Automated Filament Inking for Multi-color FFF 3D Printing

Eammon Littler
Dartmouth College
Hanover, New Hampshire, USA
eammon.a.littler.gr@dartmouth.edu

Bo Zhu
Dartmouth College
New Hampshire, USA
bo.zhu@dartmouth.edu

Wojciech Jarosz
Dartmouth College
New Hampshire, USA
wojciech.k.jarosz@dartmouth.edu

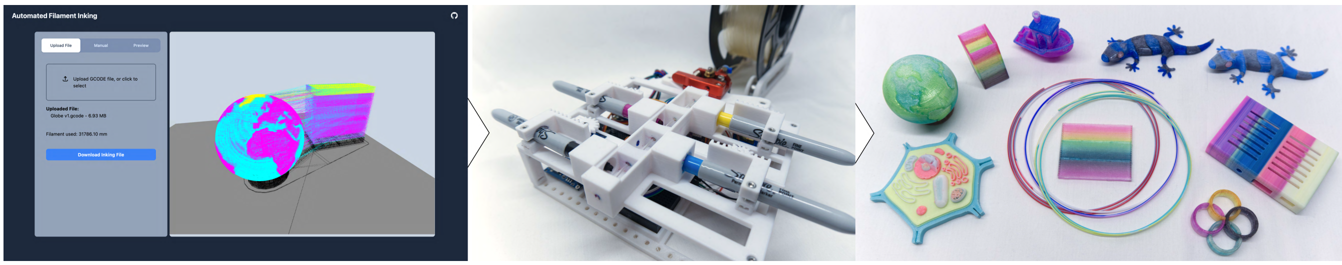

Figure 1: Automated filament inking is a novel system for producing multi-color 3D prints with an FFF printer. Shown is a collection of multi-color 3D prints created using our open-source low-cost inking device and web interface for producing custom filament profiles.

ABSTRACT

We propose a novel system for low-cost multi-color Fused Filament Fabrication (FFF) 3D printing, allowing for the creation of customizable colored filament using a pre-processing approach. We developed an open-source device to automatically ink filament using permanent markers. Our device can be built using 3D printed parts and off-the-shelf electronics. An accompanying web-based interface allows users to view GCODE toolpaths for a multi-color print and quickly generate filament color profiles. Taking a pre-processing approach makes this system compatible with the majority of desktop 3D printers on the market, as the processed filament behaves no differently from conventional filaments. Furthermore, inked filaments can be produced economically, reducing the need for excessive purchasing of material to expand color options. We demonstrate the efficacy of our system by fabricating monochromatic objects, objects with gradient colors, objects with bi-directional properties, as well as multi-color objects with up to four colors in a single print.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**;

KEYWORDS

3D printing, fused filament fabrication, multi-color, customizable filament

UIST '22, October 29-November 2, 2022, Bend, OR, USA

ACM Reference Format:
Eammon Littler, Bo Zhu, and Wojciech Jarosz. 2022. Automated Filament Inking for Multi-color FFF 3D Printing. In *The 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22), October 29-November 2, 2022, Bend, OR, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3526113.3545654

1 INTRODUCTION

The advent of low cost desktop 3D printers has afforded a growing community of makers and designers to fabricate high quality complex objects. Though these machines are capable of fabricating intricate geometries, impossible by conventional manufacturing techniques, they are limited in color options; primarily determined by the plastic filament used. As open-source 3D model repositories become commonplace [8, 23, 46], designers are given a means to share high quality files for anyone to access and 3D print. With the affordability of 3D printers and vibrant community of designers comes a natural desire to expand the color palette of fabricated objects.

Fabricating with color has far-reaching implications from providing visual clarity in representational models for educational use [28] to aiding in the study of historical artifacts [5, 49]. Among these include the use of industrial 3D printers or leverage post-processing as a means to enhance or produce colors in fabricated objects [19, 60]. We find these pose a barrier to entry for users looking to add color as a tool in their design language for being too cost intensive, time intensive, or requiring additional expertise beyond digital design. Our solution enables the use of color in low-cost 3D printers, allowing any user to take advantage of incorporating color into their designs.

As the market for 3D printers matures, the consolidation in their design has become apparent. Using the fused filament fabrication (FFF) approach, these printers lay filament one layer at a time, guided by a single nozzle. This has become the standard of modern 3D printer designs, with popular printers on the market priced in the few hundred dollar range [7]. The affordability of these machines coincides with their explosive popularity, giving rise to the democratization of complex mechanical designs for everyday consumers. In keeping with consumer demand for multi-color 3D printing, many options have appeared such as 3D printers that come equipped with two or more nozzles [10, 57], allowing for as many color options as there are nozzles. This approach, however, comes with many difficulties: the need for precise calibration of the nozzles, oozing plastic from each nozzle that translates to artifacts on the 3D print and reduced build volume, just to name a few. Other approaches include switching between multiple spools of filament and feeding material into a single nozzle [29, 43] to achieve multi-color output. This too comes with the need for calibration and troubleshooting. Advanced techniques for producing multi-color objects include combining inkjet printing with FFF 3D printing [22], binding layers of pre-colored paper [13], or using low-viscosity inks in a multi-nozzle array to switch between colors [51]. These methods require expensive devices or specialized knowledge, becoming generally impractical for the average user.

To create a low-cost multi-color 3D printing approach for FFF 3D printers, we identified a number of requirements we set out to fulfill. We arrived at these by considering typical workflows for 3D printing with FFF printers and expectations surrounding existing multi-color printing solutions. We find that the following are essential when proposing solutions aimed at conventional desktop printer users:

- **R.1 Colors must match expectations.** Failure to match resulting color to expectations would result in time spent troubleshooting rather than designing and fabricating models.
- **R.2 Must not alter geometry or quality of 3D printed objects.** In multi-color 3D printing mechanisms, printing artifacts and printer crashes are a common occurrence. Fabricated parts may pick up oozing plastic from a nozzle or collide with the hotend in a multi-nozzle setup. As a result, a fabricated objects may be unrecoverable or require extensive post-processing.
- **R.3 Require little to no modification of the 3D printer.** With the number of 3D printers increasing year after year, customizing solutions for a unique printer inhibits community adoption.
- **R.4 Must be a low-cost solution using accessible parts.** Cost and accessibility plays a large role in the adoption of a proposed solution.

