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Development of a Multicolor 3D Printer Using a Novel Filament Shifting Mechanism

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Abstract: Three-dimensional printing has become an unchallenged method for the manufacturing of complex shape objects. Although multicolor devices in Fuse Filament Feeder category recently have shown promising developments, their number still remains limited. The present study introduces the design of a new prototype of three-dimensional printer using Fused Filament Feeder and capable of printing multicolor objects. A single-color three-dimensional printer is used as a platform and is augmented for multicolor printing by the implementation of a mechatronic device that provides two functions. First, a transmission mechanism based on planetary gears allows feeding the selected filament color toward the printing head. The second function is provided by a combination of a central cam disk and several pushing rods. It allows selecting the filament color to be fed by the transmission system. The mechatronic device has been dimensioned to manage five different filament colors and the printing head has been modified to accommodate a five-to-one diamond nozzle. The filament shifting device is integrated into the single-color three-dimensional printer and a series of validation experiments has been carried out. These tests have demonstrated the new prototype ability to print out multicolor objects and to rival with commercial three-dimensional printers in terms of dimensional accuracy. This shows the ability of the proposed design and method to be used to upgrade a standard single-color 3D printer into a multicolor one. The presented multicolor 3D printer will be available to the 3D printing community for free.

Keywords: additive manufacturing; filament shifting device; multicolor 3D printer

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1. Introduction

Unlike traditional manufacturing techniques, such as casting and machining material, three-dimensional (3D) printing, also known as Additive Manufacturing (AM) is a manufacturing process that consists in creating objects by adding material layer by layer [1]. This method offers many advantages over traditional manufacturing technologies such as rapid prototyping, less waste of material, and the ability to manufacture complex geometries [2]. Although 3D printers can be classified into several categories depending on their additive manufacturing method, the Fused Filament Fabrication (FFF) is the most widely spread because its hardware and material are relatively affordable compared to other methods [3,4]. Generally, most existing FFF printers operate with single color. With the rising request for color parts, more and more designers are considering the possibilities of printing in different colors by using FFF technology [5]. In the medical field for example, surgeons and physicians want to produce specific 3D models based on patient anatomical parts for demonstration in patient consultation or for surgical pre-operative planning [6–9]. In both cases, the use of different colors can help differentiating several organs, representing different level of biomechanical properties, highlighting specific anatomical element or displaying non-biological items such as trajectories, surgical tools, etc. During their medical training, students using 3D models can benefit from an easier learning and a better understanding of the human anatomy without having to use real volunteer cadavers [10]. The 3D printing technology is also revolutionizing the fashion industry, as fashion designers are now experimenting with 3D-printed clothes and accessories [11,12]. Gruppo Meccaniche Luciani, a footwear manufacturer in Italy, has been using 3D printing technology to create a line of complex shoes and fashion pieces that would not be possible by hand or with traditional methods [13]. In the artistic field in general, more and more talented artists resort to AM methods to create impressive pieces of arts, which would be much more challenging by the mean of other creation processes. Three-dimensional printing technology has become a major tool for concretizing an interesting concept, especially for people showing limited dexterous skills [14,15].

