DESIGNING A COMPACT DUAL HEAD FOR FLM 3D PRINTING TECHNOLOGY

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This article deals with designing a compact head for 3D printing using Fused Layer Modelling technology, better known as Fused Deposition Modelling (FDM) registered by Stratasys. Technically this technology is an extrusion process, which is very popular e.g. with the RepRap community.
The aim is to design a print head based on commercially available basic components for printing two different materials, i.e. to allow control of an extrusion process for each material separately. It also has to be possible to switch nozzles with various diameters. The entire structure of the head should preferably be compact and lightweight to facilitate easy installation into the 3D printer.

KEYWORDS
FLM, FDM, 3D printing, dual head, design

1 INTRODUCTION

Additive technologies are recently on a huge rise. In the past, the 3D printers were used mainly in various fields of industry with a great pressure on reduction of production time. However, their scope of application is now much wider. Nowadays, one may encounter these printers not only in the field of medicine, arts, construction or gastronomy, but in the field of model making or in households.
One of the most widespread 3D printing technologies is an additive technology called Fused Layer Modelling (FLM) [Gebhardt 2011], more known under a name Fused Deposition Modelling (FDM) by the Stratasys company. Its origins can be traced to 1980s, however, it recently got a new impulse in a form of worldwide interest of RepRap community developers [Bowyer 2016].
The goal of this article is to replace the original non-functional printing head of a commercial printer with own design, preferably a compact one. The designed printing head must enable using two different materials in a form of thermoplastic wire with a 1.75 mm diameter. The whole solution should be as compact as possible, and both nozzles should be as close to each other as possible in order to avoid unnecessary reduction of the printable area. Additionally, the design of the head, even when using widely available basic components, should be as light as possible to ensure good movement dynamics of the head during a printing session.

2 OPERATING PRINCIPLE OF THE EXTRUSION HEAD

The extrusion head (often called an extruder) is a key component of the whole 3D printer. In case of Fused Layer Modelling, it consists of two parts – cold and hot part (see Fig.1). The material is usually in a form of thermoplastic wire (filament) fed by a feeding mechanism from the cold into the hot part, where the wire is being melted. Its continuous application on the base plate results in gradual building by stacking individual 2D layers. [Wikipedia 2016]

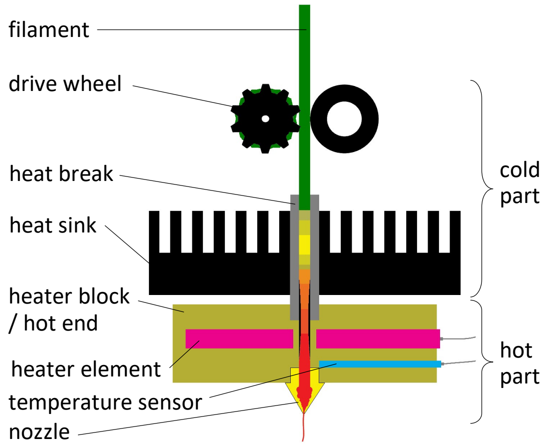

Figure 1. Principle of the Printing Head [3D Printing 2014]

The cold part of the head contains a feeding mechanism, whose task is to provide the hot part with the filament in a controlled manner. A drive wheel (a special cogwheel) is used to engage with the material. The feed of the material is controlled for example by a stepper motor, onto which the drive wheel is mounted.
The filament is being fed into heat break, which is on the borderline of the cold and the hot part of the head. The point of this component is to permeate as least heat from the heating block to the cold part of the head as possible. While the temperature in the place of contact of the heat break and the nozzle is in hundreds of degrees, the area of filament entry into the heat break is required to be as similar to the ambient temperature as possible.
The heater block is an important linker of several parts of the extrusion head. In this relatively small part, the melted material is fed from the heat break into the nozzle that is mounted to the heater block. Additionally, it contains its own heater element and thermistor for measuring and regulation of filament melting temperature. The most commonly used heater element for RepRap-type 3D printers is ceramic core element with 40 W of power and 12 or 24 V of operational voltage. One heater block is usually fitted with a single heater element. [Bowyer 2016]
Nozzle is the last part of the extrusion head. In this point, the melted filament leaves the extrusion head and is applied to the base plate or the previous layers of the printed model. The fundamental condition for a successful extrusion is to ensure as smooth feed of the melt through the nozzle as possible so that the melt does not stack and encounters minimal resistance. It is important for the nozzle to be appropriately mounted to the heating element with heat break, thus preventing leakage of the melt through gaps between the individual parts. The nozzle openings range within tenths of millimetres. Generally, it can be said that the lower the nozzle opening, the more detailed models can be created, although the print will take longer.

