 5: Results of material tests, that are fitted with the formula in (2) and selection of operating force and $Q_{\text{eff}}$ range](image)

In order to relate the occurring force to a given $Q_{\text{eff}}$, a number of material tests have been empirically performed by robotically cutting with constant velocity and constant electrical power, but differing from one cut to the other, while the occurring forces throughout the cutting process where logged. Each individual combination of electrical power and cutting velocity was found to produce a characteristic cutting force profile, with low cutting forces at the
beginning, followed by a transition period, followed by a steady state force (Figure 4) (Brooks, 2009).

To model the force $F$ in the steady state with a given $Q_{eff}$ and additionally taking the engaged wire length $l_e$[mm] into account (= actual length of wire that is within the foam) the following exponential model developed by Bain (2011) was used to correlate and match the test measurements (where the coefficients were found by model fitting, see Figure 5):

$$F = 3.4115l_e e^{-0.0015Q_{eff}} - 0.4944$$  \hspace{1cm} (2)

For the SWC procedure, this may not be fully applicable, because the wire is not always in steady state conditions, but constantly changing between transition states and experiencing forces from different directions and magnitudes. Still, this model serves as a first approximation to define the operating domains of the fabrication parameters.

![Figure 6. Graph of possible voltage/speed combinations in defined $Q_{eff}$ domain](image1)

![Figure 7. Above: $Q_{eff}$ curve and reciprocal speed curve. Below: resulting outer speed](image2)

On the basis of qualitative observation of over 100 different robotic cutting tests an optimal operating force range was defined (0.7-2.0 N, see Figure 5). A certain tension force in the wire has to be kept throughout the cutting process to achieve a corresponding surface quality and, ultimately, to efficiently control the SWC procedure.

Based on the simulated curves (see Figure 3), the engaged wire lengths $l_e$ at each step are evaluated and according to (2) the resulting $Q_{eff}$ is calculated. Together with the electrical resistance of a hot wire with length $l$, possible voltage/speed combinations that match the specified $Q_{eff}$ domain (Figure 6) can be defined. With a certain voltage selected, the speed of the wire within the foam (inner speed), and subsequently the speeds for the robotic arms (outer speeds) are computed and are used as estimated speeds for the fabrication procedure (see Figure 7).

### 3.2 ROBOTIC CONTROL AND ADAPTIVE FABRICATION

A custom control software has been developed to precisely execute the fabrication procedure driven by the settings defined by the computational simulation framework (such as path curves, estimated speeds and voltage). Within this robotic cutting process, the forces and its direction at the mounting points of the wire are continuously registered (using a custom end-effector, see Figure 10), as well as the individual speed variations and positions of the robotic arms, which is all fed back into the robotic controller. Taking the estimated speed at the current position, the on-line force measurements
(process variable) and the desired force (set point) into consideration, new velocities are constantly calculated and sent to the robotic arms (see Figure 8).

![Figure 8. Combined feed-forward/feedback control](image)

Figure 9. Logged data from the process: comparison between estimated and actual speed and force measurements (below)

Figure 10. Cardan joint end-effector with axes (A, B) rotating towards the direction of the force (D) measured by a force sensor (C)

Constant data acquisition (see Figure 9) and analysis allow for comparisons between same or similar cuts, stepwise exploring changes and effects on slightly changing parameters and further, the calibration of the feedback control.

4. Physical experimentation and validation

To validate the workflow, transferability and application of the proposed SWC design and fabrication methodology, a two-week Swisspearl® Summerschool 2015 (http://www.swisspearl.ch: Sept 2015) was pursued, focusing on the development of novel façade typologies as experimental test cases while expanding SWC towards the application at an architectural scale.