In recent years, several methods for multicolor 3D printing have been reported. G. Chen et al. [16] reviewed and grouped the color 3D printing process into five categories: powder-based color 3D printing, plastic-based color 3D printing, paper-based color 3D printing, cell-based color 3D printing, and food-based color 3D printing. Among these, the plastic-based color FFF 3D printing is a low-priced and rapid method to create colorful objects. It is possible to classify multiple colors or materials printing concepts of FFF 3D printers into four families: colored filament, color-mixing, multiple extruders, and filament/nozzle switching. The colored filament method is a great way to create colorful objects with a single-nozzle printer, for example, the multicolor filaments (widely known as rainbow filaments) for printing full range colors parts without external device. However, it is impossible for users to adjust the color of the printed object because these filaments are precolored by manufacturers. In order to overcome the disadvantage of precolored filament, Mosaic manufacturing company developed a device, namely, Palette Filament Splicer [17], that is to be associated with any single color FFF printer. It is designed to splice up to four different filaments to form a single one that will present a desired color sequence. It is formed by heating both extremity of two successive filaments and using a copper heating and cooling block assembly to merge them together. It is then guided to the 3D printer extruder. This device allows converting a standard FFF 3D printer into a multicolor one as long as it has one single hot end extruder. However, the printer must be accurately synchronized with the Paletter Filament Splicer so that the output filament color sequence corresponds exactly to the color change on the printing surface. In 2021, Mosaic manufacturing company improved this device from four strands of filaments to eight filaments, which enables the printer to produce up to eight colors in one print. In 2017, XYZprinting introduced an impressive full-color 3D desktop printer, namely da Vinci Color [18]. It uses a colorless filament that is then dyed with different color inks during printing. Although the performance of this printer has been proved with the high quality of printed products, it costs more than 3500 USD for the machine and requires specific filaments with color ink cartridges. For this reason, it is not affordable for hobbyists and makers who want to equip a multicolor printer. The second concept was firstly introduced by RepRap.me [19]. They developed a conical nozzle with three input filaments and one output of 0.4 mm diameter in 2015 and then, the improved version with five input lines and one output in 2018. Both designs are capable of melting and mixing filaments of different colors directly in a small chamber at the center of the nozzle. In order to drive three or five filaments into the hot-end, each filament requires integrating a feeder with a stepper motor and upgrading the controller board of the printer. In the similar concept, Shenzhen Zonestar Innovation Technology Company developed and commercialized a multicolor 3D FFF printer with 4-in-1-out nozzle, model Z9V5 [20]. The printer has four feeders for pushing four filaments into the 4-in-1-out hot-end to create the four-colors parts. A 32-bits microcontroller with eight stepper motor drivers is used in this printer. The third approach is that the 3D printer uses multiple extruders with multiple filament feeding mechanism. The Multi-Color RoVa3D printer developed by ORD Solution Company is an illustration of this method. It includes up to five printing heads for multi-material/multi-color printing [21]. However, using several extruders causes calibration problems and oozing issues due to the idle hot-end nozzles [22]. Indeed, all nozzles must be located at the exact same distance from the deposition surface. If the distance between the nozzles is not carefully calibrated, it may result in layers made of irregular filament sections, increasing dimension errors. Currently, most of multicolor 3D printers commercialized in the market employ this method such as BIBO 2 Extruders 3D Printer (Shaoxing Bibo Automatic Equipment Co., Ltd., Zhejiang, China), Geeetech I3 pro C dual extruder 3D printer (HK Getech Co., Ltd., Guangdong, China), or Disco Ultimate 3D printer (Dagoma, Roubaix, France). The last method is another interesting way to convert the single-color 3D printer into a multiple colors/materials printer by adding an external device for selecting the printing filament or nozzle. For instance, DGlass3D Company has developed a dual filament extruder that uses one stepper motor to feed one of the two filaments that is selected by another servo motor [23]. This printing head, named D3D filament shifter, is designed to be adaptable to any type of common printer on the market. However, the mechanical concept is only suitable for two different colors and the presence of two motors on the moving printing hot end is not advantageous in terms of mobility. DisTech Automation introduced a Prometheus dual-extrusion system that has two filament feeders and a specific device, namely Pro-feeder [24]. It directs the filaments from two extruders into a single guiding tube. The single resulting filament is then fed into the single hot-end. In order to change materials or color filaments, the extruder retracts the filament by pulling it up and pushing another filament down. Although the device is very compact, the retraction of the partially melted filament may cause struck or jamming when it re-enters the hot end. Moreover, because the device is placed just above the hot end, it is required to install two motors for feeding the two different filaments and additional filaments will require additional motors. Another example of a multicolor 3D printer was reported in 2015 [25]. A filament switching device operated by two stepper motors allows the selection of four colors. It is composed of four nozzles located on a platform that is rotated by one stepper motor. The device is also very compact and can be mounted on a 3D printer as a moving printing head. However, as for the D3D filament shifter, two motors have to be moved along with the printing head. On addition, the rotating nozzles may require a more accurate calibration than the RoVa3D printer where the nozzles are fixed with the printing head. At the end of 2021, Co Print 3D Printer Technologies launched a Co Print 3D Multi-Filament Module that can be easily integrated in the existing single-color printers for printing up to seven colors in one pass [26]. This equipment is still under development.