3 AVAILABLE SOLUTIONS OF EXTRUSION HEADS

There are many available solutions. Due to characteristics of the RepRap project, many users adjust or create extruder according to their needs and publish their solutions on the internet. The most common extrusion head designs are listed in this chapter. It shall be noted that the solution are often being combined.
One of the criteria for dividing extruders into categories is the means of feeding filament using feeding mechanism into the

hot part of the extrusion head. Vast majority of extruders using a printing wire to uses one of the following feeding solutions:

- Geared extruders
- Direct drive extruders
- Bowden extruders

Geared extruders uses a gear reduced feeding mechanism to feed the filament. Due to that, these extruders offer higher torques than direct extruders and are therefore suitable mainly for printing wires with higher diameter (3 mm). However, the disadvantage lies in somewhat more robust structure and size. [UltiBots 2016]. Example of this extruder is shown in Fig. 2.

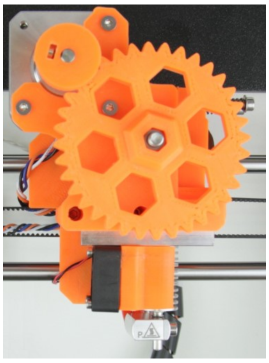

Figure 2. Example of the geared extruder [Prusa 2015]

Direct drive extruders are characteristic by their feeding wheel being attached directly to the output shaft of stepper motor. Unlike in the previous solution, the feeding mechanism is not geared and offers lower torque, which is, however, sufficient for feeding filament with 1.75 mm diameter.

Bowden extruder is one of special cases. It specifics lies in the fact that the feeding mechanism is not located in the head together with the hot part (see Figure 3), but is mounted to the printer's frame. The filament is being fed to the hot part through a tube. The filament feed can be either direct or geared. The advantage of this solution lies in lightening the moving parts, thus allowing faster printing. The disadvantage of bowden extruders lies in less accurate material feed on the start and the end of material application due to elasticity of the material and the bowden. Some of the more flexible material cannot be used for printing with this extruder type at all. [Thingiverse 2015]

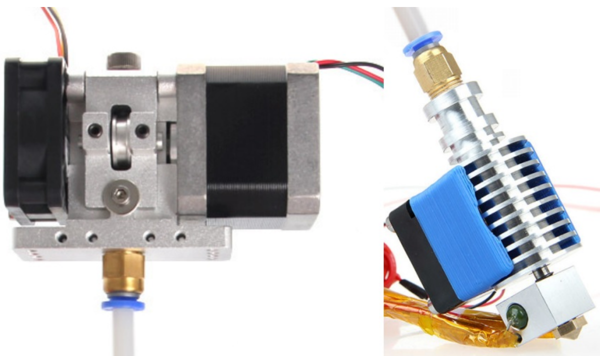

Figure 3. Example of the bowden extruder [Getech 2014]

3.1 *Dual Extrusion Heads*

Dual extrusion head is a head that offers using two independent materials (filaments) that can be automatically swapped without the necessity to change them manually. Any of the aforementioned designs can be used to feed the material into the extrusion head, including their combinations (e.g. direct drive extruder for the first nozzle and bowden for the other). [Rebel 2016]

The second material is often used as a supporting material on parts with large overhangings, where the support-less print would not be possible. In case of simple extrusion heat it is only possible to create there supports from the same material as the model, just with a smaller density of the applied material. After printing the part, these supports must be mechanically cleaned. This is not always simple and without undertaking the risk of damaging the printed part. Using another material as a supporting one may minimise the risk, or soluble material can be used, for example polyvinyl alcohol (PVA).

The performed research makes it clear that there is a wide range of dual extrusion head designs. Basically, the can be categorised into the following:

- Extruder duplication
- Two independent nozzles in one cooler
- One nozzle for two or more filaments

Apparently, the easiest solution to print on a 3D printer using more materials during one session is to duplicate the extruder – example of this solution is shown in Fig. 4. The head carriage is fitted with two identical extruders that are often used separately. In case small objects are being printed (their size on X- and Y-axis is smaller than the nozzle spacing), the print can be configured in a way so that both extruders work synchronously, meaning that two identical models are printed next to each other.

