Digital Robotic Double-Curved Hot-Wire Cutting

Ziheng Zhou[1], Da Wan[2], Xinyu Shi[3]

[1] Undergraduate Student, College of Architecture and Urban Planning, Qingdao University of Technology
[2] Lecturer, School of Architecture, Tianjin Chengjian University
[3] Lecturer, College of Architecture and Urban Planning, Qingdao University of Technology

Abstract

With the continuously development of nonlinear design in construction industry, nonlinear buildings are more inclined to be designed and constructed. However, due to the limitations of the current construction approaches, the level of construction that can be achieved is extremely limited. Consequently, complex and costly processes have inspired the rise of the building customization industry.

Generally considered, in the existing spatial wire cutting (SWC) technology, multiple robots could be used for cooperative operation, while having less flexibility, convenience than single robot operation. Therefore, different kinds of errors, and even deformation in three-dimensional space can be occurred when fitting. Thus, new methods need to be carried out.

In the preliminary experiments, we ran many tests with different voltages and wire sizes to acquire more suitable cutting conditions. Then to reduce large errors caused by cooperative operation, the following part studies on the cutting approach of complex double-curved surface operated by a single robot and reduces certain errors at the meanwhile. Every single sweeping curve will be fitted on the double-curved surface they should be lain in, with more preciseness than the cooperation of two robot arms, and experimented with cutting of polystyrene foam examples.

Keywords: hot-wire cutting; Computational design and digital fabrication; robotic construction

1. Introduction

Since 1990s, computer-aided building design has become an extremely important means, which has opened a whole new direction for the construction industry. In turn, multiple constraints that come along with computer-controlled manufacturing have also substantially fertilized 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 (Ei-gensatz et al, 2010[1]). However, several commonly used fabrication techniques, such as CNC-milling and 3D printing, are still inefficient and time-consuming (Schipper et al, 2014[2]) when it comes to the manufacturing of bespoke double-curved surfaces.

Therefore, faster speed and lower prices have become the pursuit of people, which has also promoted the continuous development of this technology. Due to the popularity of original hot-wire cutting, People are trying to explore cutting more complex forms along this way which led to the development of double-curves hot wire cutting.

Contact Author: Da Wan
Lecturer, Tianjin Chengjian University,
Address：NO.26 Jinjing Road, Tianjin, China, 300380
Tel: +86-186 2299 0292　　E-mail: wanda@tcu.edu.cn

2. The Brief of Digital Robotic Double-Curved Hot-Wire Cutting

The development of “Digital Robotic Hot-Wire Cutting” has been going on around two decades, but it has shown innovations over and over again. It has continuously promoted the architectural design industry and made more and more profiled buildings be built. By analyzing several important nodes that change over time, the hot-wire cutting’s development stage is roughly divided into three stages.

2.1. Stage 1

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[3]). To convert complex digital data into reality, digital fabrication technology becomes gradually important than ever before.

On the contrary, the progress of digitalization has also started to affect the development of the construction industry, which has made architects like Zaha Hadid’s into reality (Fig. 1). In a word, more advanced design methods have enriched the shape of the building and promoted the development of the digital customization industry.

With the development of applying hyperboloids in architecture and the development of their modernity (Fig. 2), which are enamored by designers, have gradually become a development trend. In the face of extremely complex design surfaces, how to these complex surfaces into reality make efficiently and accurately can be a question worth thinking which led to the development of double-curve cutting.

2.2. Stage 2

With the advent of construction robots, many processing methods have appeared. These includes actuation of a flexible membrane as a casting surface (Jepsen et al. 2011[4]; Hesse 2012[5]), dynamic slip-casting for column elements (Lloret et al. 2014[6]), a variant of the additive manufacturing of concrete structures (Khosnevic 1998, Lim et al 2012[7]), fabric formwork applied as an alternative technique for the casting of advanced designs (Veenendaal et. al 2011[8]).