From the above literature review summarized in Table 1, it can be concluded that although some applications would find multicolor 3D printing more advantageous, the number of multicolor 3D printers of FFF type remains limited and the large majority of instances are unveiled and commercialized by private companies, not reported by academic institutions and may not be freely accessible. Some academic reference related to FFF printing can be found but these studies generally focus on improving the fused material [27,28] and the structural aspect of printed parts [29,30]. In addition, most of previous proposed devices require the use of several filament feeding stepper motors, which requires the controller to be modified with high-speed processor along with a new firmware, which may be revealed to be difficult and expensive to implement. The present study introduces the design of a multicolor FFF 3D printer using a novel filament switching mechanism that can expand the color printing capabilities of any low-cost monochrome 3D printer. This external device is not complicated to manufacture with local material and it can use the same low-cost controller boards as those employed in a wide range of existing 3D printer such as Ramp 1.4, Ramba, or Megatronics. This proposed multicolor 3D printer is designed and developed based on the open-source 3D printer created by RepRap; therefore, the detailed drawings and the modified Marlin firmware will soon be freely distributed to the 3D printing enthusiasts. The general concept of this prototype is presented in Section 2. The design of the heart of this concept is detailed in Section 3. Section 4 will demonstrate the qualitative and quantitative results achieved by this prototype. The conclusion of this study is addressed in the last section.

Table 1. Summary of multicolor 3D printers using FFF technology.

Concept	Name of 3D Printer or Device	Manufacturer (Country)	Open-Source
Colored filament	Palette Filament Splicer [17]	Mosaic manufacturing company (Canada)	No
	Da Vinci Color 3D printer [18]	XYZprinting, New Kinpo Group (Taiwan)	No
Color mixing	Prusa 3D printer using Diamond Hotend [19]	Reprap.me (Denmark)	Yes
	Z9V5 3D printer using 4-in-1-out hot-end	Shenzhen Zonestar Innovation Technology Co., Ltd. (China)	No
	Tronxy X5SA PRO printer with Tronxy 3 in 1 out Multi-color Extruder hot end [20]	Shenzhen Tronxy Technology Co., Ltd. (China)	No
Multiple extruders	Multi-Color RoVa3D printer [21]	ORD Solution Company	No
	BIBO 2 Extruders 3D Printer	Bibo Automatic Equipment Co., Ltd. (China)	No
	Geeetech I3 pro C dual extruder 3D printer	HK Getech Co., Ltd. (China)	No
	Disco Ultimate 3D printer	Dagoma (France)	No
	Creator Pro	Flashforge (China)	No
Filament/nozzle switching	D3D filament shifter [23]	DGlass3D Company	No
	Prometheus System [24]	Eric Sammut-DisTech Automation (Canada)	Yes
	Multi-nozzle extrusion system [25]	Md Hazrat Ali, Mir-Nasiri Nazim (Kazakhstan), and Ko Wai Lun (Hong Kong)	No
	Co Print 3D Multi-Filament Module [26]	Co Print 3D Printer Technologies, England	No

2. General Concept of the Proposed Multicolor 3D Printer

After studying existing color shifting methods for FFF 3D printers introduced in the previous section, a new concept is proposed for the same purpose. It has resulted in a prototype of a multicolor 3D printer, whose general concept is discussed in this section. The first decision that has been made is to use an already existing single-color 3D printer platform. Indeed, the design of that basic part of an entire 3D printer and the programing of its elementary functionalities would have a limited contribution. So, the concept will consist in augmenting a standard 3D printer into a multicolor one. As it is expected that the final prototype will be reprogramed for the integration of a multicolor printing feature, a Cartesian motion type 3D printer will be selected in order to simplify the trajectory generation and motor control during testing experiments. Based on the literature review, specifications have been made to guide the design of the present device. First, as the use of multiple nozzles may increase the risk of calibration error and the occurrence of dripping or oozing when shifting from one nozzle color to another, we have chosen to rely on only one extrusion nozzle. Since there are still several filament paths, the question of where these paths will merge into one remains. In the present concept, the choice has been made to merge these filament paths directly inside the nozzle heating chamber where the selected filament will be melted then extruded on the deposition platform. As mentioned in the last section, the Pallete Filament Slicer creates a filament with a specific color sequence from several standard filaments, but due to the cutting and melting operations, the resulted filament has presented an irregular section. The two following specifications are related to the filament shifting method. The first one is to locate the system providing this function out of the moving printing head. It will be, therefore, embedded in a location where the 3D printer motors do not need to support their weight to avoid inertial issues. The second one is to use only one motor for shifting from a filament to another and one motor for pushing the selected filament. Indeed, this method has been used on several prototypes in the literature review and seems more effective in terms of compactness.

