Development of an FDM-based additive manufacturing system for large-scale part fabrication

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Abstract. Fused deposition modelling (FDM) is a well-known additive manufacturing technique. A part is fabricated layer a time by extrusion of a small thermoplastic filament. For large-scale part fabrication, this conventional FDM is very time-consuming process due to the small road width of the extruded plastic. Therefore a new plastic extrusion system has been developed to provide large road width. The new extrusion system consists of five liquefiers, a heat-block and a common nozzle. Five plastic filaments are fed into their individual liquefiers. The heat-block provides the heat to transform the filament to a semi-liquid state. Then the filaments are simultaneously extruded through the common nozzle and deposited on the working platform. With this conceptual design, a prototype unit of the extrusion system was constructed and tested with acrylonitrile butadiene styrene (ABS) filaments to investigate its possibility for fabricating the large-scale part. Results illustrated that the extruded ABS could flow through the common nozzle consistently. However some modifications on the hardware and further studies on process parameters identification were still required in order for this new extrusion system to be used in the real usage.

Keywords: Fused deposition modelling, FDM, Additive manufacturing, Large-scale part, Extrusion

1. INTRODUCTION

Fused deposition modelling (FDM) by Stratasys Inc. is one of a classical additive manufacturing (AM) technique. A part is fabricated layer a time by extrusion of a small thermoplastic filament, for example, acrylonitrile butadiene styrene (ABS), poly-lactic acid (PLA) and poly-carbonate (PC). The process starts from feeding the filament into the liquefier where the filament is partially melted to a semi-liquid state. Then the melted filament is extruded through a heated nozzle and deposited along the assigned toolpath. By repeating the steps, the part can be made layer by layer.

Compared with the other commercial AM techniques, the fabrication process of FDM technique is relatively simple, thus there are several low-cost FDM systems (known as Fabbers) available in the market for home desktop uses or those who cannot afford the expensive AM systems (Gebhardt, 2012). Besides, FDM also offers wide variety of materials, not limited only typical thermoplastics, for example, mixture filaments such as mixtures of ceramic particles/thermoplastic binder (Dudek, 2013; Bellini et al., 2005), a water soluble filament named WaterWorks^{TM} (Arcaute and Wicker, 2008) and biocompatible filaments such as poly-methyl methacrylate (PMMA) (Espalin et al., 2010) and poly-caprolactone (PCL) (Hutmacher et al., 2001). This has led FDM to be recognized as potential AM technique for applying in many applications.

Even though the FDM technique may have several outstanding points, there are also some disadvantages and limitations including slow fabrication process (Chua and Leong, 2015). Typically the thickness of the bead that the FDM nozzle deposits, known as road width, is very small. On each layer, the cross sectional area must be filled with part material by this small road width. Therefore the build time is very long. This issue becomes more critical for creating the large-scale parts. This issue has led to the development of a new plastic extrusion system that can provide large road width.

2. NEW PLASTIC EXTRUSION SYSTEM

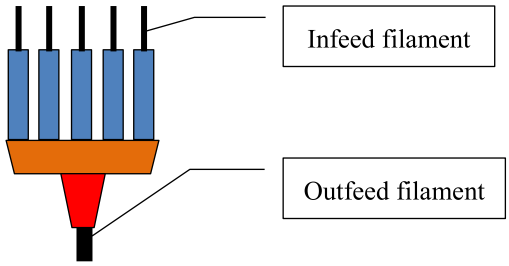
2.1 Concept Development

The developed system is based on FDM technique that the part is fabricated layer a time by extrusion of a small thermoplastic filament. For large-scale part, the road width needs to be enlarged to shorten the build time as mentioned. However this might be a tradeoff for lower resolution of the fabricated part. The road width is depended on the size of the nozzle. In addition, the supply rate of part material to the nozzle must be increased to support the large road width. In order to achieve the higher supply rate, using multiple commercial-size filaments is more suitable option than a single large filament that is non-commercially available. Besides lower material cost, the non-commercial-size filament may result to incomplete melting of the entire filament due to the foreseen problem on heat transfer from the surface to inside of the filament. With consideration of these issues, a new plastic extrusion system was designed in the followings.