Achieving the above requirements was our priority in designing our system, however we also strive to meet the following practical considerations to enhance the value of our system. In maintaining usability, simple workflow for users, and integration into existing printer systems, we present the following as concepts we kept in mind when designing our solution.

- **PC.1 Minimize points of failure.** Introducing additional mechanisms can lead to greater potential for failure. Common market solutions use multiple filaments for their mechanisms, increasing potential failure as a multiplier for each filament introduced. Mechanisms can also induce clogging in bowden tubes, grinding of material, failure to load material, and other hardware specific problems. A practical solution is one that reduces hardware failures and designs with user accessibility in mind when troubleshooting.
- **PC.2 Integrate into existing workflows.** Creating plugins or integrating solutions into existing workflows would lower the learning curve for a new system.
- **PC.3 Minimize additional time required to produce a multi-color print.** Multi-color 3D printing is a time intensive process when compared to monochromatic printing, since any change between colors equates to incurred time. Any substantial increases in time for a multi-color approach will minimize overall printing benefits gained by users.
- **PC.4 Minimal calibration.** Similar to PC.1, multi-color solutions can lead to greater failures, requiring the precise calibration of a 3D printer for a successful print. Existing solutions may have users align nozzle heights, adjust filament feed rates, adjust material temperatures, or tune purge towers to combat color bleeding. Solutions should aim to provide a user experience that minimizes or simplifies required calibration processes to place the focus of a user on fabrication.
- **PC.5 Compatibility with off-the-shelf filament.** For a multi-color solution to be economically feasible for the average user, a multi-color solution should consider compatibility with market options.

With the above requirements and practical considerations in mind, we present a novel approach for multi-color 3D printing using an open-source device for programmatically inking filament prior to 3D printing. The concept of using permanent markers as a way to color filament is a well known technique in the maker community [2, 35]. Inking filament is a simple approach to achieving colors that may not be readily available for a user, often requiring the purchase of a separate roll of filament entirely. In this way, users can quickly switch between desired colors in an economical fashion when fabricating models. We expand on this by automating the process of coloring filament as a pre-processing step separate from 3D printing. Our device is capable of holding up to four colored permanent markers, in the CMYK color scheme, that can be mixed to create a wide spectrum of color output.

We begin (Sec. 2) by discussing relevant research and market solutions for multi-color printing. Due to the many approaches taken in solving this problem, it helps to understand the benefits and limitations of similar systems since a catchall solution does not currently exist. Following this, we present (Sec. 3) our solution for closing this gap for accessible multi-color 3D printing while respecting the requirements and practical considerations outlined above. We demonstrate our results (Sec. 4) by printing objects with gradient colors, objects with bi-directional properties, and multi-color objects with distinct color separation using our low-cost inking device. We achieve this in a user-friendly workflow made possible with our web interface, allowing users to quickly view the multi-color object to be fabricated and download the inking file to be processed by our device.

2 RELATED WORK

Printing in multiple colors has been a long-standing need in additive manufacturing, leading to a variety of approaches ranging from low-cost devices to industrial solutions, and hardware modifications to programmatic manipulations of GCODE.

Filament Options for FFF 3D Printing. With access to FFF printers comes a new generation of designers fabricating with the technology. The demand for greater color options manifests in the offerings of filament on the market. Consumers can now afford filaments in a range of colors readily available on e-commerce websites [6, 14, 40]. Such filaments can be matte, translucent, reflective [20], fluorescent [30], and changing gradients [39]. Custom gradient filament can be produced with on-hand filament as explored by an Instructables user DasMia [9]. More advanced manufacturing techniques make use of co-extrusion to create filaments with directional properties [31]. This effect is possible due to the nature of laminar flow, the parallel flow and lack of mixing, involved with the extrusion of viscous material. Filament with directional properties provide users with greater creative opportunities.

No-cost Solutions for Multi-Color 3D Printing. Though color options are plentiful, most consumer grade filaments are monochromatic. Techniques have been developed allowing users to switch between colors during a print, using tools such as ColorPrint from Prusa Research [44]. This tool adds a custom line of GCODE indicating when the user needs to switch between colors. The printer automatically pauses during a print allowing users to change filament to their desired color. A similar technique uses manual filament switching to print multiple colors onto a single layer [33]. 3D models are segmented into multiple parts, aligned in a slicer software, and printed in sections to produce this result. Expanding on this concept, folding is introduced to create three dimensional multi-color objects [34]. Takahashi et al. [54] proposed Programmable Filament, achieving complex multi-color fabrication by programmatically 3D printing filament segments that are spliced together to create a continuous strand of material. The involvement of direct user interaction violates PC.3, making the above solutions impractical for larger scale or high color-detail objects.

Device Based Solutions for Multi-Color 3D Printing. 3D Print Colorizer [48] is a inking-based, low-cost process where layers are colored using permanent markers guided by the extruder head of a desktop 3D printer. Automatic color switching attachments have gained popularity as a multi-color printing solution. Common approaches include using multiple extruders, one for each color filament, to push filament into a hotend [26, 45]. A two stepper motor approach using a barrel system to engage the selected material is a cost-effective approach to expanding color options up to seven in a single print [1, 43]. A downside to this is the potential for filament jams when reloading previously unloaded filament. In general, seamless filament is desirable when 3D printing. Jubilee [58] is an open source multi tool head 3D printer capable of switching between hotends with pre-loaded filament during fabrication. One market solution splices filament together into a contiguous strand as a 3D printer prints an object [29]. Aside from switching filaments, researchers have explored variable extrusion and filament mixing to vary color output. Song et al. [52] proposed a technique using a hotend with multiple inlets and variable extrusion to mix between three and five filaments to produce multi-color prints. The technique leverages dithering and occlusion of extruded material to expose the desired color to create a controlled gradient. Similar color mixing approaches have been seen in the form of market solutions and DIY projects, combining cyan, magenta, yellow, black, and sometimes white (CMYK or CMYKW) filaments in a custom hotend [21, 27].

GCODE Modification Techniques. 3D hatching [25] modifies GCODE toolpaths to achieve high resolution grayscale appearances on dual extruder printers. Reiner et al. [42] proposed a method for interleaving two colors in a dual extruder printer for controlling the tone of a print. DefeXtiles [16] varies the tone of a print in a single extruder printer by leveraging underextrusion. Clean Color [18] is a technique for optimizing the motion paths of a multi-color print to remove artifacts present when switching between nozzles in a dual-extruder printer.