The proposed multicolor 3D printer is composed of three main parts: one 3D printer, one multicolor filament shifting mechanism, and one nozzle, as shown in Figure 1. The single color FFF 3D printer uses classical Cartesian motion to manipulate its printing head. A Cartesian planar manipulator is moving the printing head along a vertical plane, while the deposition platform is moving along the normal axis to this mechanism plane. Its workspace is estimated to 300 × 300 × 400 mm (Length × Width × Height). This 3D device is then equipped with a new filament shifting device, with a design that constitutes the main contribution of the present work. Located on the top of the 3D printer, it allows the selection and the extrusion of a specific color filament out of five different ones. All five filaments are exited from this device and lead to the printing head that has been modified to accommodate a five-to-one nozzle. It has five inputs for 1.75 mm filaments and one output for 0.4 mm melted filament. Although a reprograming of the machine is required for the implementation of this function, the design modification on the original platform is very limited. Indeed, only the five-to-one nozzle has to be installed on the mobile printing head and the motor that pulls the filament is relocated, which lightens the printing head and represents a certain advantage. Once fully designed and manufactured, the installation of the filament shifting device is also very simple. Its design is detailed in the next section.

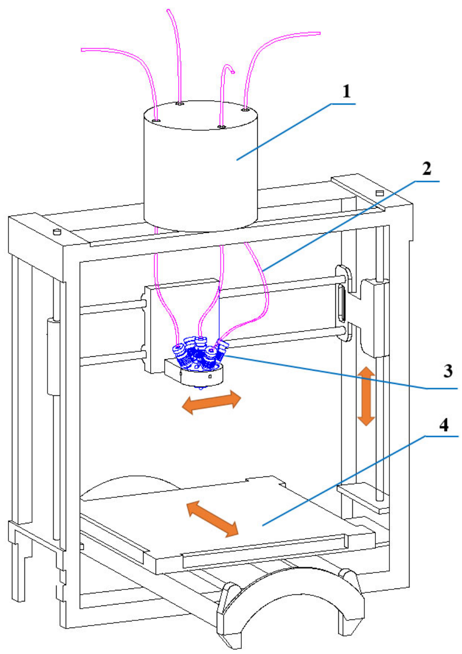

Figure 1. Illustration of the multicolor 3D printer concept; 1—Filament shifting device; 2—Filament; 3—Printing head including 5-to-1 nozzle; 4—Mobile printing support.

3. Design of the Filament Shifting Device

The most important part of the concept introduced in the last section is the filament shifting device that will be attached to the 3D printer. It is composed of two main parts providing a specific function each: the shifting mechanism that selects the filament to be pushed out of the device to the printing head nozzle and the transmission system that pushes the selected filament. The global design is illustrated in Figure 2, where several parts are identified by different colors. The details of their design are addressed in the following sub-sections.

