Do-It-Yourself Multi-material 3D Printer for Rapid Fabrication of Complex Luminaire

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Abstract

We present a do-it-yourself (DIY) 3D printer developed for rapid manufacturing of light fixtures (otherwise called luminaries) of complex and nonstandard shapes. This low-cost printer uses two individual extruders that can apply different filaments at the same time. The PLA (Polylactic acid) filament is extruded for essential parts of the luminaire while the PVA (Polyvinyl alcohol) filament is used to build supporting structures. PVA can be later effectively rinsed with water, leaving the luminaire with complex shape and diverse light channels. We provide a detailed description of the printer's construction including specification of the main modules: extruder, printer platform, positioning system, head with the nozzle, and controller based on the Arduino hardware. We explain how the printer should be calibrated. Finally, we present example objects printed using our DIY printer and evaluate quality of these prints. Our printer provides low-cost manufacturing of single copies of the complex luminaries while maintaining sufficient print accuracy. The purpose of this work is to deliver the luminaries for the experimental augmented reality system, in which virtually rendered lighting should correspond with the characteristics of the physical lighting.

Keywords: do-it-yourself 3D printer, multi-material fabrication, manufacturing luminaries for lighting design, 3D printing.

1 Introduction

The most important function of the *lighting luminaire* is as a holder for the light source. The *luminous efficacy* defines the amount of usable light emanated from the luminaire per used energy, usually measured in lumen per watt. It can be also defined as the percentage of light passed from the "bulb" to the surroundings. The more transparent the lighting luminaire is the higher efficacy. Shading the light will decrease efficiency but, at the same time, increase the directionality and the visual comfort probability. People prefer the lighting luminaire to be an interesting design and emanating a pleasant light. The lighting design techniques can determine the luminaire design, which provides comfortable lighting from a photometric point of view [3]. These designs must follow the rigid illumination constraints that it has to follow specified standards depending on the usage. An even more complex process is the evaluation of the *perceptual comfort* of the lighting, which is defined as the human satisfaction rather than a photometric quantity [15]. To assess the perceptual comfort, the lighting luminaire design must be evaluated in psychophysical experiments involving humans. Physical luminaries of versatile shapes and light paths must be manufactured to conduct such experiments. These luminaries must strictly follow the dimensions and structures defined by the lighting design computer-aided-design (CAD) software.

In this work we describe the process of building a multi-material 3D printer, which was designed for rapid and accurate manufacturing of the luminaries. The main feature of this printer is the use of different filaments for transparent and reflective parts of the luminaries, and a filament that can be washed out is applied for the supporting structures of the printed luminaries.

The printer was built of cheap components available on the market. It works based on the fused filament fabrication (FFF) technology, in which melted filament is extruded on the platform in successive layers to form the object. Our do-it-yourself DIY printer consists of two extruders for printing using PLA and PVA filaments. Its head with nozzle is additionally equipped with the BLTouch sensor for leveling of the platform. The head positioning system follows the CoreXY arrangement (sec 3.2).

In the paper we present a number of printed luminaries of different shapes and light paths. These printouts demonstrate the good quality of fabrication and the diversity of possible designs.

In Section 2, we introduce basic concepts related to 3D printing, especially the fused filament fabrication technology. We also described the technological assumptions of multi-material printing and the possibility of using it for rapid manufacturing of lighting luminaries. In Section 3, a detailed description of the construction of our DIY printer is presented. In Section 4, we show example prints of the

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lighting luminaries and evaluate their quality.

2 Background and Previous Work

Fused filament fabrication (FFF) is an additive manufacturing technology commonly used for 3D printing [8]. FFF printers lay down plastic *filament* to produce successive layers of the object. FFF begins with a software process, which mathematically slices and orients the model for the build process. Additionally, *support structures* are generated to avoid unsupported stalactites. A filament is delivered as a thin wire unwound from a coil. It is supplied to an *extrusion nozzle* which can turn the flow on and off. An accurately controlled drive pushes the required amount of filament into the nozzle. The nozzle is heated to melt the filament well past their glass transition temperature. The material hardens immediately after extrusion from the nozzle when exposed to air.

