Supplementary Material for
FrameFab: Robotic Fabrication of Frame Shapes

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This supplementary material elaborates on the hardware setup of our prototype robotic fabrication system, which is used to fabricate the frame objects shown in the paper.

The Robotic Fabrication System   Figure 1 illustrates the hardware setup of our robotic fabrication system.

After obtaining feasible printing sequence, associated with feasible printing orientations from our algorithm, printing hardware control code is written into KRL (KUKA Robotic Language) according to each printing state. Then KUKA Robot Controller (KRC) sends digital and analog signals to each executor in the system. In a word, using information of our printing sequence, KRC weaves controlling signals into the right order and perform the printing task.
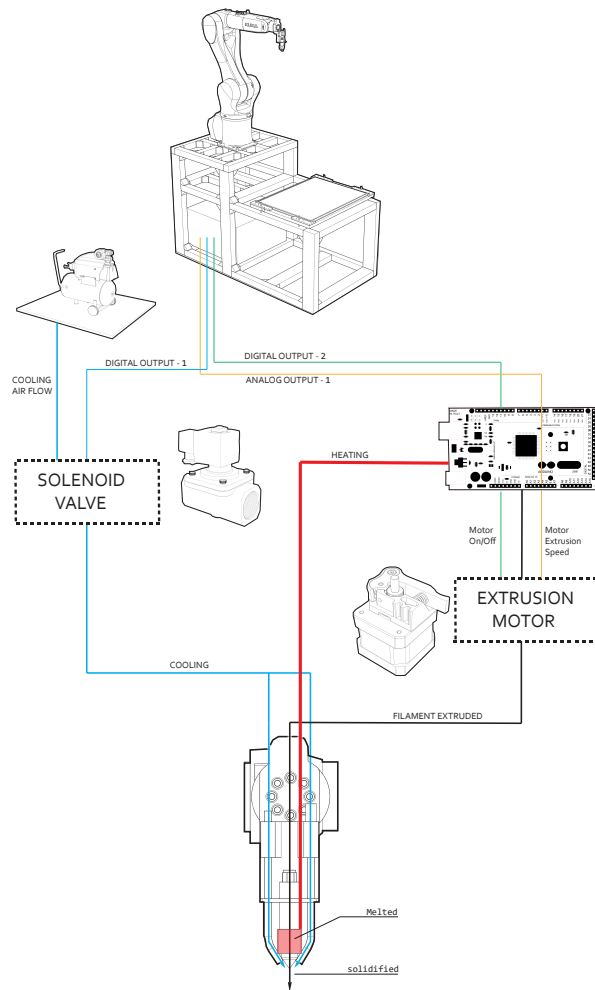
Figure 1: *Hardware setup of our robotic fabrication system.*

Experimental Parameters   To create accurate and sturdy frame shapes, our printing system needs to take into account the edge deformation that appears when filament is not yet solidified.

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We classify the entire printing process into two stages, called "Connecting Stage" and "Creating Stage" (Figure 3), and use different printing strategies and associated printing parameters to get better printing result.

Printing strategies   Strong cooling system is essential for solve the deformation problem caused by unsolidified filament. However, when two printed struts need to be connected, overcooling will result in unconnected nodes and still mess up the following printing process. In this paragraph, we present our printing strategies that address these challenges.

1. The extruder tip reaches the start point of the strut.

2. Start extruding, use pre-connect flow rate (30%) and wait for 2 seconds.

3. Open the cooling air pipe, start extruding at 80% (or 100%) flow rate and the robotic arm starts moving towards the end point.

4. Reach the end point.

5. Slow down extrusion flow rate to 30% and wait 2 seconds.

6. Open air pipe to let the connection node solidify.

7. Extruder leaves the end node, finish the current printing process.

In general, the printing strategy first lets the extruder extrude some printing material under no-cooling environment and thus makes the strut's end point "welded" to the already printed structure. Then, the airflow is turned on to let the extruded filament solidified right after it leaves the heating cavity of the extruder. In this way, a straight printed strut with strongly connnected node is printed (Figure 3).

(a)   (b)   (c)
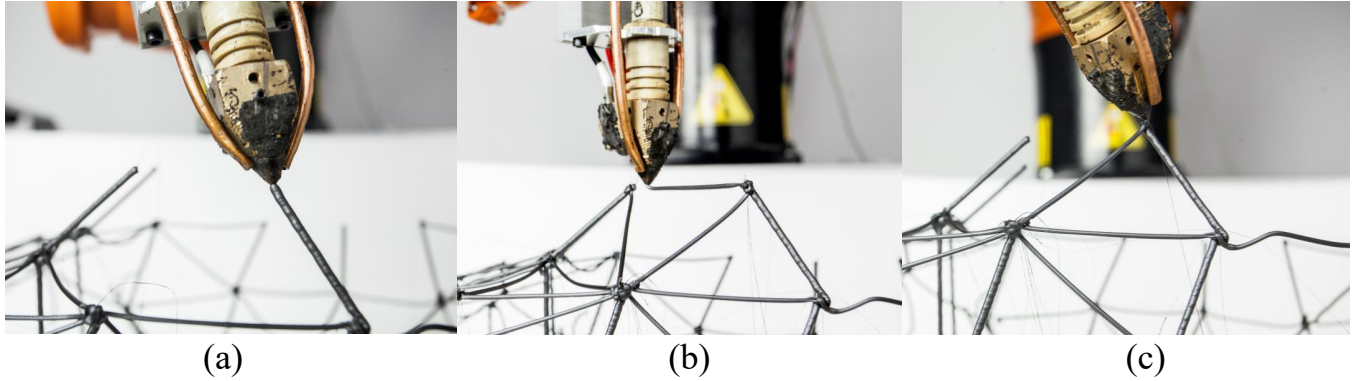
Figure 2: *(a) Creating stage: One end of the printing strut hasn't been printed. Filament is extruded and aggregated to form a strut. (b) Connecting stage: Both ends of the printing strut have been printed. The filament is dragged from one end to another to create a new strut. (c) "Welding" end point at Connecting Stage.*