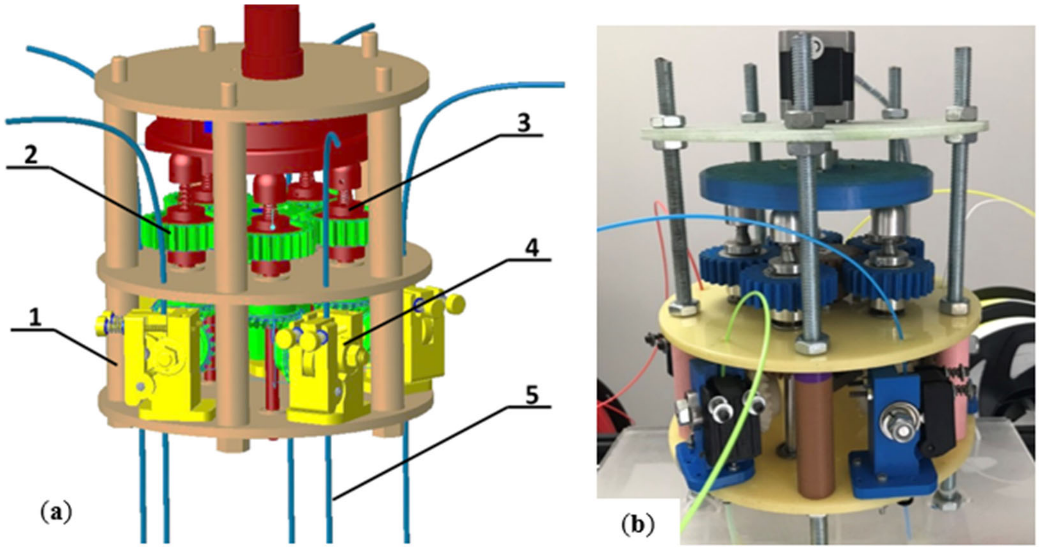

Figure 2. (**a**) CAD view of the multicolor filament shifting device; 1—Main frame; 2—Transmission system; 3—Filament shifting system; 4—Filament feeding mechanism; 5—Filament. (**b**) Manufacture prototype of the filament shifting device.

3.1. Filament Feeding Transmission System

As part of the shifting filament device specifications, only one motor must actuate the motion of one selected filament. Each filament is pushed toward the 3D printer nozzle by a filament feeder using a revolute motion. It is, therefore, necessary to use a transmission system to transfer this revolute motion to all filament feeder mechanisms at the same time. A specific combination of gears is used to provide this function. The whole mechanism can be divided into two different stages. The first is composed of one sun spur gear directly attached with the motor shaft and five planet spur gears located around the first one. This configuration allows transmitting the power from the stepper motor to five different shafts. The second stage consists in five couples of two bevel gears. Each of them transfers the revolute motion from a vertical axis (on the shaft) to a horizontal axis (filament feeding mechanism). The transmission from the motor to the filament feeder is detailed in Figure 3. It illustrates the transmission between the first and second stages using one of the five transmission housing shafts. Each housing shaft has a specific design to enable or disable the transfer from the first stage to the second stage. It will be addressed in the next sub-section.

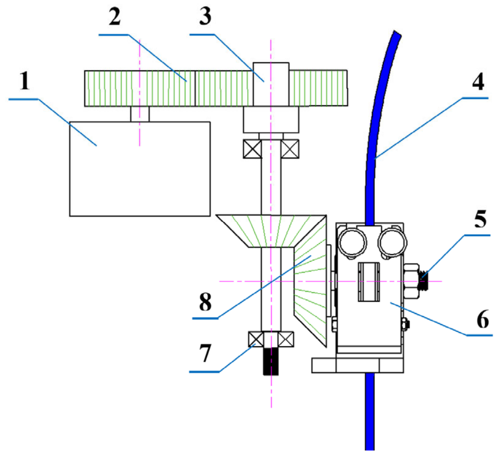

Figure 3. Schematic view of the transmission from the motor to the filament feeder. 1—Stepper motor; 2—Sun spur gears; 3—Planet spur gear; 4—Housing shaft; 5—Filament; 6—Knurled bolt; 7—Filament feeding mechanism; 8—Ball bearing; 9—Bevel gears.

3.2. Filament Shifting Mechanism

As it is mentioned in the previous sub-section, the transmission between the first and second stage of the filament feeding system is provided by a special housing shaft. This shaft accommodates a specific mechanism that enables or disables the transmission between these two stages. This allows the selection of the appropriate filament feeder to be operated. The concept relies on two specific items. The first one is a cam disk that is rotated by a stepper motor. Pending on its position, the cam disk will press or release one of the five pushing rods. Each of these pushing rods is integrated into one housing shaft, the design of which constitutes the second item. As illustrated in Figure 4, a total of four balls are installed between the housing shaft and the planet spur gear of the transmission first stage. When the pushing rod is released, the balls are pushed toward the spur gear. As a result, the power transmitted from the sun spur gear to the planet spur gear is then also transmitted to the housing shaft and by extension, to the filament feeder mechanism. The corresponding filament is, therefore, pushed toward the printing head. On the contrary, pushing the pushing rod downward will remove the balls from the spur gear, which will no longer transfer its revolute motion to the housing shaft, which then remains motionless, so as the corresponding filament.