The nozzle is moved in both horizontal and vertical directions to built an object from the bottom up, one layer at a time. It is moved using stepper motors or servo motors that are controlled by a computer-aided manufacturing (CAM) software package.

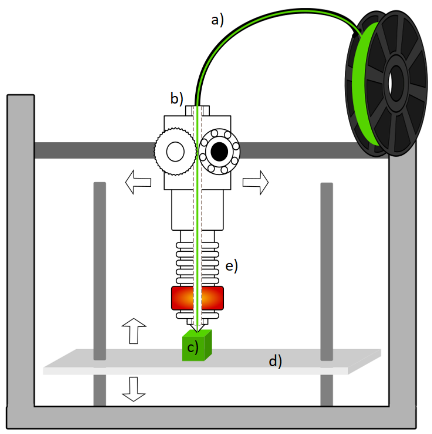

Figure 1: FFF 3D printing technology.

a) Filament used in printing b) Extruder c) Printed model d) Platform where printed is model

A number of filaments with different trade-offs between strength and temperature properties is available for FFF printing, such as Acrylonitrile Butadiene Styrene (ABS), Polylactic acid (PLA), Polyvinyl alcohol (PVA), Polycarbonate (PC), Polyamide (PA), Polystyrene (PS), lignin, or rubber. There are *water-soluble filaments* that are used to print the support structures and can be washed out from the object.

Multi-material 3D printers. Multi-material fabrication platforms simultaneously support more than one material (filament). They are used to create objects made of materials with different properties. Especially, these printers can be used to manufacture lighting luminaries of complex external and internal shape. Transparent light diffusing materials can be combined with the light paths build of the fiber optic tunnels. The supporting structures required to print the tunnels can be build of the material, which is later washed out using a solvent.

Some FFF 3D printers support dual or triple extrusion (e.g. MakerBot Replicator 2X, Ultimaker 2 with Dual extruder upgrade, Zortrax Inventure). In this work we develop a similar printer using inexpensive off-the-shelf components. In FFF printers, the materials cannot be mixed at high spatial resolution. We evaluate if the obtained resolutions are sufficient for printing prototypes of the light luminaries (see details in Sect. 3 and 4).

The multi-material fabrication platforms are also build based on other technologies. Stereolithography has been adapted to support multiple materials using multiple vats with UV-curable polymers [11]. The printing process is slow because materials must be change for each layer and the printed model must be cleaned from the previous resin. An additional disadvantage of this technique it is losing resin at cleaning time. The polyjet technology uses multiple inkjet print heads placed side next to the lamp of UV used to cure the polymer. This technology ensures high quality printing and large workspace, is one of the most advanced multi-material printing technologies, but it's very expensive. Selective laser sintering has been used with multiple powders [7]. The multi-material systems have been developed for powder-based 3D printing [2], inkjet-based systems [13, 5], and printing with multiple syringe-based extruders [9].

On the commercial side, the multi-material printing is supported by the powder-based 3D printers developed by Z Corp. The multi-material inkjet printers are provided by 3D Systems and Stratasys.

Printing for lighting design. Lighting design [4] works cannot be limited to photometric calculations performed in the CAD software. These works include consideration of the light energy expanded as well as the atmosphere for e.g. interior design while keeping in mind issues of aesthetic, ergonomic, and energy efficiency. The objective of lighting design is the human response, to see clearly and without discomfort [14].