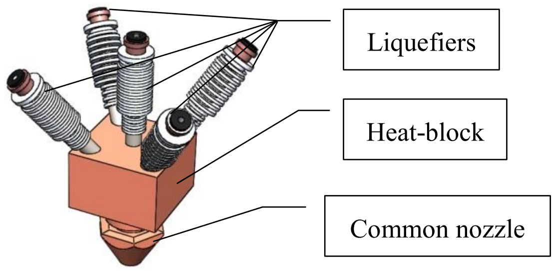
Figure 1(a) illustrates the schematic of the developed system. The system consists of five liquefiers and a common nozzle. Five filaments are fed into their individual liquefier. Then the semi-liquid filaments are simultaneously extruded through the common nozzle and deposited on the working platform. A foreseen problem is homogeneity of the extruded filament due to unsuitable heating condition. Therefore the heating temperature and the feeding speed of the infeed filament will be investigated in this study also.

2.2 Unit Construction

Based on the conceptual design as aforementioned, the design was further developed as presented in Figure 1(b). Five liquefiers are placed on top of a brass heat-block in the direction that all filaments converge to a point inside. This orientation helps the heated filaments combine together easier. The heat-block is designed with modular architecture that all relating components, a common nozzle (∅5 mm), a thermocouple, two cartridge-type heaters (50w) and five liquefiers, can be assembled and disassembled for maintenance. In addition to the liquefier, typically this component has own heater inside (hot-end section) and filament barrel with external heat fin (cold-end section). To make the system more compact, the individual heaters are replaced with two heaters installed in the heat-block. Thus, only the filament barrels are assembled to the heat-block. Five stepper-based feeders are used to deliver the filaments to their individual liquefiers. With this detail design, the prototype unit was constructed as shown in Figure 2.



(a)



(b)

Figure 1: Schematic diagram of developed system.
(a) Conceptual design
(b) Improved design

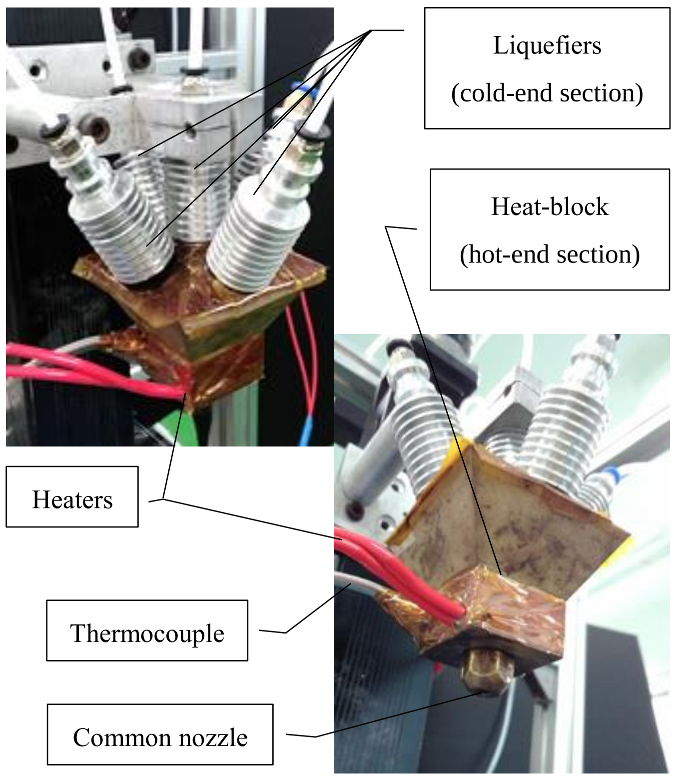


Figure 2: Prototype unit of the developed system.