Advanced Techniques in Multi-Color Fabrication. Post-processing of extruded material or fabricated objects has been another approach for producing multi-color results. The da Vinci Color printer [22] utilizes inkjet printing to color individual layers during a 3D print. ColorMod applies photochromic inks to an object, which is programmatically activated with a UV light source [41]. PhotoChromeleon expands on the previous technique by mixing CMY inks to create higher resolution results [24]. Computational hydrographic printing calculates the deformation of a 3D model required to accurately transfer color inks to an object [60]. Skylar-Scott et al. [51] proposed a 3D printer utilizing low-viscosity inks that can rapidly switch in a single nozzle to produce multi-material voxelated objects. Advanced techniques have been developed for resin-based 3D printers to reproduce high quality full color 3D prints [11, 50, 59]. While producing high quality results, specialized hardware and materials places these options outside the realm of possibility for most conventional FFF 3D printer owners.

3 AUTOMATED FILAMENT INKING

The goal of our system is to expand color option availability for low-cost desktop 3D printer users, makers and artists. We accomplish this by adding color directly to the length of the filament used for a print prior to printing. Our process is composed of the five steps illustrated in Fig. 2: calibration of the 3D printer, modification of the 3D print profile in a slicer software, generating an inking file, inking filament with the device, and 3D printing.

3.1 Coloring The Filament

In order to automate the process of inking filament, we developed an open-source low-cost device that can be made with off-the-shelf parts. Unlike most multi-color systems, we decided on a standalone device to process filament prior to a print. We made this decision facing several issues with developing a system that runs during a 3D print [A.1]. A standalone device benefits from not interfering with a 3D printer should issues arise, meeting our R.1 criteria and PC.1. As per PC.2, we introduce steps III and IV 2 as flexible steps in the typical workflow of 3D printing. Users have the option to disregard adding color to their prints.

3.1.1 The Device. In Fig. 3 we show our inking device, which holds up to four permanent markers, actuated by servo motors using 3D printed rack and pinions. We space the permanent markers

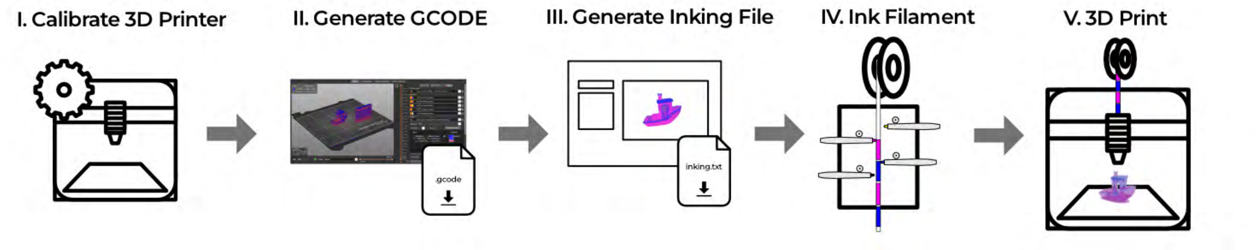

Figure 2: The workflow of our five step process for multi-color 3D printing. The steps include calibration of the printer, generating GCODE for the 3D printer, generating the inking.txt file for the inking device, inking filament with the device, and 3D printing with the filament and the GCODE file.

three centimeters apart and place spacers between to help level and guide the filament while being inked. We make use of a Creality 3D printer extruder to load the filament, selected for its low cost and ease of calibration discussed in Sec. 3.1.2. We designed our device to be easy to print and assemble using common tools accessible to makers. Most of the parts are flat with little to no overhang and

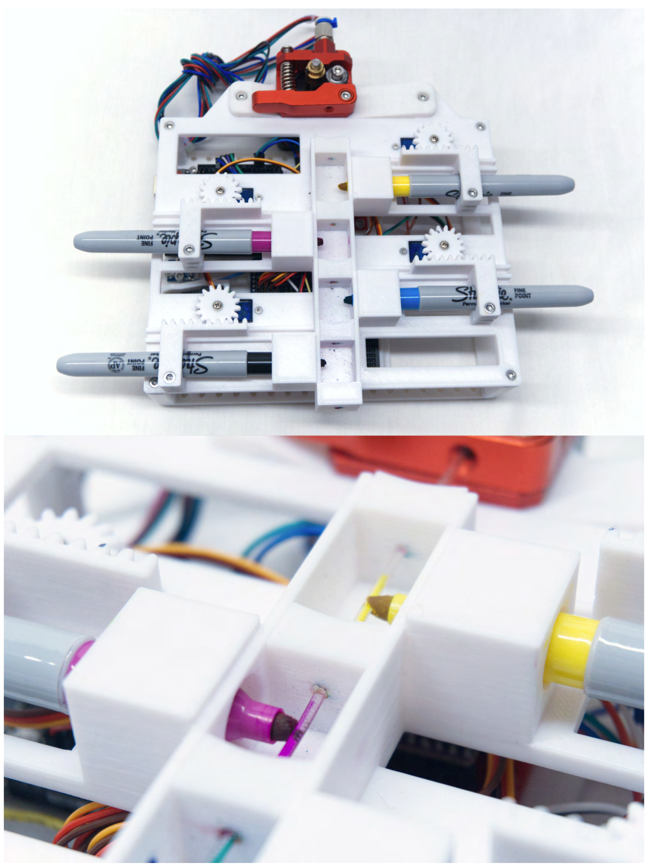

Figure 3: Our inking device loaded with cyan, magenta, yellow, and black permanent markers, inking translucent PLA filament.

can be printed in a total of two prints. We chose an open design to easily diagnose issues that may arise during inking.