Within the design and conceptual phase of the workshop, students explored the technique first through a series of manual tests, using a handheld hot-wire cutting device and graphite enhanced expanded polystyrene blocks of 300 x 400 x 600 mm to develop an intuitive understanding of the material and its (coordinated) manipulation. Subsequently, based on the exploration of the typology of individual elements, these manually-derived concepts were transferred into the computational simulation framework (as described in Section 3.1) to elaborate an overall design concept and parametric model for the aggregation of full scale, robotically-cut (see Figure 11) prototypes, featuring panel sizes of 1200 x 600 mm. These were then used as moulds for the lamination with the fibre-cement composite Swisspearl® (also known conventionally as Etermit), a well-established manufacturing procedure (Affolter, et al., 2003), that, however, requires substantial manual labour and
craftsmanship (see Figure 12). The challenge of this unique combination between fully automated SWC and manual lamination was to operate within two different material systems and constrained design spaces.

![Employed robotic setup in the Summerschool, consisting of two Universal Robots UR5 robotic arms, cutting graphite enhanced polystyrene blocks with a size of 1200 x 600 x 800mm.](image)

*Figure 11.* Employed robotic setup in the Summerschool, consisting of two Universal Robots UR5 robotic arms, cutting graphite enhanced polystyrene blocks with a size of 1200 x 600 x 800mm.

![Workflow: a) design, b) robotic fabrication, c) manual lamination.](image)

*Figure 12.* Workflow: a) design, b) robotic fabrication, c) manual lamination.

Four different design concepts of four student groups have been developed and demonstrated through full scale prototypes (see Figure 13, Figure 14):

1. The first group developed the concept of controlling the intersections of two surfaces to produce crest lines as design patterns on the façade. This has been realised by a parametric differentiation of the edge curves (varying heights and positions of the control points), from which the surfaces were generated with the simulation framework.

2. The second group explored edge curves with alternating combination of sharp peaks and valleys. Combined with the controlled direction of the hot-wire’s movement, the uniqueness of the process was demonstrated expressively in the fabricated surfaces (see Figure 15).

3. The concept of third group was based on the idea to hide the vertical connections between the panels by using ‘waves’. Through empirical testing the maximum range of surface stretch and compression of the cement composite was defined and integrated as a design constraint for the parametric control of the edge curves, thus pushing the boundaries of the material process (see Figure 16).

4. The fourth group’s concept was to assemble six smaller fabricated pieces into one single mould for the lamination of larger panels. This system combined with the controlled changing of edge curves to generate ruled surfaces, explored panneling as strategy to widen the spectrum of possible surfaces.
Overall, the pursued physical explorations within the framework of the Summerschool led to a variety of different results, promising interesting avenues for SWC to be used for 1:1 constructive processes (e.g. façade panels or complex concrete formwork elements). The speediness and efficiency of the SWC process and the lamination allowed for a large number of iterative tests and design explorations. As such, a comprehensive investigation into the architectural potentials of the discussed technique was possible and has clearly proven the viability and application range of SWC.

In fact, these studies have successfully shown that a) the developed computational simulation tool (see Section 3.1) can be employed for digital design explorations that are coherent with their fabrication and b) in combination with advanced robotic control (see Section 3.2) can foster the efficient fabrication of unique and differentiated double-curved surfaces through a synthesis of material system and digital manipulation.
5. Conclusion

One of the major challenges regarding the fabrication prior to the start of the workshop was the upscaling from model scale to full architectural scale. Whereas the procedure in terms of scalability of material properties proved to match to the findings in Section 3.1, the limits of the robotic workspaces were reached and therefore required custom path planning.

The applied workflow of computational design and simulation, joint with the adaptive fabrication procedure proved to be successful in terms of design strategy and production efficiency. Fabrication related constraints could be identified in early design stages, included into the considerations and the computational model, which was directly linked to the fabrication, requiring no further post-processing.

In this current state of research a clear definition about evolving fabrication tolerances and simulated geometry can yet not be given in full detail. Further tests and explorations, such as detailed analysis of scanned physical objects for the purpose of optimising and calibrating the digital model of the simulation and fine tuning of the adaptive fabrication software, will be pursued in further development. Additionally, one of the main interests of this research is to frame the process inherent geometric formulations and to expand the catalogue of viable surfaces.

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References