In aesthetic appeal, the lighting designer attempts to assess what kind of emotions the lighting should evoke. The scientific approach to this issue is to conduct experiments during which people declare their emotions related to a given lighting. In Ramirez et al. [12], the visual-tactile experiments are performed with the use of 3D printed lights. These printed objects look different to what it feel like to touch. An experimental gap between vision and touch through 3D printing is investigated. Willis et al. [17] present 3D printed custom optical elements for interactive devices. Using these elements, unique display surfaces, novel illumination techniques, custom optical sensors, and embedded optoelectronic components can be fabricated. 3D-printed light-emitting diodes (LEDs) based on quantum dots [6] are semiconducting nanocrystals that exhibit tunable color emission. These quantum-dot-based LEDs can be patterned on e.g curved surface of contact lenses.

3 Do-It-Yourself Printer

The general view of our 3D FFF printer is presented in Fig. 2. The *positioning system* (see Sect. 3.2) is mounted on the *printer frame* (see Sect. 3.1). It moves the *platform* on which the object is printed. The *material feeding system* (see Sect. 3.3) supplies filament to the heated *head* (see Sect. 3.4), which moves parallel to the platform. The positioning system, material feeding and head operation is controlled by the *Arduino module* (see Sect. 3.5). This module is also responsible for the *printer calibration* (see Sect. 3.6).

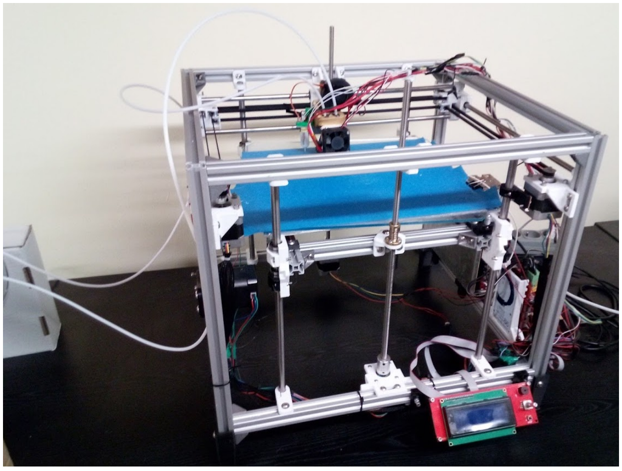

Figure 2: DIY 3D printer.

3.1 Frame and platform

Our printer measures 44x58x48 cm (width, depth, and height respectively). Its frame is built of aluminum rods (with a cross-section of 20x20 mm) that provide adequate structural strength and rigidity. The 30x30 cm platform was built with four linear guides made of 10 mm rods placed two at the front and back of the platform. The outer surface of the platform consists of three layers (see Fig. 3); first is a silicone hot pad that is responsible for heating table. The next layer is a 4 mm aluminum plate, which stiffens the structure and fixes it to the rods. The last layer is a glass, attached with clips, which gives the opportunity to remove this layer and clean it after printing. Useful function is to put the glass with the sticked object into the water to gently separate it from the glass.

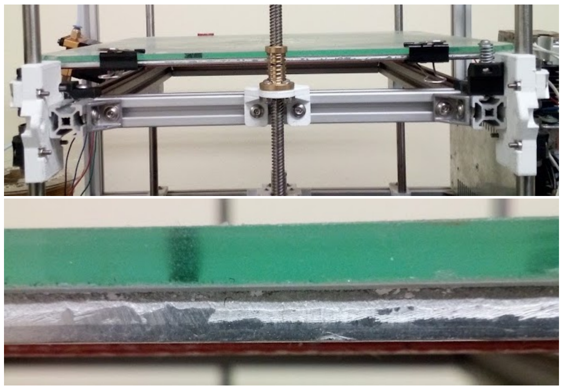

Figure 3: Top: printer platform. Bottom: layers of the outer surface of the platform (from top: glass, aluminum, and silicone heating pad).

3.2 Positioning system

The positioning system in our DIY printer is responsible for moving the head in XY directions and the platform in Z direction. The head movement is based on the CoreXY arrangement (see Fig. 4). It moves the head in straight lines along axis 90 degrees from the other axis. CoreXY mechanism consists of two stepper motors and two pulleys to equilibrate loads and so the carriage stays always perpendicular without relying on the stiffness of the sliding mechanism.