Below the rack and pinions are the electronics of the device. This includes an Arduino, micro SD card reader, PCA9685 servo motor controller, stepper motor shield, DRV8825 stepper driver module, Nema-17 stepper motor, micro servo motors, 12v female power adapter, and micro USB breakout board. The all-in cost for the device is under $100 and roughly $50 to build a single unit when adjusting for bulk quantity pricing of electronic parts, excluding M2 and M3 screws, micro SD card, and 3D printed parts. This fulfills our requirement R.4 in building a low-cost device. While some soldering is required for parts that do not have header pins, most components can be connected using breadboard jumper wires. A 12 volt power supply is necessary to run the stepper motor and a 5 volt power supply powers the servo motors. A separate USB B cable powers the Arduino. Color is achieved using off the shelf markers. In particular, we use cyan, magenta, yellow, and black markers with our device. A "U" shape cut is made on the felt tip to increase ink flow and filament coverage. The coverage of ink on the permanent marker is roughly half of the surface of the filament. The inked filament can be inserted into the 3D printer upon completion, however the ink is prone to rubbing off. We recommend allowing 5-10 min for the marker to dry prior to handling. If handled gently, we find the time taken to print with inked filament is ample time for the marker to dry.

3.1.2 Arduino Code. The Arduino Uno is a low-cost low-power microcontroller, which requires the efficient use of memory when calculating color ranges read from the micro SD card. For each color being applied in a given color range, we must determine which servo motor to engage and which ones to disengage. Our reference for the position of the filament is the current position readout from the stepper motor. Due to the three centimeter spacing between the permanent marker slots, there are situations in which multiple markers must be engaged simultaneously. Fig. 4 illustrates how the offset issue requires a dynamic checking approach to engaging and disengaging servo motors. For example, if the inking file specifies coloring 100 mm of material alternating between cyan and magenta for 600 mm with an offset distance of 130 mm for cyan and 100 mm for magenta, the true coloring ranges for the servo motors is as follows; Cyan [130–230, 330–430, 530–630] and Magenta [200–300, 400–500]. With the Arduino reading in each line from the micro SD card in the format "E0 C1 M0 Y0 K0", the offsets must be calculated as each line is read in. We use a queue for each color that sets the "active" color range for each servo motor. As the position of the stepper motor meets the bounds of the color range, the next set of color ranges are dequeued from their respective queue and values are enqueued as they are read in from the micro SD card. This allows for many color changes and even color mixing in a relatively short span of filament. Algorithm 1 shows the complete algorithm for this process.

Algorithm 1 Queuing Color Ranges from Inking File

```
for Line in inking.txt file do
    Get extruder target position and color strength values
    for each color in line do
        if strength of color > 0 then
            Enqueue color range: [previous target, current target]
        end if
        if motor disengaged and extruder pos. > color range end then
            Dequeue color range from queue
        end if
    end for
    while Extruder target not met do
        for each color do
            if extruder position is within current color range then
                Engage motor
            end if
        end for
    end while
end for
```

Before inking, we must calibrate the E-steps, the number of pulses for a stepper motor to extrude one millimeter of filament, for the coloring device to ensure the accuracy of the amount of filament extruded. Prior to calibration, the stepper motor driver must be set to a microstepping resolution of 1/32. This can be done by setting the M0, M1, and M2 pins to high or by turning on the switches present on the stepper driver breakout board. This vastly increases the accuracy of the filament extruded from the device and is a necessary step in accurately inking filament. As a baseline, we know that Creality 3D printers use 1/16 microsteps for their motors, with an E-step value of 95. This means that our stepper motor running at 1/32 microsteps is likely to have an E-step value of 190. This can be tested with the Arduino library AccelStepper[1] and extruding 100 mm of material as described in Sec. 3.5. The same process and calculations can be performed to calculate the proper E-steps.

3.2 Inking Overview

3D printing can be conceptualized as a process for translating one dimensional material into a three dimensional object. We can simplify the problem in this way since standard filament rolls come in diameters of 1.75 mm or 2.85 mm with high tolerances. As such, filament usage estimates are often given in the form of meters of material used upon generating GCODE. If a 3D printed multi-color object uses a total of M meters of filament, changes in color for the model can be represented as a range of colors in this single strand of material. For example, suppose a 3D print consisting of

[1] AccelStepper Arduino Library

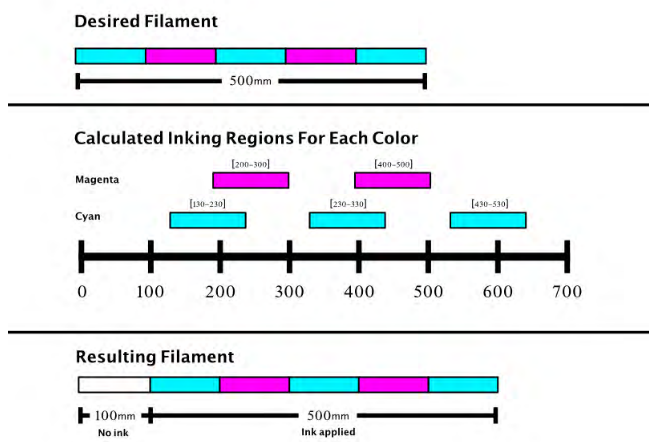

Figure 4: Permanent markers on our inking device are spaced 30 mm apart, changing the regions in which each servo motor is engaged for coloring filament. An initial region of filament is left uncolored to compensate for the distance from the extruder to the last permanent marker.

two colors, cyan and magenta, uses a total of 3 meters of filament (Fig. 5). Since a 3D printer lays material down one layer at a time, the color in our 3 meter filament must alternate when printing the object. This may take the form of 10 cm of cyan followed by 10 cm of magenta repeating for the full length of the filament. The translation of instructing how a 3D printer fabricates an object is handled by a 3D printer slicer software, PrusaSlicer [47] in our case, generating GCODE to be read by a 3D printer. Most modern slicer software can generate GCODE files for multi-color printing.

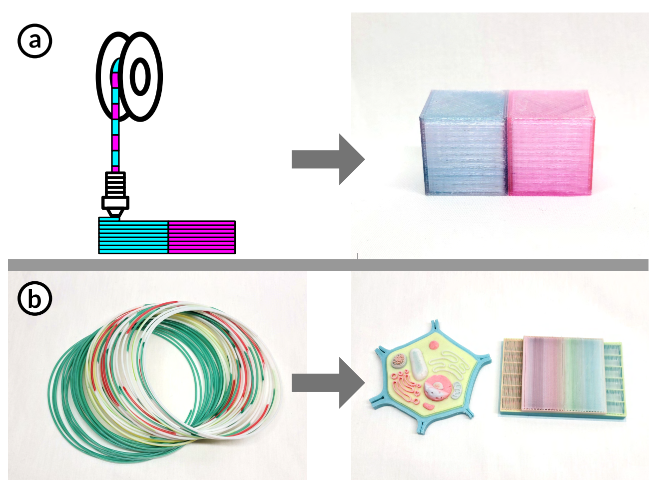

Figure 5: Illustrations of inked filament becoming a 3D object. (a) Alternating regions of inked filament results in the conjoined cyan and magenta cubes. (b) Complex multi-color objects require varying regions of inked filament.

