Freeform Volumetric Fabrication Using Actuated Robotic Hot Wire Cutter

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Abstract. This paper discusses the design, fabrication and operational workflow of a novel hot-wire cutter used as an end effector for a robotic arm. Typically, hot wire cutters used a linear cutting element which results in ruled surfaces geometry. While several researchers have examined the use of hot wire cutter with cooperative robotic arms to create non-ruled surface geometry, this research explores the use of an actuated hot wire cutter manoeuvre by a single robotic arm to produce similar form. The paper outlines the machine making process and its workflow resulting in a 1:1 scale prototype. The paper concludes by examining how the novel tool can be applied to an urban stage design. The research set up a fabrication procedure that has the potential to be deployed as an on-site fabrication methodology.

Keywords: Robotic · Digital fabrication · Hot-wire cutting · Machine making

1 Introduction

The paper outlined the design and fabrication of a novel hot wire cutter used as an end effector for a robotic arm to create non-ruled surface geometry. Most hot wire cutters used a linear cutting element to achieve single ruled surfaces geometry (Bidgoli and Llach 2015). Rust et al. (2016) have explored using cooperative robotic arms to develop non-ruled surface geometry with linear hot wire cutting element. This research furthers the enquiry within the field by exploring non-linear cutting element for a hot wire cutter and thereby achieving non-ruled surface geometry with a single robotic arm. The novel tool utilises a curved hot wire cutting element with up to three controlled nodal points to shape Expanded Polystyrene (EPS). The actuated Interpolating Polynomial-Curve Hot Wire Cutter (IP-CHWC) used only a single robotic arm to achieve complex network surface geometry. Unlike conventional hot wire cutter, the IP-CHWC is numerically controlled and can perform variable cut sections with a single robotic movement to produce complex surface. In this research, the end-effector is used to cut EPS which is coated with resin-infused fibreglass to create a durable surface for architecture or sculpture application. The advantage of the novel end-effector provides a more significant degree of freedom for manufacturing complex form without the need for two collaborative robots.

The research is conducted through physical prototyping of the end-effector resulting in several full-scale furniture prototypes. We observed the potential of the fabrication techniques and tested the new tool through a design project: an urban performance stage design titled Motion Imprint. Critical to the design process is the integration of knowledge from the tooling to the design workflow. Later sections discuss the data extraction procedure and fabrication workflow as well as the difficulties encountered during the design of the end effector.

The design team utilised the geometric nature of an interpolating polynomial curve as a starting position. The IP-CHWC translates the parametric curve into actuated behaviour to articulate the cutting profiles. Here, the geometric description is aligned with material behaviour to develop a productive mechanical system. The paper concludes by examining future research and applications associated with the novel tool.

2 Background

Numerous researchers have explored hot wire cutting technique using a robotic arm (Pigram and McGee 2011; Martins et al. 2019; Kaftan and Stavric 2013). The technique has proven to be an effective fabrication methodology that offers a low cost and flexible production of non-standard volumetric components that could be used for prototyping mould for casting panels (Martins et al. 2019). Typically, nichrome wire is used as a cutting element which is stretched taut over a supporting frame. A spring mechanism is used to ensure there is no slack in the wire when it is heated. An alternative technique to cut EPS is to use a thicker gauge nichrome wire and bend it into shape as a sculpting knife. This technique is further developed by using two cooperative robotic arms to create a non-ruled surface (Søndergaard et al. 2016). In this research project, the two cutting techniques are combined into a single end-effector for robotic cutting.

2.1 Research Objectives

The IP-CHWC utilised the basic principle of interpolating polynomial curves to create a UV network surface that is not based on ruled surface geometry (Pottman 2007, Burry 2011). The IP-CHWC determines the horizontal curves (U) while a set of design parameters determines the vertical curves (V), see Fig. 1. The technique relies on the hot wire to be shaped into a desired interpolating curve. As the wire passes through the EPS, IP-CHWC continues to transform its curvature. The resulting cut is a smooth and non-developable surface.

3 Interpolating Polynomial Curve

The hot wire behaves like an interpolating polynomial curve. Mathematically, such curve used Lagrange polynomials as a basic polynomial; Lagrange polynomials force the curve to pass through the nodal points, unlike a Bezier curve. Lyche and Morken (2008) highlight the difference between the property of the curve and its parametric representation. They define a curve as the collection of all the different parameter representations of

Fig. 1. Matrix showing variable surface based on five-point interpolating polynomial curves to form network surfaces

the curve. Here, it is essential to distinguish the two as in this project; both are present simultaneously to provide the geometric description of the resulting form. The parametric curve is the underlying principle of the machine as the vector along the line of the hot wire connected at the nodal points. The resulting curve exists in the digital simulation of the form as a series of UV network surface.