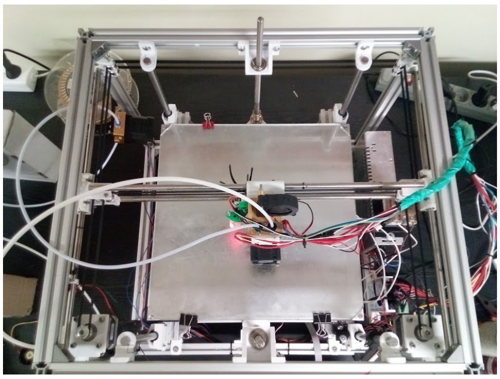

Figure 4: CoreXY cartesian arrangement.

The platform is moved by two motors attached to the bottom frame (see Fig. 5). They turn the threaded rods through the clutch (see Fig. 6). Additionally, four rods located at the corners of the platform stabilize its Z-movement.

3.3 Material feeding system

We decided to use the bowden filament feeding mechanism with the stepper motor attached to the printer frame. The motor pushes the filament through a teflon tube connected to the printer head. The advantage of this technique is reduced weight of the element moving with the head.

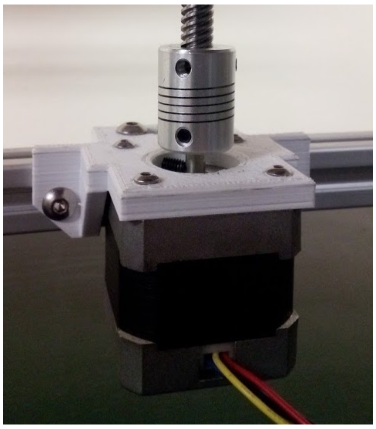

Figure 5: Stepper motor used to move the platform in Z direction.

Actually, we use two heads to support multi-material printing. Two motors moving together with the head would significantly affect quality and speed of the printing. For printing luminaries we use the PLA and PVA filaments that are rather rigid and do not require close connection between the stepper motor and the head. The material feeding system is presented in Fig. 7.

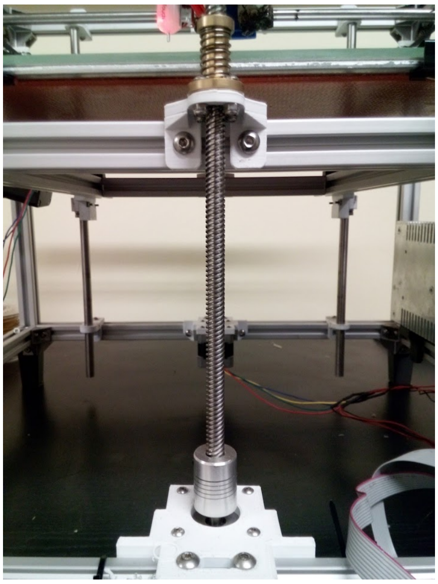

Figure 6: Threaded rod moving the platform.

3.4 Head

The filament delivered to the printer head (see Fig. 8) is preheated to high temperatures of 150-250 degrees Celsius. This temperature is controlled by the temperature sensor. An important part of the head is the *heat sink*, which prevents the dissolution of plastic at the beginning of the head. Dissolved plastic is applied to the glass surface of the platform with the *nozzle* of an arbitrary diameter (0.2-0.8 mm).