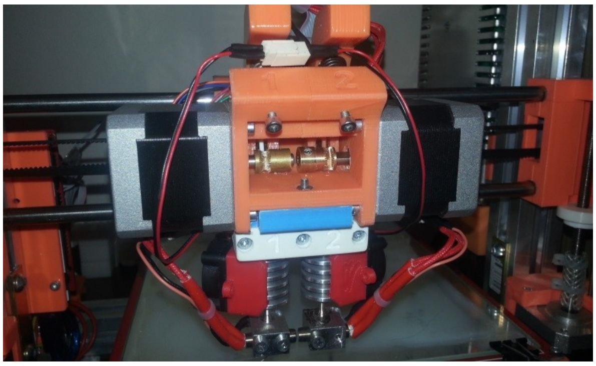

Figure 4. Duplication of two simple direct drive extruders [Rebel 2016]

Logically, such solution requires twice the number of components necessary to implement one dual head. Using two independent stepper motors is quite demanding in terms of space, leading to decrease of maximum printing space. Additionally, the total weight of the extrusion head will increase as well, causing deterioration of print dynamics.

Another difficulty lies in the nozzles being in the same height. After switching from one nozzle to the other, a small amount of filament (residue) may leak from the previous nozzle, which may negatively impact the printing quality. However, this negative phenomenon may be partially prevented for example by cleaning the nozzles during printing by means of a brush and proper retraction, unfortunately, that leads to increased complexity of process control. Also, it is important to correctly set the height (Z-axis) of both nozzles.

Obviously, the advantage is to have two independent nozzles, while each of them can contain various materials with different melting temperature. This offers the possibility to print more complex objects etc., since one of the nozzles can be used for supporting material. When using this solution, the amount of

nozzles can be increased by more than one nozzle, which, however, leads to increased weight and reduction of maximum printing space of the printer.
Another possible solution of dual extrusion heads is shown in Fig. 5. Two independent nozzles with optional diameters are locked in the heat blocks, while each of them is heated by own heating element. Heat break is locked to a heating element on one end, and to a solid block-shaped cooler, while the cooler is fitted with a fan and used by both nozzles. Two stepper motors are handling the material feeding, each of them handles one nozzle.
Advantages and disadvantages are the same as in the previous solution, except the spacing of both nozzles is smaller. That allows printing on larger area while having the same feed rates in X- and Y-axis.

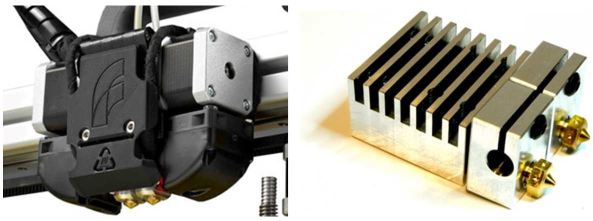

Figure 5. Examples of dual head and hot end with one heat sink [E3D 2014]

The concept of having one nozzle for two or more filaments is suitable rather for mixing or switching two colours of the same material, since different materials are most often of different melting temperatures. The advantage of this single-nozzle solution is that the printing space of the printer is not reduced. Additionally, the non-used nozzle will not be eventually blocked by the printed object. Hot end of this concept is shown in Fig. 6. [E3D 2014]
Printer which uses this type of hot end with bowden extruders for printing up to four colours was introduced in October 2016 by Prusa research [Prusa 2016].

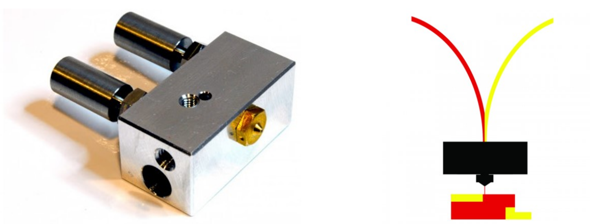

Figure 6. Cyclops hot end [E3D 2014]

4 DESIGN OF COMPACT DUAL EXTRUDER HEAD

It is necessary to integrate a new extrusion head as a substitute for the original one into the existing design of experimental printer. The new head should be able to print from at least two different materials, including flexible. Furthermore head should be as light as possible with regard to the speed and dynamics of 3D printing. Also, head's dimensions and in particular the distance of the nozzles should be minimal because of the minimal reduction of usable workspace of the printer. Due to unsatisfactory properties of the found dual extrusion head solutions, it was decided to use own extrusion head design.
Based on the previous experience with FDM technology in 3D printing, the option to use bowden feeding mechanism was rejected. A suitable initial concept seemed to be using two independent hot ends in one cooler with small geared stepper motor. Unfortunately no compact gearbox with the required gear ratio, ideally integrated onto a motor, were available. Printed gears used in RepRap community were disproportionally large. That is why it was decided to use direct drive mechanism. But in order to lower the weight of the whole head as much as possible, the feeding mechanism will be fitted with a single stepper motor. This motor will feed both materials by changing the direction and changing the thrust applied on the first of the second filament on the drive wheel. A servo-motor for model making could be used to change the thrust, since its weight is approximately ten times smaller than the feeding stepper motor. Principle of the first concept is shown in Fig. 7.