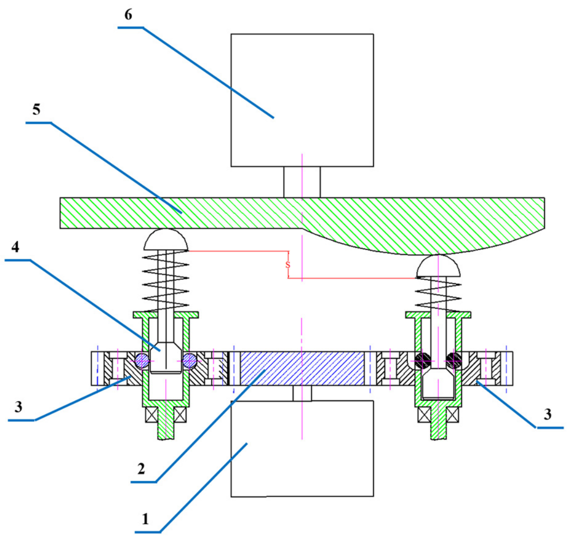

Figure 4. Schematic view of the filament shifting mechanism; 1—Stepper motor; 2—Sun spur gear; 3—Planet spur gear; 4—Pushing rod; 5—Cam disk; 6—Stepper motor.

In order to prevent the balls from being stuck during the operation, as well as to facilitate the assembly, the design must guarantee that most part of each ball remains inside the hole of the housing shaft. So, the thickness of the housing shaft wall must be larger than the ball radius. Moreover, the dimensions of the entire design are calculated to guarantee that the cam profile will push and release the pushing rod with enough amplitude to manipulate the ball appropriately. Based on Figure 5, it is assumed that:

- S is the displacement of the pushing rod
- d_1 and d_2 are the diameters of the two sections of the pushing rod
- l_{21}, l_{22}, l_{23} are section length of the pushing rod
- d_b is the diameter of the ball
- S_2 is the displacement of the ball
- w_1 is the width of the chamber of the spur gear
- h_1 is the height of the chamber of the spur gear
- w_2 is the thickness of the housing shaft wall

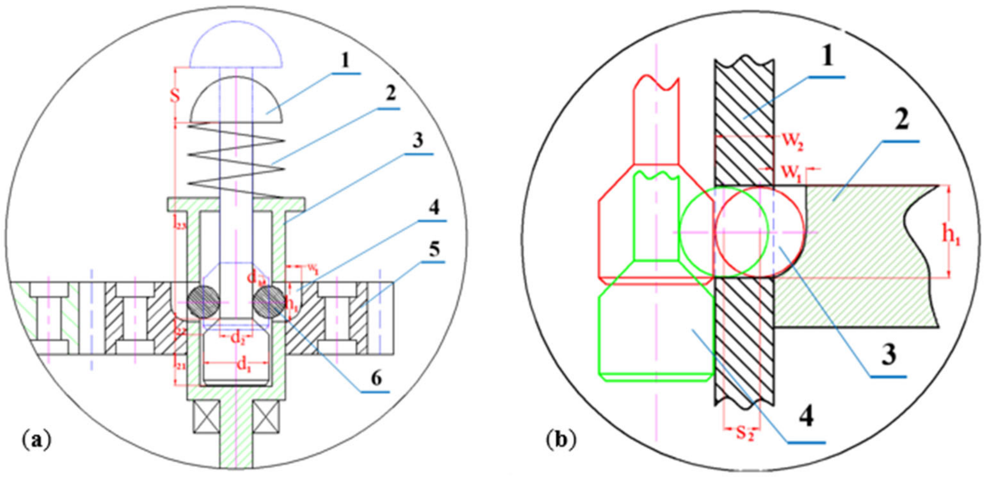

Figure 5. (**a**) Schematic view of the ball shifting mechanism; 1—Pushing rod; 2—Spring; 3—Housing shaft; 4—Ball socket; 5—Planet gear; 6—Ball. (**b**) Schematic view of the ball motion; 1—Housing shaft; 2—Planet gear; 3—Ball; 4—Pushing rod.