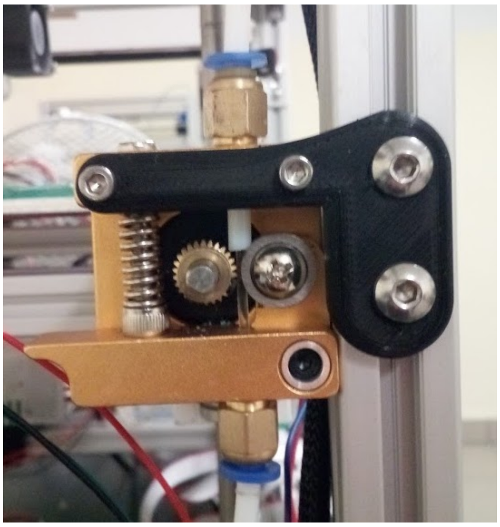

Figure 7: Material feeding system with the stepper motor.

For multi-material printing we decided to use two separate heads connected to each other. This solution allows to print simultaneously using two different filaments of different melting temperatures. The disadvantage of this solution is the need to use the nozzles of the exactly same hight and to position both heads in relation to the surface of the platform. Unwanted leakage of the filament from the second nozzle during printing is also possible.

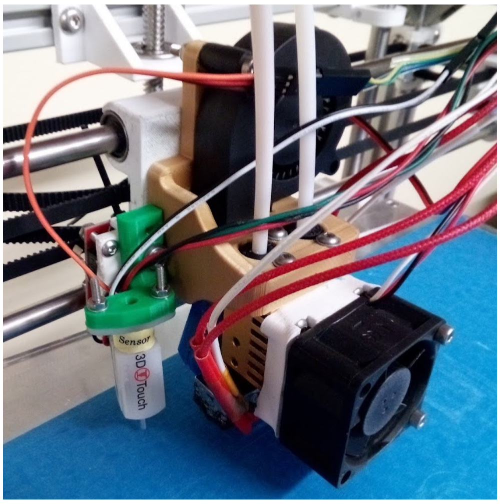

Figure 8: Printer head with the BLTouch sensor.

3.5 Control module

The entire hardware system is controlled by the Arduino module with RAMPS 1.4 (see Fig. 9). It controls the motors, temperature thermistors, extruder heaters, and platform heater.

We design the 3D model using the CAD/CAM software (Fusion 360). Then, the model is prepared for printing