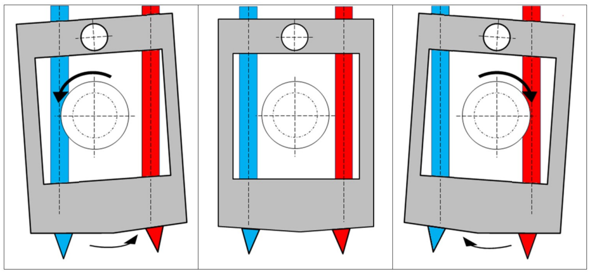

Figure 7. Principle of the first concept of dual extruder head [Safr 2016]

The middle figure shows the extrusion heads in neutral position. The side figures show change of thrust on one or the other filament by overturning a part of the printing head.
Another advantage of this concept is that the currently unused nozzle is raised above the level of the currently applied layer and does not negatively affect the part's building process. Later it was found that idea of this principle was patented by Stratasys company [Stratasys 2007]. Due to this fact this concept is not possible to use.
It was necessary to change the head concept so that the both nozzles position towards the carriage is fixed. This is the main difference from the patented solutions. CAD model of this new concept is shown in Fig. 8.

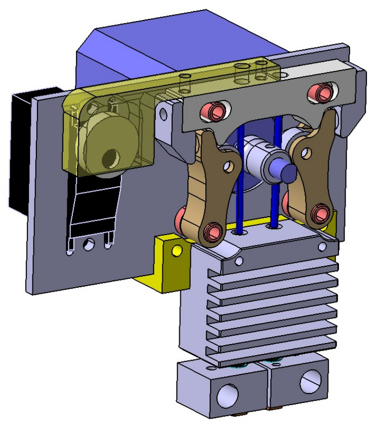

Figure 8. CAD model of the second concept of dual extruder head

Heat sink with both hot ends (extruders) and also stepper motor with the drive wheel are fixed parts of head. Above the drive wheel is a sliding bar connected to a cam mechanism. The sliding bar is in touch with two levers that ensure feeding of one or the other filament. The positioning of this mechanism is ensured by a small servo-motor for model making. There is not

used any sensor for position feedback of the mechanism to the controller, assuming correct positioning of the servo-motor.
In the spirit of RepRap community philosophy, most parts of the cold part were created from ABS material using 3D printing. A Mazak Integrex 100-IV 5-axis turning-milling centre was used to create the quite complicated cooling block.
The initial assumption to use two widely available and completed hot ends proved to be not good. The first tests of a head fitted with such hot ends showed problems with production quality and insufficient tightness between the nozzle and the heat break. Both, the nozzle and the heat break, were terminated with a planar surface, however, those surfaces were not parallel after the assembly and did not fit so close to each other. Due to this, the melted plastic started to leak through this gap and then along the thread of heater block.
Therefore, it was decided to design and then created own parts of hot end. Both, the nozzle and the heat break, now have conical contact surfaces (see Fig. 9). There were no issues with these components during testing.

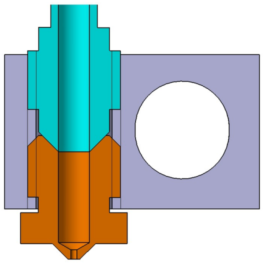

Figure 9. Detail of seating surfaces of the nozzle and heat break

Next problem there were with filament thrust onto the drive wheel in this variant as well, fortunately, by a simple adjustment of thrusting levers and spring holders, the problem was successfully solved.
Originally, most of the cold head parts were built on a 3D printer, but in order to increase the durability and improve accuracy of individual parts, one tested part after another were swapped for machined. The prototype solution of dual extrusion head partially consisting of printed components is shown in Fig. 10 on the left.
Arduino Mega2560 with Repetier firmware [Repetier 2016] was used for process control and filament switching along with temperature regulation, a system often used for control of so called hobby printers. It was necessary to adjust the part of the firmware responsible for control of the servo-motor and adjust the stepper motor control so that it rotates in one direction for the first filament and in the other direction for the second one.