2.3 Testing the Concept

To check its possibility for fabricating the large-scale part, an experiment was conducted on two factors: heating temperature and feeding speed of the filament. Both were varied as presented in Table 1. All 12 conditions had two replications each. The heating temperature was varied four levels from 160 to 190°C by using temperature control device. The feeding speed was varied three levels from 0.71 to 5.86 mm/s by adjusting the delay time of the stepper control device. Initially, the prototype unit was tested with acrylonitrile butadiene styrene (ABS) filaments (∅1.75 mm). The experiment was done in open environment at room temperature (25°C). The compressed air of 1 bar was applied to prevent heat accumulation at the filament barrel. The common nozzle was fixed at 100 mm above the working platform. The evaluation was performed on the physical characteristics of the outfeed filament. The criteria for evaluation were consistency of filament flow and surface roughness of the merged filament.

3. RESULTS AND DISCUSSION

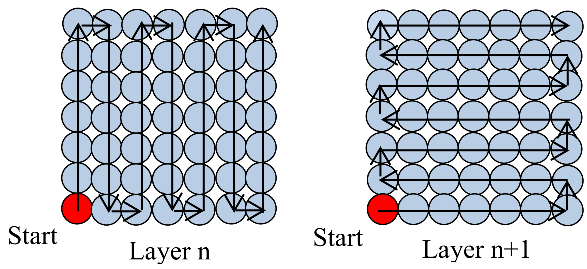
Table 1 presents the experimental results (coding each condition as A to L). Except the conditions that used the feeding speed of 0.71 mm/s (A, D, G and J), the remaining eight conditions could pass the consistency of filament flow criteria. By using the low feeding speed, the filaments absorbed a lot of heat and tended to be liquid state, not semi-liquid state. Vice versa, the conditions that used the feeding speed of 5.86 mm/s (C, F, I and L) could provide good flow consistency but the surface quality was quite rough due to less heat absorption. The filaments had less time to absorb sufficient heat. As a result, the filaments could not completely merge together. This comparison could show that lowering the feeding speed could improve the surface quality of the merged filament but it is also a tradeoff for inconsistent flow. For the effect of the heating temperature, the obtained results showed that increasing of the heating temperature could improve the surface quality also. For example, the condition L (190°C) provided better surface quality than the condition C (160°C). However, this factor should be well controlled to conform to the cooling rate at the filament barrel.

From the experimental results, the developed system was possible to provide large road width. The most suitable condition was to use the feeding speed of 3.22 mm/s and the heating temperature of 180-190°C (condition H and K). With these two conditions, the outfeed filament could flow consistently and the surface roughness was quite good relative to the other conditions.

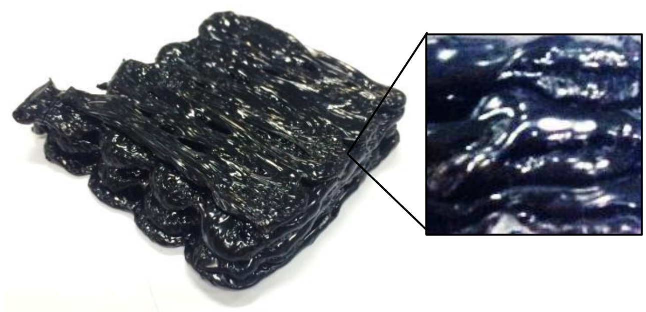
4. IMPLEMENTATION

After the prototype unit had been investigated in static condition, it was also tested in the practical condition, i.e., the common nozzle deposits the filament while moving in XY (horizontal planar). Therefore the prototype unit was installed on an X-Y-Z stage that was controlled by a LabVIEW-based program. A test 3D part was designed to be a block of 50×50×12.5 mm^3. The part was made with the condition H that used the feeding speed of 3.22 mm/s and the heating temperature of 180°C. The control process parameters were: standoff distance of the common nozzle 2.5 mm and transverse speed 2.65 mm/s. The layer was formed by applying raster fill. The contour toolpath was a back-and-forth pattern with distance of 7.5 mm. For the next layer, the raster pattern was at 90° relative to the previous layer. Figure 3(a) illustrates the toolpaths used for fabrication