However, there are also many disadvantages of these operations. The degrees of freedom of surfaces and control points cannot be fully achieved, which leads to the uncontrollable result, which cannot achieve the requirements of customization and has no specific use value.

Fig. 1. Bee’ah Headquarters, Zaha Hadid Architects, Sharjah, UAE,2014[9]

2.3. Stage 3

Among plenty of digital customization industries, Odico Construction Robotics (a European construction company applied robots for manufacture formwork) has made many attempts. Around 2013, the design of the Waalbrug bridge expansion project in which Odico Formwork Robotics participated, required thousands of square meters of double-curvature surface templates. Due to the limitation of the double-curvature surface, it cannot be achieved by rationalizing the ruled surface and hot wire cutting. Therefore, the hot wire cutting method was not available and traditional wood formwork method was used in the end. Although the wood formwork method solves the required task, its accuracy cannot be guaranteed. From here, the original SWC limitations were discovered, which also led to formwork customization companies’ further research.

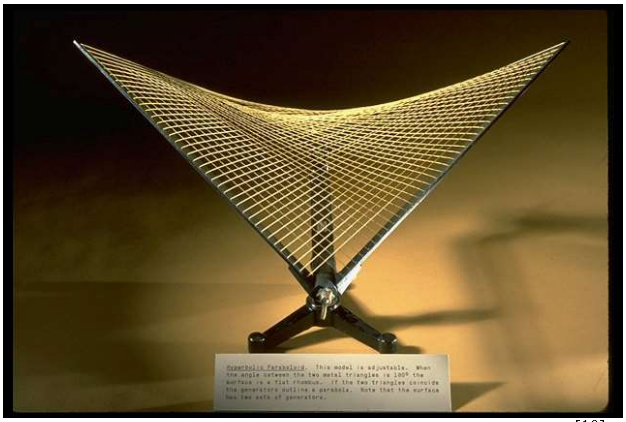

Fig. 2. Geometric Model, Hyperbolic Paraboloid [10]

After more than four years of research, Odico has developed a new technology called Hot-blade-cutting (Fig. 3). Hot-blade-cutting (HBC) can produce unique double curved geometries in large-scale productions. The technology is up to 100 times faster than CNC-milling; it offers a customizable flexibility in an industrial digital setup and creates double curved organic formwork. (GXN et al. 2016[11])

Fig. 3. Odico’s Hot-blade-cutting Technology[12]

3. Preliminary Experiment

3.1 Working Principle

Fig. 4 and Fig. 5 are showing the surface condition of the foam after handheld hot-wire cutting. The unevenness is extremely high, and the resistance can be felt during the handheld process, which cannot achieve the desired effect. This illustrates the influence of factors such as temperature and cutting speed on the smoothness of the foam surface is extremely huge. Although the resistance between the hot wire and the foam is unavoidable, a portion of the resistance can be reduced if the temperature is maintained at a stable temperature. Therefore, in the following content, we will study the effects of temperature, cutting speed on foam.