Printing parameters   In our printing system, three printing parameters are essential to improve the quality of a frame shape's printing:

1. Robots moving speed while printing a strut.

2. Filament extrusion flow rate.

3. Cooling air pressure.

To get better result, different combinations of printing parameters are applied adaptively to specific printing stages. We summarize our parameters in Table 1.

Printing Parameters	Connecting Stage	Creating Stage
Robotic moving speed	0.009 m/s	0.00132 m/s
Extrusion flow rate	80%	100%
Cooling air pressure	0.02 Mpa	0.02 Mpa

Table 1: *Printing parameters*

Extruder Design   A custom-made extruder is installed on the 6th axis's plate. To reduce extruder size, stepper motor is installed on the 4th axis top (Figure 3(a) in paper). This extruder takes the reference of Bowden extruder, which is popularly used in a lot of desktop 3D printers like Ultimaker 3D printer. In this way, the robot effector has more lightness and less interference. The effector length and tip angle also have big amount of influence in the validation phase, which has been modified many times.
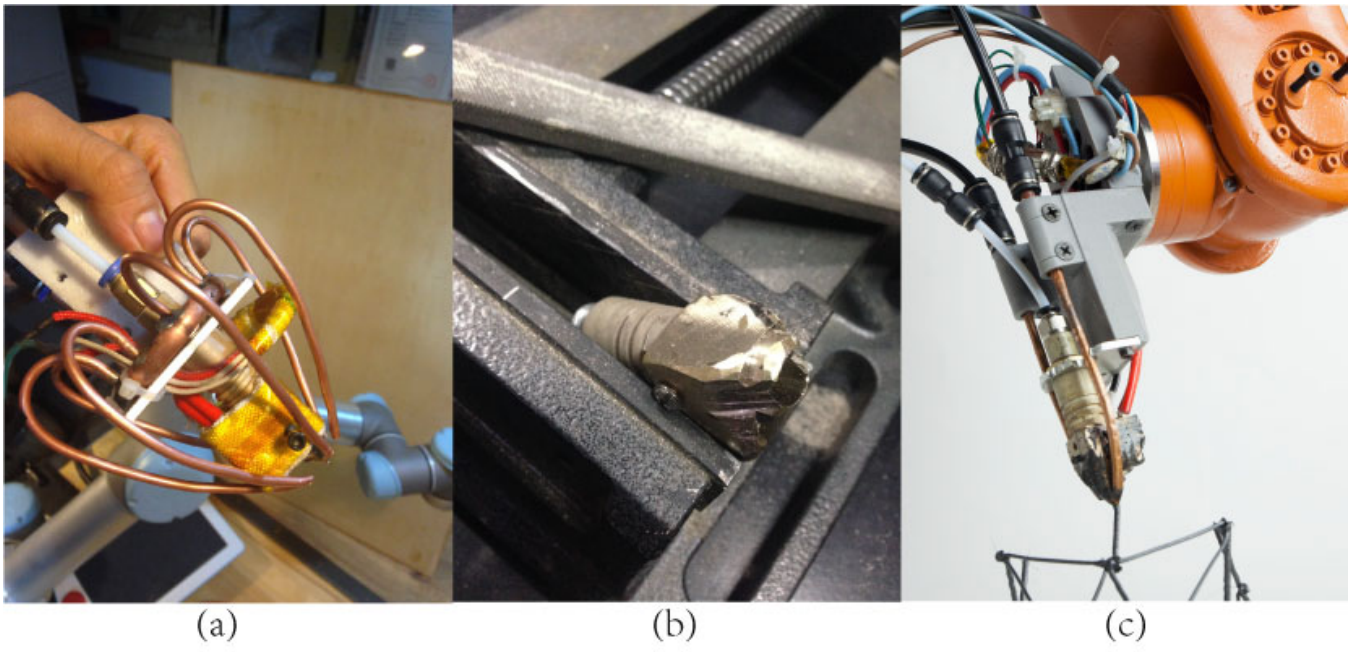
Figure 3: *(a) early stage extruder prototype. Various directions of air pipes were added but limited number of feasible angle would be expected due to the large volume occupied by the extruder. (b) Cutting down the volume of the extruder. (c) Current version of the extruder.*