Figure 3(b) presents the fabricated part. Solid layers could be made following the raster patterns. The successive roads and also layers were successfully bonded together. The obtained road width was 8 mm on average. However the physical characteristics of the roads were unstable because of the occurred bubbles during extrusion process. These bubbles might be the result from humidity in the filament. When the humidity was heated inside the heat block, it will boil instantly that caused bubbles.



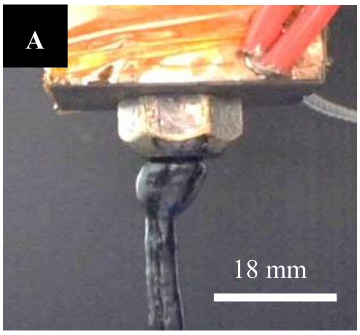
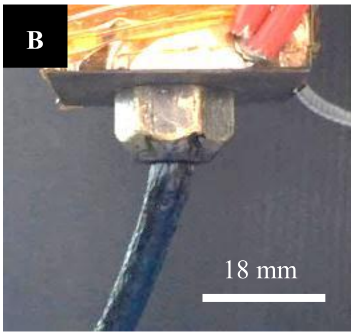
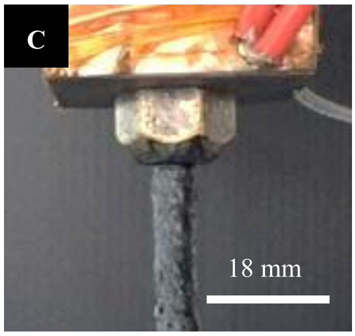
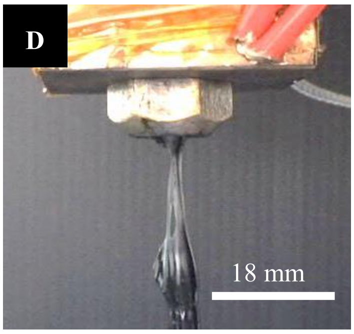
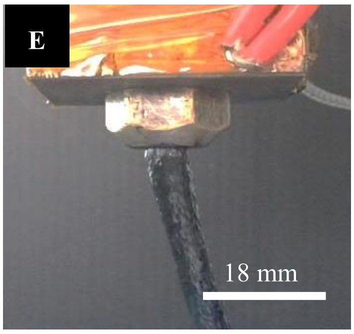
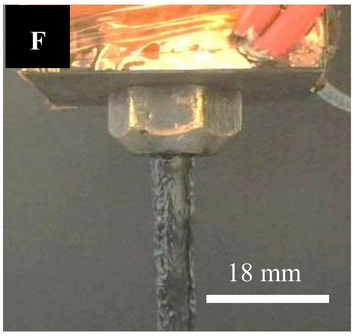
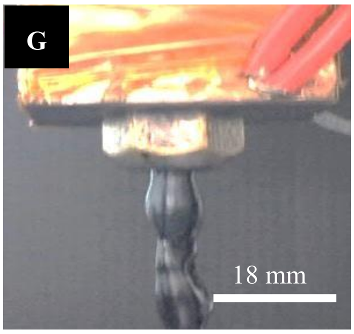
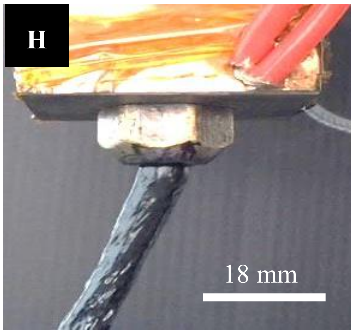
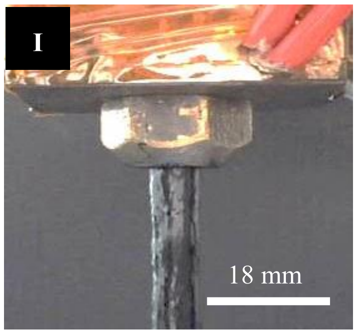
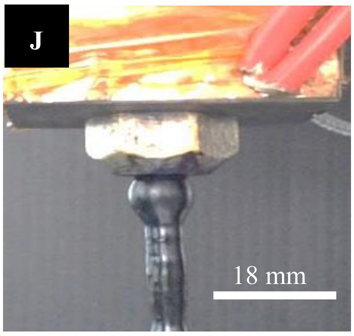
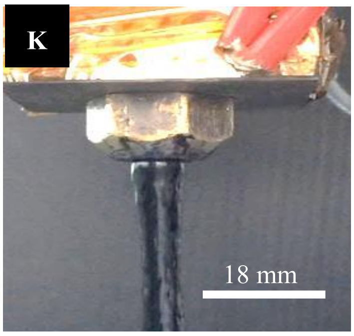
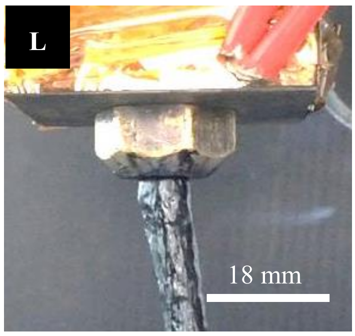
(a)