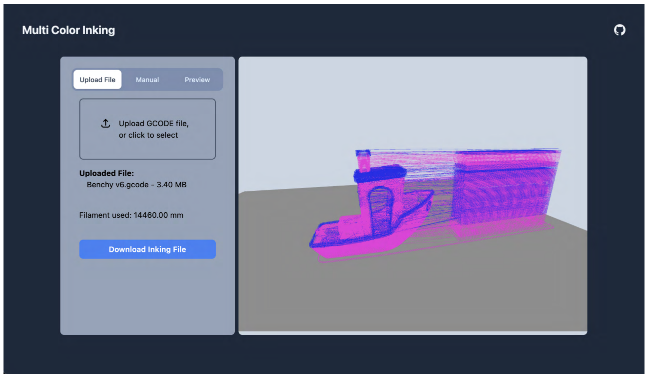

Figure 6: A screenshot our web interface with built in custom GCODE viewer for visualizing the outcome of a multi-color print.

Normally, a tool change command (`T0–T6`)[2] determines when a 3D printer changes between filament and subsequently color. It should be noted that color changes during a print are not instantaneous and requires the previous color to be purged before moving on to the next, ensuring colors are not mixed; an issue we detail in Sec. 4.3. Purging of material in a color change process is typically done in a tower that rests beside the primary print called the purge tower. Tool change commands are generated automatically by supported profiles in PrusaSlicer when importing multi-part 3D models. By reading the total amount of filament used prior to a tool change command, we can determine the ranges in which color needs to be applied. This can result in tens or hundreds of tool changes for palm sized objects and hundreds or even thousands for larger scale models.

3.3 Generating an Inking File

We have developed a web-based interface for generating inking files. Fig. 6 shows a sample of the UI. Running completely client side, a user can upload a GCODE file to the web interface and download an inking file. There are three tabs for our web interface; upload file, manual, and preview. The Upload File tab accepts any GCODE file, allowing users to view the toolpath of the extruder in a 3D environment and visualize the colors that will be present in the final print. Our viewer is capable of displaying up to five colors, with the fifth color representing the base filament being used. We use a React based framework alongside the Three.js library to quickly and efficiently generate the 3D environment. Different GCODE files can be uploaded successively to generate new toolpath views. The entirety of the toolpath is displayed in the 3D environment, including both the primary 3D model, the Benchy boat, and a purge tower seen to the right of the boat. Upon loading a GCODE file into the file upload region, the web interface generates an `inking.txt` file which can be downloaded immediately and loaded onto a micro SD card to be read by the inking device. In addition, the web tool reads the GCODE file to display the amount of material that will be used in the 3D print. The Manual tab allows users to create custom filament profiles for a specified length of filament. Custom filaments that can be created include monochrome and gradient filaments for up to four colors in one strand. Similarly, an `inking.txt` file will be generated for the user to download. The Preview tab displays the lines of inking file code that is generated. Users can edit the inking file directly for greater control over filament customization beyond the tools we offer.

As described in Sec. 3.2, the color of a multi-color print can be represented by a range of values along a single strand of filament. After generating a multi-color GCODE file, we determine the regions of the filament that needs to be colored by identifying all tool change commands (`T0–T3`) in the GCODE file. The length of filament to be colored can be calculated as the sum of the preceding extrusion commands. All extrusions can be identified by the `G1` command followed by the use of an `E` parameter (e.g. `G1 X20 Y20 Z10 E0.2`). We now have a list of material extruded leading up to each tool change. Our inking file is a human readable format similar in structure to GCODE. Each line indicates the amount of filament extruded and the color to be applied. For example, `E10 C0 M1 Y0 K0` would indicate to our device that at 10 mm of filament, begin inking with magenta. The inking continues until a subsequent line deactivates the previous color. Colors can be activated simultaneously as well. This is all compiled into a single `inking.txt` file to be read by our inking device.

3.4 Inking Filament and 3D Printing

To begin inking, we load the filament through the extruder of the device pictured in Fig. 3. This helps prevent the marker accidentally obstructing the path of the filament should the marker be prematurely engaged. With the inking file loaded on the micro SD card, the Arduino will automatically begin inking the filament. With the stepper motors set to move at a speed of 4000 steps per second, translating to 21.05 mm of filament extruded every second given an E-step of 190, the process can take over ten minutes to ink a palm sized print such as the Benchy boat[3]. This however, is significantly faster than inking during a print, keeping the exposure of the permanent marker to a minimum, preventing the tip from drying out. Once the filament is inked, the filament can be cut flush against the end of the device.

It is important to note that the amount of material that is loaded into a 3D printer during a filament change differs for each 3D printer. In the case of the Prusa i3 MK3S, 31.5 mm of filament is purged upon loading filament. This offset must be adjusted in the Arduino inking file in order to properly align the filament before printing. A mark will be made to indicate where the filament should be cut prior to loading. The 3D print can now be started by selecting the proper GCODE file.

3.5 3D Printer Calibration

Calibration of the 3D printer is key to ensuring the success of a multi-color print. We explain the steps taken to ensure printer accuracy to be compatible with our inking system. This calibration process only has to be done once for every routine maintenance a 3D printer goes through. 3D printer stepper motors are an open loop system, where its position is calculated based on the command given, rather than a true reading using a sensor. As an example, a

[2]Marlin Toolchange Command – https://marlinfw.org/docs/gcode/T001-T002.html

[3]Benchy Benchmark Boart

3D printer may be given the command `G1 F200 E100`, extruding 100 mm of filament at a rate of 200 mm/minute. If the user neglects to heat the nozzle, the filament will not extrude, causing the stepper motor to skip steps and remain in its original position. Internally, the 3D printer will assume the extruder's position is at 100 instead of the true value of 0. Temperature, extrusion speeds, and material all factor into the true extrusion of filament. Modern 3D printers come equipped with high accuracy stepper motors that mitigate the open loop issue, and any extrusion missteps causing only minor surface artifacts. This slight difference however, causes colors to drift over time for a multi-color print. Therefore, it is paramount to calibrate a 3D printer prior to printing with inked filament in the following order.