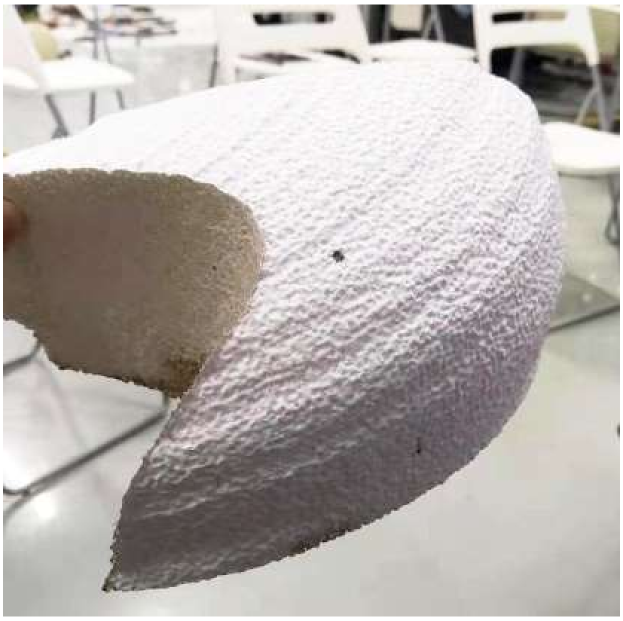

Fig. 4. Handheld Hot-wire Cutting Test 1

Fig. 5. Handheld Hot-wire Cutting Test 2

There are many factors that can affect the quality of cutting process. First, we need to study the process of hot-wire cutting. The cutting stage can be divided into about three phases.

In Phase I, thermal technology dominates, where the reduction of material is caused by the vaporization of the foam due to the high temperature of the wire. Phase III is mainly controlled by a mechanical process. In this process, the metal wire and the foam are in close contact with each other which indicates the reduction of the foam is cut by the metal wire. Phase II is the transition stage between the Phase I and III. In Phase II, material reductions occur due to the combined effect of thermal and mechanical processes. These three phases mainly depend on the selected wire diameter, feed rate and power supply voltage.

3.2 Tool Preparation

Main working material used in the cutting tests is Expanded polystyrene (EPS) foam which is inexpensive and widely available. We used both Nichrome wire and stainless-steel spring wire to test their property which will be mentioned later. The power supplied is 12V-24V DC.

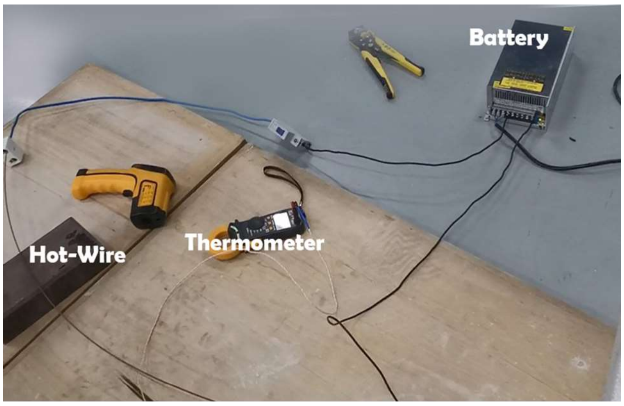

Fig. 6. Tool Preparation

3.3 Experimental Procedure

The cutting steps for all cutting tests are as follows:

1) Fix the EPS block on the cutting position.
2) Power the metal wire by controlling the switch and adjust the voltage to a certain fixed value.
3) The temperature of the wire is continuously monitored by means of a thermocouple connected to the cutting wire. When the temperature is stabilized, the cutting motion is started at a predetermined feed rate.
4) After cutting, change the same feed voltage to the next value. This process is repeated until the metal wire begins to bend due to mechanical contact with the polystyrene foam.
5) After that, change the voltage. In the experiments, different voltages in the range of 12V-24V were selected.
6) Then repeat steps (2) to (5) to change the cutting wire of different specifications. In the experiment, three different wire radius were used: 1.6mm, 2mm, 2.5mm

3.4 Results and Analyze

A. Material of Cutting Wire

First, the types of wire need to be selected. According to the data and early tests, we used the material in Cr20Ni80 nickel-chromium wire and stainless-steel spring wire for this test.

Nichrome wire is the material for ordinary hot wire cutting, and stainless-steel spring wire is chosen because of its good elasticity and thermal conductivity.

It can be seen from Fig. 7 that on the premise of ensuring good bending cutting performance, the effect of using a stainless-steel spring wire of about 3mm is the best. The heating process is fast, and the range is wide. It can still maintain a good bending performance at the temperature around 300 degrees.

Although the stainless-steel spring wire has the best heating performance, but what kind of material and the specific temperature is appropriate for cutting requires further research.