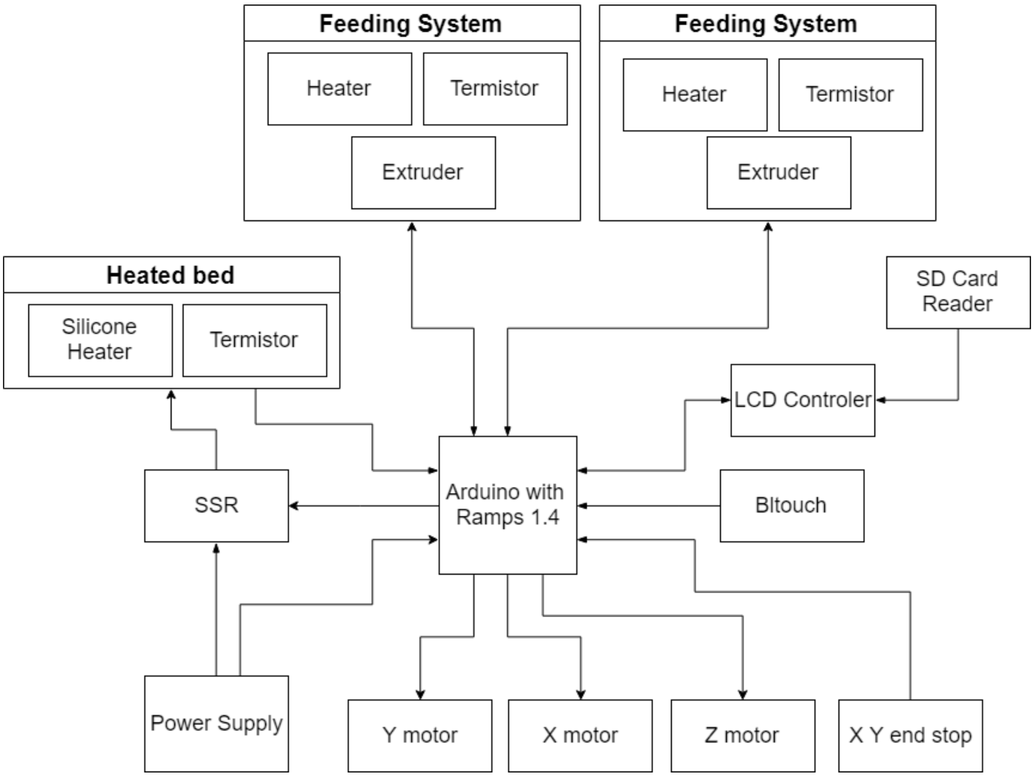

Figure 9: Control module of the DIY printer.

by cutting it into individual layers (slices) and generation of the supporting structures. Finally, data, which controls movement of the head and platform is delivered to the printer on the SD memory card.

Important feature of the Fusion 360 is a possibility to indicate that supporting structures should printed by different head than the main model. In other words, the software prepares the data for the multi-material printing.

3.6 Printer calibration

Before connecting motors to the to the controller, a voltage V_{ref} applied to each motor must be calculated:

$$V_{ref} = A * 8 * RS, \tag{1}$$

where A is the current required by the motor, RS is the controller resistance. V_{ref} can be adjusted manually in the controller.

The essential element of the calibration is to calculate the number of motor steps per centimeter. It should be done for both positioning motors and extruder motors.

For the XY positioning, the following formula is used:

$$XY_{steps} = \frac{MS * MI}{PP * PT}, \tag{2}$$

where MS is the number of motor steps per full rotation, MI depicts number of microsteps per one motor step, PP is the stroke of the toothed belt, and PT is number of teeth in the toothed belt. All listed values can be read from the motor and toothed belt parameters.

Positioning of the platform (Z-direction) requires the formula taking into account the thread parameters of the screw:

$$Z_{steps} = \frac{MS * MI}{RP}, \tag{3}$$

where RP depicts pitch of the screw.

The stepper motors of the extruders require the following formula:

$$E_{steps} = \frac{MS * MI * WGR}{\pi * HBC}, \tag{4}$$

where WGR is gearing on the gears of the extruder, and HBC is diameter of the extruder screw at the point of contact with the filament.

XY_{steps}, Z_{steps}, and E_{steps} are delivered to the Arduino software.

The last step of the printer calibration is leveling of the platform. The distance between the head nozzle and the platform should be known for each location on the platform. Leveling can be performed manually by adjusting the height of each corner of the platform. However, the surface of the platform is not perfectly smooth and some irregularities can occur e.g. due to using liquids that improve the adhesion of the object to the surface or mechanical defects. Therefore, in our printer we use Auto Bed Leveling (ABL) technique. In the ABL technique several measurements of the platform height are performed using the BLTouch probe (see this sensor in Fig. 8) that emulates the servo through the retractable pin.

4 Test Prints

In this section we evaluate accuracy of the multi-material printing with our DIY 3D printer.

The first object is a cube-shaped luminaire with a complex internal structure (see Fig. 10). It requires many support structures that fill the whole empty interior of the luminaire (see Fig. 11). We used the PLA filament to print the white elements of the luminaire, while the supporting structures were printed with PVA. The PVA filament was further rinsed with water (see Fig. 12). For this shape, it would be hardly feasible to remove the supporting structures printed with the same material as the main parts of the object. Most probably, this process would have to damage some part of the luminaire.