We tune three values for calibrating a 3D printer, specifically the Prusa i3 MK3S; the 3D printer flow rate, E-steps, and extrusion multiplier. The first value, though simple, is worth noting since different printers approach setting the flow rate in different ways. The flow rate, set by `M221`, is a percentage applied to the extruder when extruding material, known as the feedrate. A `M221 S95` command would set the feed rate to 95 percent of any command given to the extruder. PrusaSlicer sets the default flow rate to 95 percent rather than 100 percent. To simplify subsequent calibration steps, we set this value to 100 percent under the "Start G-code" section in "Printer Settings".

Next, we calibrate the E-steps for the printer. Under a Marlin-based[4] 3D printer firmware, E-steps are calculated as the number of stepper motor steps taken to move one millimeter of material. We follow the steps per millimeter calibration process laid out by Grames [17] to arrive at our proper E-steps. Finally, we calibrate the extrusion multiplier value. While the extrusion multiplier influences the same property as the flow rate, the former can be set specific to a filament profile, providing more flexibility when calibrating new filaments. We follow the calibration guide laid out by Engineering [12] to arrive at an extrusion multiplier for our filament. With the above changes made, it is best to save these values under a new filament profile.

We further modified Prusa's MMU2 profile to be compatible with our filament inking system. In particular, the tool change parameters have been modified to prevent unloading of filament during a tool change since an MMU2 system would completely change the filament being used. Our configuration file (`ini`) can be imported to PrusaSlicer and used without further modification.

4 RESULTS

In fabricating multi-color objects with our system, we primarily use a Prusa i3 MK3S in our tests. PrusaSlicer is used as the GCODE slicer for testing since it has native support for multi-color 3D printing. We have modified the Multi Material Upgrade 2 (MMU2) profiles to support our system, with changes made in "Printer Settings" and "Filament Settings". For materials, we use a 1.75 mm diameter roll of PLA as it is the most common material used in FFF printing.

4.1 Color Reproduction

As a simple test for displaying color reproduction (Fig. 7), we have printed rectangular prisms with dimensions of 25 x 25 x 50 mm

Figure 7: A comparison of color reproduction using 13 different colored permanent markers on 3D printed objects. (a) and (b) show the color results of ink applied to filament prior to 3D printing. (c) shows the color results of ink applied after 3D printing. Filaments used: (a) opaque white PLA, (b) translucent PLA, and (c) opaque white PLA.

using the spiral vase mode setting in PrusaSlicer. Spiral vase mode is useful for examining color visibility of ink applied to filament with a single wall thickness. It is also a quick and efficient mode to print in, with no time wasted in travel motions present in typical 3D prints. We make use of a 12 pack of Sharpie brand permanent markers with the addition of magenta to color the filament using our device prior to printing. These colors include brown, purple, berry, magenta, red, orange, yellow, lime, green, turquoise, aqua, blue, and black. This is in no way a comprehensive list, with color options ranging beyond the variety listed. The colors were applied to both translucent and opaque white PLA to varying degrees of color reproduction. We can see vibrant colors present in the set of translucent PLA prints as opposed to the opaque white PLA prints that are more akin to pastels. In our device, ink is applied to less than half of the surface of the filament for any given color range. 3D printers exhibit laminar flow when extruding material, where the directionality of the filament is maintained. This means if filament is inked on the front half and extruded, then the color will be most present on the front facing portions of the print. In this way, colors can be hidden behind layers of material resulting in less vibrant prints in opaque filaments. In translucent PLA, the color visibly permeates through the material and produces more vibrant results.

We can take advantage of this directionality to produce filaments with properties that mimic coextruded filaments [31]. More complex than traditional filament production, coextruded filaments require joining two separately colored filaments into a unified strand.

[4]Marlin Firmware – https://marlinfw.org/

Printing with this filament produces fabricated objects that exhibit directional properties, such that the apparent color of the object changes based on the viewing angle. Reducing both material cost and complexity in manufacturing, our automated inking approach provides customizability for producing coextruded filament-like results.

It is important to point out the inconsistent color layers in the opaque white PLA prints. Though the color is applied in a controlled manner, we see regions of strong and weak color. Since the pressure applied by the permanent marker tip is binary in this process, the flow of the ink from the felt tip cannot be accurately controlled, causing striations in our results. Another factor responsible for the striations is the shape of the permanent marker. Since a permanent marker tip comes shaped into a conical point, the tip tends to slide above or below the filament when actuated on the device. In testing two cuts, flat and v-shaped, we use flush cutters to cut the felt. While the flat felt tip produced more consistent results, the ink coverage is less than half of the surface of the filament, producing faded colors. The v-shaped tip on the other hand dispenses more ink with a coverage of roughly 50 percent and produces vibrant results. The drawback to this shape is the difficulty of controlling the ink flow, leading to greater color strength inconsistencies.

In examining the 13 colored prints in Fig. 7 and comparing them to their respective ink colors on paper, we notice a stark difference for a selection of colors. In particular, the red and green markers produce 3D prints with colors resembling orange and teal. This holds true in the case of both translucent and opaque filaments. This may be due to the coloring agents used undergoing a chemical change upon exposure to high temperatures, as the apparent color is markedly different when applied directly to plastic (Fig. 7 (c)). Another contributing factor may be the reduced concentration of the ink when extruded during a print. The intermittent bands produced on several of the colors cannot be adequately explained in the same way. Due to the differing properties of the color agents, it is possible that certain colors stain plastics better than others. A lack of adherence to the filament surface may result in accumulation of the ink in the nozzle, not adequately purged in a consistent manner.

4.2 Multi-Color Objects

We validate our inking system by 3D printing a number of multi-color objects as seen in Fig. 8. Our results show that distinct color 3D printing, in which color gradients are not present, is possible using our system. We are capable of producing up to four distinct colors in a single 3D print using our inking device. The base filament can be specified as a fifth color in PrusaSlicer. Multi-color prints with our system make use of purge towers comparable to filament swapping solutions.