The balls used in this design are standardized with a diameter of 4 mm, so the dimensions of all the other components are calculated from this specification. The width and height of the ball socket in the spur gear are given by the Equations (1) and (2) respectively:

$$w_1 = \frac{1}{3} \times d_b \quad (1)$$

$$h_1 = d_b + h_{1s} \quad (2)$$

The thickness of the housing shaft wall is given by:

$$w_2 = \frac{2}{3} \times d_b + w_{2s} \quad (3)$$

where h_{1s} and w_{2s} are safety margin in Equations (2) and (3). The diameter of the pushing rod bottom section is calculated as:

$$d_1 = d_2 + 2 \times d_b - 2 \times w_2 \quad (4)$$

The length of the pushing rod is then calculated:

$$l_{22} = \frac{d_1 - d_2}{2\tan\left(\frac{\pi}{6}\right)} \tag{5}$$

$$l_{21} = 2h_1 - l_{22} \tag{6}$$

The total amplitude of motion that the cam disk must profile must provide is calculated bellow:

$$S = \frac{1}{2}l_{21} + l_{22} \tag{7}$$

As the 3D printer is operating, only one filament at a time must be pushed toward the printing head. According to the filament shifting mechanism design detailed above, it means that only one of the five pushing robs must be released while the other are pressed down by the cam disk. To allow the use of a specific filament, the corresponding pushing rod must be released and lifted up of a distance given by Equation (5). The cam disk profile has been adjusted for this purpose.

4. Development of Prototype and Experimental Results

The prototype of a multicolor 3D printer was manufactured (Figure 6) and then tested in order to evaluate its qualitative and quantitative performances. After a series of minor technical adjustments, several types of experiments were carried out. First, the accuracy of the printing was measured in order to evaluate the prototype. Then, the quality of multicolor printing was visually observed.

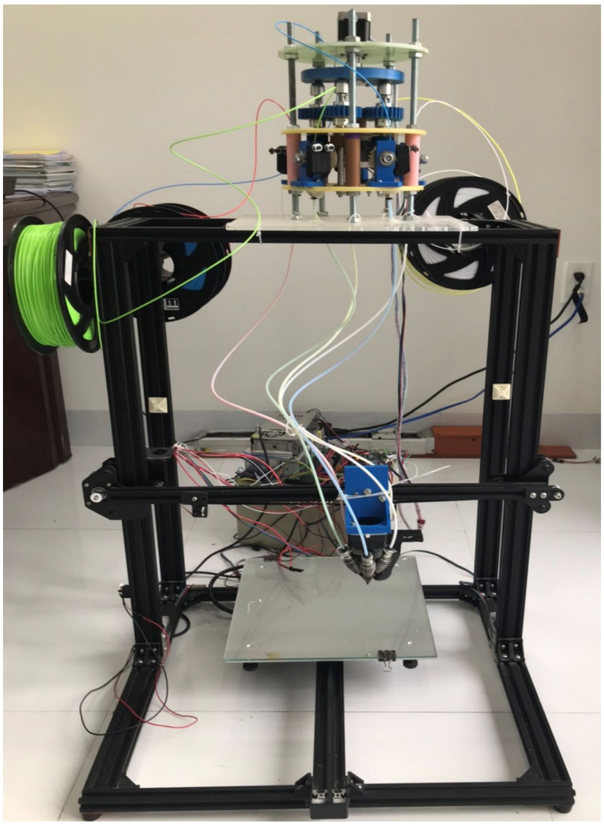

Figure 6. The prototype of the proposed multicolor 3D printer.

The first type of validation experimentation was carried out with the objective of testing the printing accuracy. Mainly, it was necessary to guarantee that the filament feeding transmission system is capable of pushing the filament toward the printing head. Any technical issue at this level would compromise the accuracy of the printing as the geometric section of the filament printed on the platform may be modified in result. A series of objects representing standard geometric patterns were printed out using Ultimaker PLA filament of diameter 1.75 mm with the same printing conditions: layer height, printing temperature, printing speed, and infill density are, respectively, 0.15 mm, 210 °C, 40 mm/s, and 30%. The dimension of these objects was then measured using digital calipers. The testing results on several objects for each geometric pattern are displayed in Table 2.