(b)

Figure 3: 3D part fabrication test
(a) Toolpaths
(b) Fabricated part

Table 1 Physical characteristics of the outfeed filaments.

Heating temperature (°C)	Feeding speed (mm/s)		
	0.71	3.22	5.86
160			
170			
180			
190			

5. FUTURE DEVELOPMENTS

Since the presented study was in the early state, future developments of the system was still required. Three main issues were taken into the consideration including part fabrication speed, quality of the fabricated part, and size of the developed system.

Currently, the part fabrication speed was limited by the feeding speed of the filament (the maximum feeding speed 5.86 mm/s). In order to reach the higher part fabrication speed, the feeding speed must be increased. The stepper control device might be replaced with an industrial grade device that can give higher frequency of the pulse train for the higher feeding speed. The process parameters identification will be revisited to determine the optimal condition at the high fabrication speed. Besides heating temperature and feeding speed that were investigated in this study, the other process parameters, e.g., cooling rate at the filament barrel, transverse speed, and standoff distance of the nozzle, will be considered also.

Besides, a foreseen problem of using the large nozzle and high standoff distance will be low resolution and poor surface quality due to the large road width and staircase effect respectively. An idea on hybrid processes, which combined additive manufacturing process and CNC milling process, was examined (Lee et al., 2011). The CNC milling process that can provide high resolution and good surface quality of the fabricated part might be integrated with the developed system. After the entire part is fabricated by the developed system, the milling cutter will trim the staircase surface to obtain the accurate and smooth surface. With this integration, the system should be redesigned to be more compact size.

5. CONCLUSION

In order to shorten the build time of the large-scale part, a conventional FDM was further developed. For FDM, the build time is depended on several process parameters including road width. Typically this process parameter is quite small and related to the nozzle size and the supply rate of part material to the nozzle. This paper presented a proof-of-concept to use large nozzle that could provide large road width. An idea of merging many small filaments to provide higher supply rate of part material was tested. Results illustrated a good sign for applying this developed system to fabricate the large-scale part. Much effort will be put in order for the developed system to be used in practice including (1) increasing the feeding speed of the filaments, (2) improving the quality of the fabricated part and (3) redesigning the system to be more compact size.

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