3D printing multi-color objects requires a precisely calibrated 3D printer. Without proper alignment of the filament upon starting a 3D print, the colors can begin to shift. This results in fabricated objects with mixed colors or inverted colors as seen in Fig. 9. Multi-color 3D print files come in the form of multiple 3D model files. When imported together in a slicer software that supports multi-color printing, a dialog box prompts the user to have the software automatically align the models. An option appears allowing users

Figure 8: Samples of multi-color objects printed using our inking device. (a) Two-color print of a Benchy boat.(b) Four-color print of overlapping rings. (c) Three-color lizard printed in opaque white PLA (left) and translucent PLA (right).

Figure 9: Examples of color shifting when filament is not properly lined up with the GCODE executed by the 3D printer. Globe and tree frog prints retain distinct colors though shifted throughout the print.

to select different extruders for different 3D models. This changes the color applied to each 3D model.

4.3 Gradients

It is common in multi-color printing to focus on the separation of distinct colors in a print. This however requires a mechanism for purging material during a color transition. The same is true for our system. Purging material is necessary as colors tend to accumulate in a nozzle. One way to visualize this is noting that a 1.75 mm or 2.85 mm diameter filament of plastic is extruded through a nozzle with a diameter of 0.4 mm. Using the volumetric calculation of a cylinder, 1.75 mm diameter filament with a length of 1 cm would amount to 24.05 mm^3 of material. A cylinder extruded from the tip of a 0.4 mm nozzle would therefore have a theoretical length of 191.4 mm; a 19 fold increase in length. In reality, the extruded material will have a wider diameter and can be controlled via software. In our settings, we use a value of 0.48 mm, resulting in a roughly 13 fold increase in length from the input material. This explanation is meant only to highlight the difficulty of switching between colors in a binary fashion. There are other factors to consider when changing colors such as the tone. As noted in Programmable Filament [54], switching from dark to light tones takes much longer to purge than light to dark tones. This can be the result of the visual persistence of darker tones when diluted by white material.

Figure 10: Sample of spiral vase mode prints using translucent PLA colored with black, cyan, yellow, and magenta inks with increasing perimeter counts. The number of perimeters in a print affects the strength of the perceived color. From left to right: single perimeter, two perimeters and three perimeters with no ink overlap, and three perimeters with 200 mm of ink region overlap between colors.

While producing distinct colors is desirable in a multi-color print, gradient filaments [39] have become a popular choice among makers looking to add more color variety to their 3D prints. Using our inking device, it becomes possible to produce custom gradient filaments. This can simply be done by taking the total filament to be used in a 3D print and alternating between the desired colors. The color bleeding that occurs naturally in the inked filament can result in an interpolation effect between each color as they transition in a print. We explore the creation of gradient filaments using CMYK colors as seen in Fig. 10. The perceived color correlates strongly to the number of layers present in a 3D print. Each of these rectangular prisms has been printed in spiral vase mode; a mode in which the 3D printer continuously extrudes material throughout a print while gradually increasing in z height rather than pausing between individual layers. This continuous extrusion mode allows us to better visualize when the transition between color takes place, since the path that the nozzle takes while printing becomes clear. The first three vases are printed with one, two, and three perimeters, with no overlap in the inked region of the filament between the black, cyan, yellow, and magenta colors. The vase on the right hand side is printed with three perimeters and have an overlapping inked region between each color change of 200 mm. The cyan and yellow permanent markers lie on the same side of the device, in which the cyan marker picked up the ink from the yellow marker. Subsequent testing with the cyan marker resulted in green ink, requiring purging of the residual yellow ink before returning to the expected color.

4.4 Color Mixing

We have begun exploring the potential of mixing colors. With the availability of near CMYK colors of Sharpie brand markers (aqua, magenta, yellow, and black), we are capable of producing

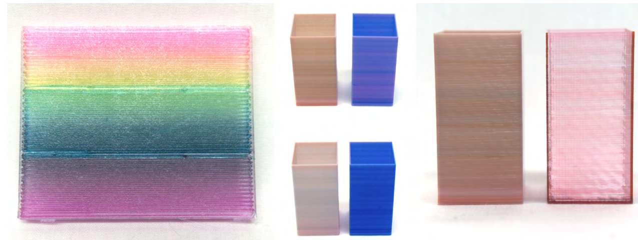

Figure 11: Color mixing samples producing varying effects; rainbow gradients made using CMYK color mixing (left), directionally dependent prints where certain colors appear stronger from different angles (middle), and mixing differences between opaque and translucent materials (right).

a wider spectrum beyond the four distinct colors capable with our device as seen in the left image on Fig. 11. Though capable of producing more than four colors in a single print, this technique faces difficulties in maintaining constant color in the permanent marker. For example, if green is the desired color, cyan and yellow would have to be mixed. Were these two markers to rest on the same side of the device, the ink from one marker would be picked up by the other, causing contamination. Without proper purging or clearing of the contaminated marker, it would continue to ink with mixed color. One approach to mitigating this issue is to place lighter tone markers closer to the extruder than the darker tone ones.

Using markers on opposing sides of the inking device allows for creating filament with properties similar to coextruded filaments (Fig. 11 (middle)). This effect is most evident in the opaque white filament, with partial blending of color depending on the tone of the marker used. When inking translucent filament in the same way, a blending of the colors can be observed. As seen in the right image on Fig. 11, inking red and green colors on opposite sides of opaque filament results in a dull reddish brown color. Using translucent filament creates a color resembling burgundy. Due to a lack of white pigment to dilute the color, the translucent material allows ink colors to blend more naturally.

5 DISCUSSION, LIMITATIONS, AND FUTURE WORK

5.1 Compatibility

Since our approach involves the modification of a continuous strand of filament, our process can be reproduced for other 3D printers, given the same calibration steps are taken. The device can be operated separately from a 3D printer, allowing for rapid production of customized filament. There is no limitation to the length of filament that can be colored, as long as the strand is continuous. In this way, filaments can be colored for any number of 3D printers and does not have to be tied to one machine as in traditional multi-color approaches. In order to print distinctly colored multi-color objects, a 3D printer profile will have to be created with the adjusted values for extrusion width, extrusion multiplier, and additional print settings. PrusaSlicer is an open source software with many common 3D printers being natively supported. Creating custom profiles

Table 1: Fabrication times for inking filament and total 3D print time taken for each object.