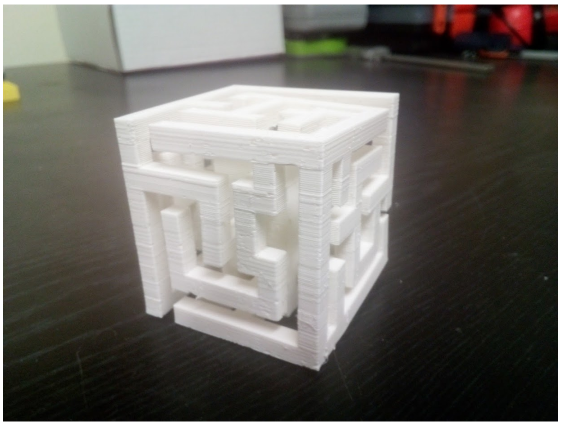

Figure 10: Cube-shaped luminaire.

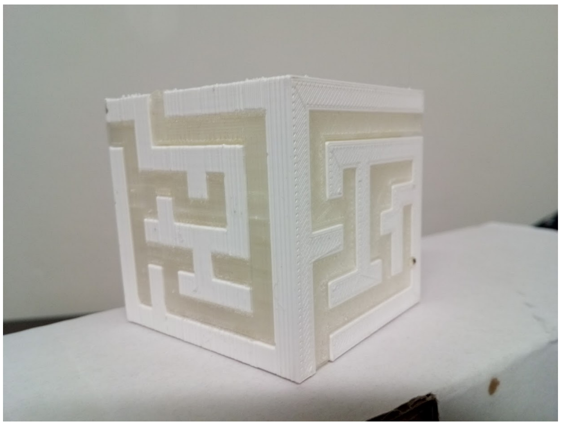

Figure 11: Cube-shaped luminaire with the supporting structures.

Another luminaire is presented in Fig. 13. As can be seen this luminaire has the shape of a twisted tube, which is empty inside. In the case of such objects only the multi-

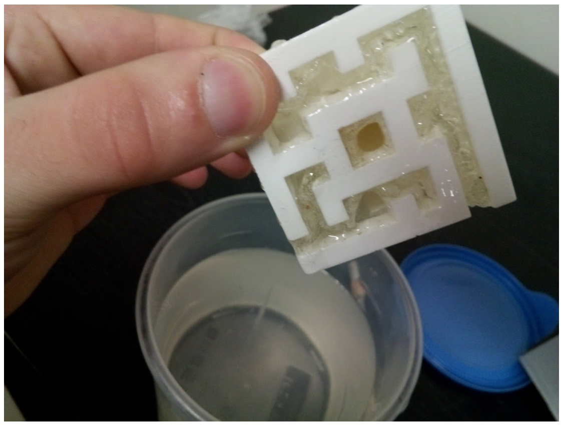

Figure 12: Rinsing the supporting structure with water.

material printing and rinsing enable removing the supporting structures.

Figure 13: Tube luminaire.

Discussion. The use of two heads also has its drawbacks. It is difficult to stop the leakage of the melted filament from unused head completely. This leakage causes extruding of small amounts of PVA filament on the main parts of the object. After rinsing, there are micro-holes on the PLA surfaces. The solution to this problem would be better head cooling system, however, these micro-holes should not substantially affect the characteristics of the luminaire.

Another problem is a low adhesion between PLA and PVA filaments causing delamination of the printed object (see Fig. 14). We managed to reduce this drawback by slowing down the printing process. In future work we plan to find filaments that would have better inter-adhesive properties.

Figure 14: Vertical delamination of the PLA and PVA filaments.

5 Conclusions and Future Work

Construction of a 3D printer is a challenging technical task, which requires specialized skills in the field of mechatronics. We have extended the typical FFF printer design by the dual-material module with separate extruders for each filament. Our low-cost DIY printer has been used to print luminaries of a complex shape. It was possible by rinsing in water the supporting structures printed using a PVA filament.

In future work we plan to print the luminaries of known photometric characteristic and evaluate if the printed objects follow these characteristic. In other words, we plan to use our DIY printer to prototype the complex luminaries.

There are also possibilities to improve the printer itself through testing another printer heads that would reduce the unwanted leakage of the filament. Testing other types of filaments should improve the quality of printed objects.