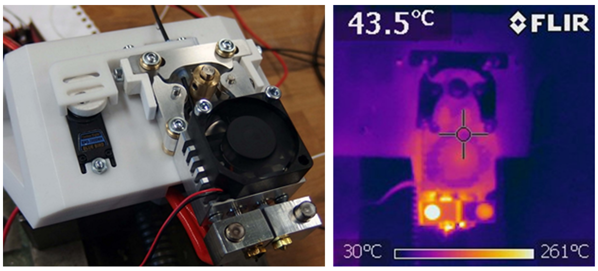

Figure 10. Prototype of the second concept and heat distribution

To create a notion regarding the heat distribution between the hot and the cold part of the extrusion head, a thermal image was created. The Fig. 10 on the right shows a steady state after the left heater block was heated to 260 °C, while the right heater block is on stand-by at approximately 100 °C.
After successful test of extruding individual materials, including switching both nozzles of the heat, a test print was performed. After the calibration of the 3D printer fitted with a new head, during which it was primarily necessary to fine-tune the spacing of both nozzles, a print of a "bridge" was performed; see Fig. 11 on the left. The model was intentionally oriented so that it is necessary to use a supporting material. A blue ABS plastic was used as a building material (manufactured by Plasty Mladec), for supports, a P400SR Soluble Support by Stratasys was used as a soluble material. Although it is recommended to temper the surrounding environment to approximately 70 °C when printing using ABS material, all tests were performed in the ambient temperature, since the used experimental 3D printer does not have such heating feature implemented. First attempts of 3D printing using this head were resulting in a failure, where the printed model was broken by the unused nozzle during the movement. It was necessary to align both nozzles to a same height and performed software adjustments of so called retractions, slightly feed the material in the opposite direction (towards the cold part) after the extrusion is finished. That prevented leakage of the residual material from the currently unused nozzle, which would cause issues when moving above the printed model. After this optimisation, the head was operating without any major issues; see Fig. 11.
Results of these prints are visually comparable with the printers of similar design at this moment. Also time consumption was comparable with these printers. But these parameters are dependent on characteristics of the whole system, not only on the print head properties.
After completing the tasks related to designing of whole 3D printer, larger objects from various materials will be printed, followed by a print quality inspection using the methodology described in [Mendricky 2016].

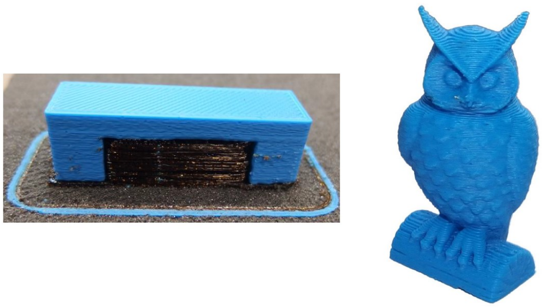

Figure 11. Results of the first tests

The following Tab. 1 contains overview of essential dimensions and further technical parameters designed and optimised design of the extrusion head.

Basic technical parameters of designed dual head		
Weight of head	about 0.5	[kg]
Head dimensions (H x W x D)	90 x 100 x 75	[mm]
Distance of nozzles	10	[mm]
Used nozzles diameter	0.4	[mm]
Range of temperature regulation (independently for each nozzle)	70 – 270	[°C]
Input power of heaters	2 x 40	[W]

Table 1. Basic technical parameters of designed dual extruder head

5 CONCLUSIONS

This article presents the result of dual extrusion head design for 3D printing using FLM technology. After the performed research regarding the existing solutions, it was decided to design an own head that is smaller and lighter than the solutions available on the market. Additionally, it is important to have as small nozzle spacing as possible, since it affects the size of printing space. In comparison to relatively widely available solution to duplicate a simple extruder, the nozzle spacing was decreased approximately four times, while the weight was reduced to half.

Concepts with many partial modifications were created during the design creation. When creating the prototypes, the advantage of 3D printing to build the necessary parts was taken, since the commercial printers available in the laboratory were used. However, in the final solution, most of the parts were replaced by machined pieces in order to improve accuracy and life time of the whole head. Some of the partial results of the designed were independently published on the internet by other solvers, e.g. conical contact surfaces of a nozzle and a heat break.

The designed head is used as a fundamental part of the experimental printer. In the future, it will be necessary to finish safety elements of the head; primarily its automatic shut-down in case the fails of control unit regulation of heating. Absence of this element brings many risks, including fire. This protection can be easily implemented by fitting a thermal fuse onto a bottom part of a cooler. Additionally, the whole head will be covered. To finish further tasks related to designing the whole 3D printer, printing of larger objects from various materials will be performed and followed by testing.

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