4 Design of IP-C Hot Wire Cutter (IP-CHWC)

Six hot wire cutter prototypes are developed during the research, see Fig. 2. Of the six prototypes, V3 and V4 utilised tension only to shape the nichrome wire while the remaining used a combination of tension and rigid armatures to control the curvature. The connection points between the nichrome wires act as the nodal points which control the curvature of the cutting shape. It became apparent that a series of hot wire knife acting in compression is needed to allow the cutter to slice through the dense EPS. The hot wire knife enables both pushing and pulling of the nodal point.

Figure 3 illustrates the current design of the IP-CHWC. The end effector is connected to the robotic arm via a connector [A]. The aluminium frame [B] holds three stepper motors [C] which each drives a corresponding hot wire knife [D]. The outer frame holds the 0.4 mm thick nichrome wire [E] retracted by two further stepper motor [F]. The nichrome wire passes through a pin-head size hole at the end of the hot wire knife [G].

The difficulty in this research lies in the design of the bespoke hot wire knife, see Fig. 3 (Right). The knife-edge is lined with a 1 m long (1.5 mm thick) nichrome wire, adhered to the edge with a high melting point silicone mastic. With a 12 V power supply, the cutting knife reaches a temperature of 150 °C. The current design of the knife is

Fig. 2. Prototypes developed from the research, V6 is the most developed working prototype

Fig. 3. Left, design of V6 prototype. Right, detail of hot wire cutting knife

temperamental as when the wire is heated, and it expands faster than the silicone mastic. If the nichrome wire [E] accidentally meets the knife [D], it causes a short circuit which would foul the machine.

5 Parametric System and Mechanisms

The fabrication procedure translates the UV network surface into G-code for the stepper motors and the robotic movement, see Fig. 4. Using KUKA PRC, the movement of the robotic arm with variable velocities can be precisely scripted and simulated before cutting the EPS. Firefly plugin for Grasshopper 3D is used to transform the nodal point of the UV curves which forms the network surface geometry into G-codes. To operate the five stepper motors simultaneously, we use a Girbl-Panel controls Arduino Mega R3 with Ramps 1.4.

A given form is typically sectioned to produce a set of contour curves on the X-Y plane, for example from wire 01(W01) to wire 104(W104), see Fig. 5. The profile of the U curve contains the same number of nodal points as the IP-C cutter, in this case, three only. The number of U lines decided the number of commands for steppers. A and B refer to the two-steppers which adjust the length of the primary nichrome wire, while X, Y and Z represent each of the three transforming nodal points driven by three cutting knives. The operation time frame is set as 12 s per command. The displacements

6 Fabrication Workflow

Figure 6 illustrates the overall workflow of the technique. Through evaluation of the geometry input [A-B], the workflow synchronised the actuation of the IP-CHWC [D-F] with the robotic workflow [E-G] to produce a fabricated outcome [H-I]. The following sections will unfold these procedures in detail.

Fig. 6. The overall workflow of IP-CHWC

6.1 Geometry Input and Evaluation

The IP-CHWC and the robotic arm both provide constraints to the size of the EPS stock, see Fig. 7[A]. The height of the stock is limited by the maximal reach of Kuka KR120 R2500 [A.1]. The frame width of IP-CHWC determines its width (<300 mm), while the stock length (<330 mm) is constraint by the length of the cutting knives [A.2]. Here, we test the IP-CHWC to fabricate an outdoor seat design on an EPS stock: 1200 mm deep x 400 mm wide x 1200 mm tall [A.3]. The digital freeform surface is divided to suit the stock size, Fig. 7[B]. Through evaluating the curvature of the surface, the robotic cutting procedure is divided into 3 continuous parts: top, seat and bottom, as T1, T2 and T3 respectively, see Fig. 7[C].

6.2 Actuated Movement of the IP-CHWC

The intersection of the UV curves forms the nodal point of the cutting profile, Fig. 8 [D]. Driven by the movement of the cutting knives' displacement, each U curve is translated into a line of command for the IP-CHWC. The total cutting time of T1, T2 and T3 are calculated on the number of command lines over the operation period (set as 12 s for this research), see [F.1]. The cutting time of T1, T2 and T3 are used as inputs to calculate the robotic velocity.