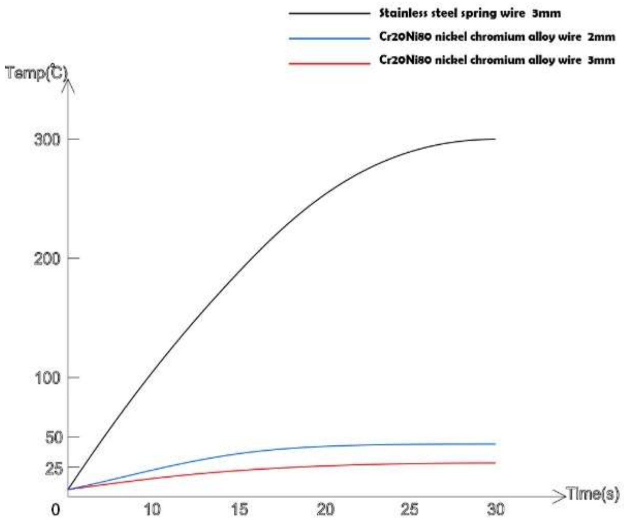

Fig. 7. Different Temperatures for Different Materials

B. Temperature of Stainless-steel Spring Wire

We started measuring the most suitable values of stainless-steel spring wire cutting. The temperature of the hot wire is continuously monitored by means of a thermocouple connected to the hot wire. The initial data in the table 1 shows the temperature of the stainless-steel spring wire in the open-air environment before entering the foam. Table 1 shows three different wire sizes (1.6mm, 2mm, 2.5mm). And the temperature for these three-gauge wires at different supply voltages.

Table 1. Temperature of Different Wire at Different Voltages

Voltage(V)	1.6mm	2mm	2.5mm
12			309
14		368	330
16		436	373
18		503	435
20	192	498	511
22	216	524	
24	253		

When cutting begins, the temperature starts to drop, but once it reaches a steady state, the temperature of the wire almost becomes stable for a constant feed rate. Table 2 shows temperature of 2.5mm wire during cutting at various feed rate.

The steady state temperature for other two size of wires (1.6mm&2mm) during cutting are shown in table 3&4.

C. Surface Roughness

A contact type profilometer is used to measure the surface quality. The stylus of the profilometer was moved 15 mm in 3 different directions at 120 positions, and then averaged to obtain the surface quality of the foam. We draw the tables between surface roughness and feed rate using the same values. The surface roughness of the foam was measured at four different voltages under three stainless-steel spring wire sizes (1.6mm, 2mm, 2.6mm), represented by Ra (Average value of roughness).

Table2. Cutting Temperature of 2.5mm Wire at Different Voltages

Feed Rate (mm/min)	14v	16v	20v
0	320	384	500
200	294	305	416
400	198	256	387
600	182	264	273
800	162	217	254
1000	153	184	215
1200		198	213

Table 3. Cutting Temperature of 2mm Wire at Different Voltages

Feed Rate (mm/min)	18v	20v	22v
0	368	426	492
200	241	253	287
400	137	203	239
600		176	236
800			187

Table 4. Cutting Temperature of 1.6mm Wire at Different Voltages

Feed Rate(mm/min)	22v	23v	24v
0	183	223	248
100	176	179	189
200	147	152	157
300	142	144	148
400			137

Table 5. Surface Roughness (Ra) for 16V (Sandeeep Dasgupta,2016[13])

Feed Rate (mm/min)	1.6mm	2mm	2.5mm
200	27	30	34
400	23	27	31
600	17	22	27
800	20	19	23
1000	22	21	20
1200		25	22

D. Discussion

It can be clearly seen from the surface roughness graph that in the upper part of the table, when the feed rate is very low, the surface is quite rough, but as the feed rate increases, the surface roughness value decreases which indicates the surface quality will increase. This improvement in surface quality continues until a certain value of the feed rate, then the surface quality starts to deteriorate and the surface roughness value increases. The value of the critical feed rate depends on the wire size and the supply voltage. When the wire size increases at a certain voltage, the minimum surface roughness will occur at a higher feed rate, while the minimum surface roughness value will increase for larger diameter wires.