References

[1] Marlin Frimware Configuration. `http://marlinfw.org/docs/configuration/configuration.html`. [Online; accessed 27-January-2018].

[2] Wonjoon Cho, Emanuel M Sachs, Nicholas M Patrikalakis, and Donald E Troxel. A dithering algorithm for local composition control with three-dimensional printing. *Computer-aided design*, 35(9):851–867, 2003.

[3] Zumtobel Lighting GmbH. *The Lighting Handbook*. Zumtobel Lighting GmbH, 2013.

[4] Alyn Griffiths. *21st Century Lighting Design*. A&C Black, 2014.

[5] Saif Khalil, Jae Nam, and Wei Sun. Multi-nozzle deposition for construction of 3d biopolymer tissue scaffolds. *Rapid Prototyping Journal*, 11(1):9–17, 2005.

[6] Yong Lin Kong, Ian A Tamargo, Hyoungsoo Kim, Blake N Johnson, Maneesh K Gupta, Tae-Wook Koh, Huai-An Chin, Daniel A Steingart, Barry P Rand, and Michael C McAlpine. 3d printed quantum dot light-emitting diodes. *Nano letters*, 14(12):7017–7023, 2014.

[7] Pranav Kumar, James K Santosa, Elizabeth Beck, and Suman Das. Direct-write deposition of fine powders through miniature hopper-nozzles for multi-material solid freeform fabrication. *Rapid Prototyping Journal*, 10(1):14–23, 2004.

[8] Gideon N. Levy, Ralf Schindel, and J.P. Kruth. Rapid manufacturing and rapid tooling with layer manufacturing (lm) technologies, state of the art and future perspectives. *CIRP Annals*, 52(2):589 – 609, 2003.

[9] Jeffrey I Lipton, Daniel Cohen, Michael Heinz, Maxim Lobovsky, Warren Parad, Garrett Bernstien, Tianyou Li, Justin Quartiere, Kamaal Washington, A Umaru, et al. Fab@ home model 2: Towards ubiquitous personal fabrication devices. In *Solid Freeform Fabrciation Symposium*, 2009.

[10] Nik Markellov. Maze Lamp. `https://www.thingiverse.com/thing:2071943`. [Online; accessed 27-January-2018].

[11] Shoji Maruo, Koji Ikuta, and Toshihide Ninagawa. Multi-polymer microstereolithography for hybrid opto-mems. In *Micro Electro Mechanical Systems, 2001. MEMS 2001. The 14th IEEE International Conference on*, pages 151–154. IEEE, 2001.

[12] Edgar R Rodríguez Ramírez, Sebastien Voerman, and Helen Andreae. Designed for delight: Surprising visual-tactile experiences using 3d printing in lighting design. In *Proceedings of the Conference on Design and Semantics of Form and Movement-Sense and Sensitivity, DeSForM 2017*. InTech, 2017.

[13] Pitchaya Sitthi-Amorn, Javier E Ramos, Yuwang Wangy, Joyce Kwan, Justin Lan, Wenshou Wang, and Wojciech Matusik. Multifab: a machine vision assisted platform for multi-material 3d printing. *ACM Transactions on Graphics (TOG)*, 34(4):129, 2015.

[14] Gary Steffy. *Architectural lighting design*. John Wiley & Sons, 2002.

[15] Rosella Tomassoni, Giuseppe Galetta, and Eugenia Treglia. Psychology of light: How light influences the health and psyche. *Psychology*, 6(10):1216, 2015.

[16] Jonas Unger, Andreas Wenger, Tim Hawkins, Andrew Gardner, and Paul Debevec. Capturing and rendering with incident light fields. Technical report, UNIVERSITY OF SOUTHERN CALIFORNIA MARINA DEL REY CA INST FOR CREATIVE TECHNOLOGIES, 2003.

[17] Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. Printed optics: 3d printing of embedded optical elements for interactive devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, pages 589–598. ACM, 2012.