Table 2. Accuracy of the printing objects.

Geometry	Nature	Reference	Measured Error (%)					Average
Square	Edge	40 mm	0.63	0.70	0.43	0.38	0.15	0.5
			0.70	0.68	0.75	0.28	0.28	
Circular ring	Inner Ø	20 mm	0.28	1.50	0.50	0.83	0.53	0.73
	Outer Ø	40 mm	3.75	3.70	1.50	1.10	3.35	2.68
Triangle	Edge	40 mm	0.30	0.60	0.50	0.35	0.90	0.50
			0.23	0.83	0.43	0.55	0.90	
			0.38	0.60	0.35	0.10	0.63	
Ellipse	Major axis	50 mm	0.18	0.40	0.26	0.30	0.00	0.23
	Minor axis	30 mm	0.53	0.30	0.37	0.33	0.57	0.42

According to these results, it appears that the external dimensions of the printed object present limited errors of 0.84% in general. The printing errors measured from the present 3D printer is often observed in general FFF type machines. It is caused by plastic shrinkage and mechanical component backlashes. In a recent study from 2017, a total of five commercial 3D printers were evaluated in terms of accuracy [31]. When printing several types of regular geometry objects, the measured accuracy of all the devices oscillates between less than 0.5% and more than 2.5%. With a global accuracy of less than 1%, the present multicolor 3D printer prototype is clearly capable of competing with commercialized platforms.

After the validation of the prototype in terms of accuracy, its ability to print out multi-color object was visually evaluated, with the same PLA material and printing conditions in previous tests. Several objects presenting several colors were successfully printed as illustrated in Figure 7. The results show that the 3D printer is capable of printing several colors on the same layer and will, therefore, show no difficulty in generating multicolor 3D objects.

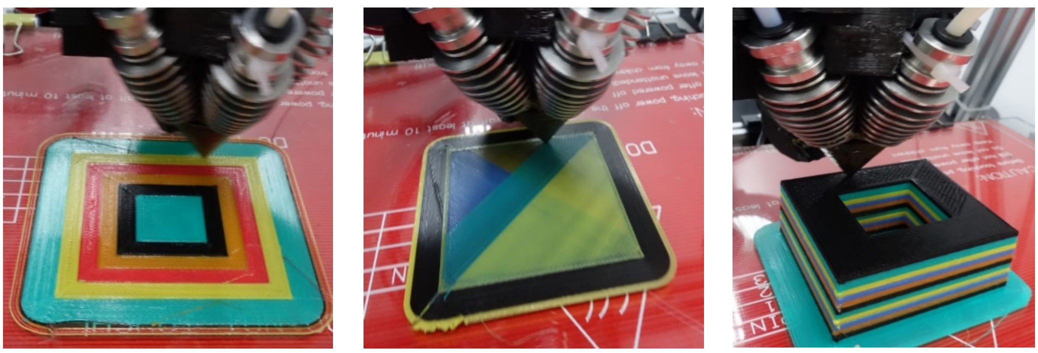

Figure 7. Printing objects with multiple colors.

5. Conclusions

The aim of the present work is to design a new multicolor 3D printer using FFF process that can create complex geometry objects. Most multicolor 3D printers are generally equipped with multiple extruders to drive different color filaments. Each extruder requires an individual stepper motor to push the filament into the hot-end for melting. This study proposes a novel filament shifting device that uses only one stepper motor to drive multiple filaments of different colors. This device can be implemented into most of the single-color 3D printer platform, which is, therefore, augmented into a multicolor 3D printer. The filament shifting device is composed of two main systems: one transmission mechanism that allows pushing the filament toward the printing head; and one shifting mechanism that allows selecting the filament to be pushed. Based on this concept, a prototype of a multicolor 3D printer was manufactured. The five different filaments are guided to a "five-to-one" diamond nozzle. The newly assembled multicolor 3D printer was then subject to a series of testing. The results of these experiments revealed that not only the present prototype is capable of successfully shifting from one filament color to another, but its dimensional accuracy is competing with commercial platforms. In the future, the filament switching mechanism will be optimized in dimension and shared to the 3D-printing community.

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