E. Conclusion

From the tables above, it is easy to observe the optimal cutting conditions for minimum surface roughness. The minimum surface roughness depends on the wire size, power supply voltage, and feed rate. The smallest surface roughness could be obtained by bigger size of wire and higher feed rate value (Table 6).

Table 6. Optimum Cutting Conditions

Wire Radius(mm)	Feed Rate(mm/min)	Voltage(V)	Steady state temp(C)	Surface Roughness(Ra)
1.6	600	16	170	17
2	800	20	190	19
2.5	1000	16	190	20

4. Further Propose about End-effector

When considering the requirements of complexity and low cost, compared with operating two or three robot arms, the flexibility and convenience of operating a single robot are highlighted. Therefore, in order to adapt to the operation of a single robot, the research of end-effector is particularly important.

When designing the end-effector, it is necessary to take the wire's shape into consideration when the hot-wire is bent, which is, what kind of bending shape will occur under the action of external force, so that the end-effector can be better designed. From the paper "Snap buckling, writhing and loop formation in twisted rods [14]", we can find several important factors related to the deformation of the line: the length of the wire, the distance between the two robotic arms and the angle of two end-effectors when they are squeezed inward.

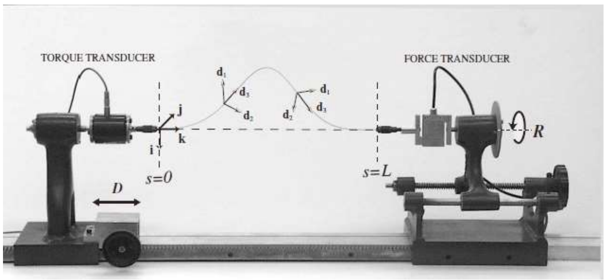

Fig. 8. Prototype of the Squeezing Tool From Graz University

As we can see from the Fig. 8 and Fig. 9, most researchers follow the same idea and explore the relationship those factors during the experimental stage.

In the design of our original frame-type end-effector (Fig. 10), two arms are fixed and cannot be rotated. For the future, we are planning to add stepper motors to make these two fixed arms can be rotated. The arm starts to move and at the same time translates inward or rotates a certain angle at the same time, which are achieved by the operation of stepper motors.

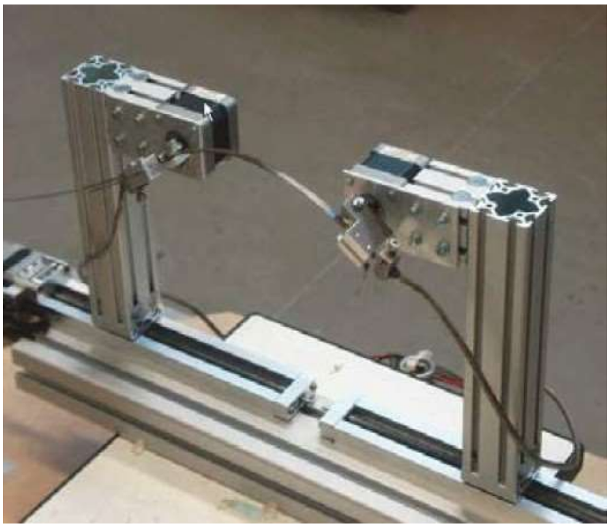

Fig. 9. Prototype of the Cutting Tool Made By Romana Rust[15]