6.3 Synchronisation of IP-C with Robotic Arm

The boundary curve of the surface (H1, D and H2) is used to generate the robotic movement in Kuka PRC, see Fig. 9[E.1 and E.2]. The travelling speed is critical as

Fig. 7. Geometry input and evaluation

Fig. 8. Data generation for the IP-CHWC

it needs to synchronise with steppers motion described in Sect. 5.2. Thus, the robotic velocity $V3$, $V4$ and $V5$ for cutting the continuous parts are set by dividing the lengths of routine ($H1$, D and $H2$) with same travelling time corresponding to $T1$, $T2$ and $T3$ [E.3]. The synchronised movement of IP-CHWC and the robotic arm is further simulated in SprutCAM before proceeding to actual cutting [G].

Fig. 9. Data generation for the robotic movement

7 Future Enquiries and Potential

Current research has identified several limitations of the system. Future research will explore an increase cut edge to the boundary to avoid a framing of the cut profile; this enables a more continuous curvature between cuts. The joint between the knife cutter and the frame needs to stiffen significantly to avoid the cutting knife from twisting and bending under the force of the robotic movement. Another significant improvement will be to re-design the circuit to minimised uneven heat distribution and potential for short-circuiting of the system.

7.1 Design Implication: Radical on-Site Fabrication

Fig. 10. Left, construction sequence for on-site fabrication. Right, 1:1 scale prototype with the resin-infused coating to cut EPS

The design team tested the tools in a speculative design, titled Motion Imprint. The proposal is an urban performance stage located in the city of Melbourne. Using Kuka KR120 working envelope as a design constraint, we speculate on how the design can

be fabricated based on the limitations and opportunities of the tool through an on-site fabrication scenario, see Fig. 10. The cut EPS is coated with a 2-part polyurea which is then covered with fibreglass and infused with resin. A 1:1 scale prototype following the geometric description is developed as a proof-of-concept, Fig. 10 (Right).

8 Conclusion

The research presents a novel hot wire cutter that has the potential to produce non-ruled free form curved surface using a single robotic arm. The design team aligns both the material system necessary to construct the device with the fabrication workflow to extract data from the parametric curve. In this research, the parametric curve is used to drive the time-based transformation of cutting profile to create an intricate doubly curved surface. Data is processed through the electronic system, scripted and transferred into mechanical movement. The synchronised movement of the robot arm and IP-C hot wire cutter enable the production of a complex form with better time efficiency than standard CNC milling procedure currently used in the construction industry. The research speculates on how IP-CHWC could be adopted as on-site construction methodology, allowing design, fabrication and building construction to be fully integrated into a unified system.

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References

- Bidgoli, A., Cardoso-Llach, D.: Towards a motion grammar for robotic stereotomy (2015)
- Burry, M.: Scripting Cultures: Architectural Design and Programming. Wiley, New York (2011)
- Kaftan, M., Stavric, M.: Robotic fabrication of modular formwork. In: International Conference of the Association for Computer-Aided Architectural Design Research in Asia. Research Publishing Services (2013)
- Lyche, T., Morken, K.: Spline methods draft. Department of Informatics, Center of Mathematics for Applications, University of Oslo, Oslo (2008)
- Martins, P.F., Nunes, S., Fonseca de Campos, P., Sousa, J.P.: Rethinking the Philips Pavilion through robotic hot wire cutting. -An experimental prototype (2019)
- Pigram, D., McGee, W.: Formation Embedded Design: a methodology for the integration of fabrication constraints into architectural design (2011)
- Pottmann, H.: Architectural geometry. Bentley Institute Press (2007)
- Rust, R., Jenny, D., Gramazio, F., Kohler, M.: Spatial Wire Cutting: Cooperative robotic cutting of non-ruled surface geometries for bespoke building components (2016)
- Søndergaard, A., Feringa, J., Nørbjerg, T., Steenstrup, K., Brander, D., Graversen, J., Markvorsen, S., Bærentzen, A., Petkov, K., Hattel, J., Clausen, K., Jensen, K., Knudsen, L., Kortbek, J.: Robotic hot-blade cutting. In: Reinhardt, D., Saunders, R., Burry, J. (eds.) Robotic Fabrication in Architecture, Art and Design 2016, pp. 150–164. Springer, Cham (2016)

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