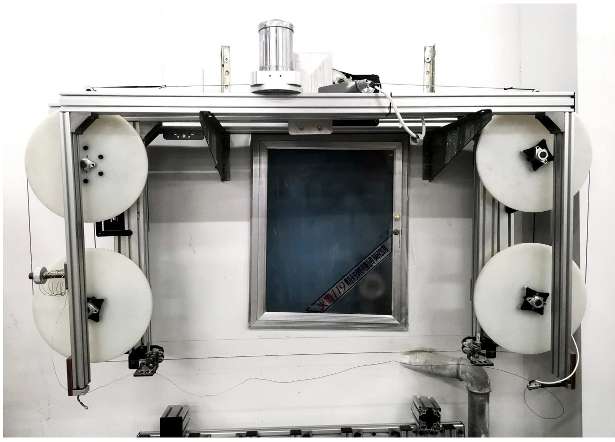

Fig. 10. Cutting Tools from DAMLAB

The number of stepping motors is not limited. It can be installed at the two ends of the main horizontal aluminum bar connected to the quick-change tool to control the rotation and movement of the arms. It can also be installed on the end axis which is to control the angle of the ends of the wire, to control the wire's shape in turn (Fig. 11).

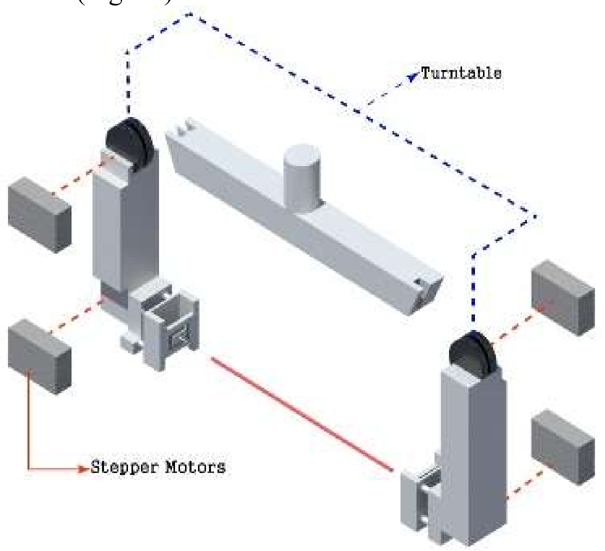

Fig. 11. End-effector with Stepper Motors

While designing the end-effector, reducing deviation is also a very important issue. In terms of reducing deviation, it's better to add multiple stepper motors and hot-wires between the main horizontal aluminum bar and main hot-wire (Fig. 12). One endpoint is fixed near the stepper motor on the aluminum bar and the other is fixed on the hot wire.

During the cutting process, the fixed endpoints will stabilize the hot-wire in the same plane, thereby reducing deviation. However, the disadvantage is that only several complete parts can be reached, and the remaining part is invalidated.

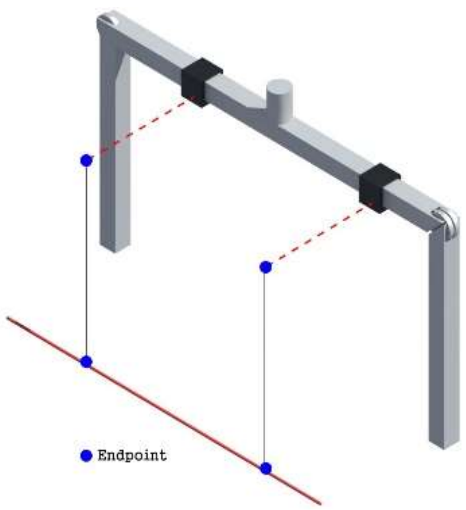

Fig. 12. Fixed Endpoint to Control Wire's Shape

5. Conclusion and Outlook

Under the background of the increasingly mature of digital design and construction technology, the demand for irregular curved surfaces is also rapidly increasing. Double-curved hot-wire cutting provides a new direction for the future development of additive manufacturing which also promote us to dig into this area.

Through multiple tests, we have figured out a series of suitable data for hot-wire cutting such as temperature, voltage, and cutting speed, which will lay the foundation for the next experiments. We will carry out a series of experiments based on the proposed end-effector to prove the feasibility of it and find new solutions for double-curved hot-wire cutting.

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