Name	Inking Time	Print Time	Material Used
Benchy Boat [56]	6m 8s	2h 8m 37s	7.74m
Overlapping Rings	3m 9s	1h 27m 59s	3.98m
Lizards [55]	4m 42s	1h 34m 52s	5.93m
Plant Cell Model [37]	7m 1s	3h 45m 41s	8.86m
Globe [36]	12m 4s	4h 23m 39s	15.24m
Tree Frog [38]	7m 1s	4h 56m 53s	9.08m

should be well within the capability of 3D printer owners. Should this technique be extended to other slicer software, users must note that color changes are identified by the T0-T6 commands. Any Marlin based 3D printers would be compatible with the web interface for generating inking files. Klipper firmware 3D printers have not been tested.

PLA was the primary material used in developing this system, chosen for its affordability and ease of use with FFF printers. We tested our solution with off-the-shelf white and translucent filaments priced under $25 in compliance with PC.5. We plan to continue testing with other rigid plastics such as PETG and ASA to better determine material compatibility with our approach. It has yet to be seen how different materials would react to inking. It may be possible for permanent marker inks to better stain certain plastics, producing more consistent color results. Since the coloring process requires the inked filament to maintain its shape, our device is likely not compatible with flexible materials. As the market availability for niche materials is smaller, the price of each spool tends to be higher than their PLA counterparts. This can be a use case for users wanting to customize niche materials that have reduced color varieties. Further testing with ink varieties such as metallic and fluorescent markers have the potential to further expand the visual properties of fabricated objects.

5.2 Total Fabrication Time

As mentioned previously, our inking device is capable of coloring filament at a rate of 21.05 mm/s. The time taken to color filament will vary depending on the material used in an object. Table 1 shows the inking times and print times for the fabricated objects we have displayed. It should be noted that the number of colors used during inking does not affect the total time taken to ink filament. Due to the relatively short time taken for inking, the permanent markers do not dry out while exposed to air for the duration of the inking process. The addition of a cover placed above the inking region prevents the marker from drying for a number of hours in our tests.

5.3 Advantages Over Existing Systems

Our inking system improves greatly on PC.1 over existing solutions, removing the possibility for printing failure during a multi-color print entirely. Since there are no filament changes or differences materials used, no troubleshooting is required beyond what a typical single extruder 3D printer requires. At worst, we observe filament color shifting as seen in (Fig. 9), but this approach will always result in a complete 3D print. Using our web tool and producing inked filament, users will always know how much filament is required for a multi-color print, removing the concern for exhausting material during fabrication.

Table 2: A comparison between our solution and existing solutions for multi-color printing with FFF 3D printers.

Device	Color Palette	Coloring Approach	Cost (Base Device)	Cost (Per Color)	Adaptability
Filament inking (ours)	4 colors	Filament inking	$50	~$1 per marker	Any FFF 3D printer
da Vinci Color 3D Printer [22]	Full Color (CMYK)	Inkjet Printer Ink	$3499.95	~$69.95 per cart.	Da Vinci Color 3D Printer
Mosaic Palette 3 [29]	4 colors	Filament switching	$300	~$25 per filament spool	Any FFF 3D printer
Prusa MMU2S [43]	5 colors	Filament switching	$699	~$25 per filament spool	Prusa i3 MK3S or MK2.5S
Programmable Filament [54]	Dependent on number of filament changes	Filament switching	$0	~$25 per filament spool	Any FFF 3D printer

Table 2 shows a comparison between different multi-color printing approaches, associated costs, and adaptability to existing FFF printers. In contrast to most market solutions which modify or attach hardware to enable multi-color 3D printing, our system runs independent from 3D printers, allowing for greater compatibility. Colors are not limited to the rolls of filament a user has, rather by the permanent markers available. We find this to be a more economical choice as permanent markers are inexpensive and offer more color variety in comparison to purchasing individual rolls of filament. A concern that has been voiced in the 3D printing community is the accumulation of filament spools once the filament has been used [32]. While some companies offer no-spool options [15], these are in the minority and require users to supply their own spool. Our inking system leaves a lower plastic footprint, affording users a variety of color options using a handful of permanent markers rather than purchasing multiple spools.

Reducing the need for multiple spools has additional benefits. With filament switching based multi-color devices comes the increased possibility of filament jams as mentioned previously. Filaments, PLA in particular, have a tendency to become brittle when exposed to moisture. This places a shelf life on filament, with older material becoming more susceptible to snapping during fabrication. This issue only worsens in a bowden extruder system[5] where the travel distance of the filament is greatly increased prior to extrusion. Making use of one filament reduces any potential for snapping and minimizes the number of spools exposed to ambient humidity.

Dual extruder and multi tool head 3D printers are a common choice for multi-color 3D printing. They often cost more than single nozzle 3D printers due to the additional hardware. Aside from this, they require precise calibration of nozzle height in order to have material properly adhere to the surface of the print. Tool changing approaches must also accommodate additional hardware, increasing

[5] Bowden Extruder 3D Printer

the size of the 3D printer or in some cases reducing the available build volume. Our system requires no special calibration of a 3D printer beyond what a typical single nozzle printer requires.

Our device benefits from off-the-shelf components, allowing for the total cost to be well below most hardware based solutions. Customized parts are kept to a minimum, allowing for changes to the design to be made in a simple manner. We are cognizant of the ever changing and evolving nature of the 3D printer community, requiring designs to be adapted to users' needs. As ideas evolve and improvements are made, devices must not inhibit this progress and ideally be open to allow for experimentation. We believe our design makes this possible for the end user and aim to encourage further innovation.

5.4 Limitations

For multi-color prints with distinct colors, our system is dependent on the calibration of the 3D printer. Though a user is required to calibrate their device only once per routine maintenance of their 3D printer, this fails to address our PC.4 criteria. In pre-processing filament, there is no simple way to interface the position of the filament to the 3D printer when loading the material. This problem arises from the aforementioned open loop stepper motor issue. Measurements of the amount of material extruded upon loading filament must be taken. Though the extrusion of material can be inferred from the "M701" GCODE command, Prusa does not provide the value used for their devices[6]. We have measured this value manually and adjusted the filament to account for the extruded material; 31.5 mm in our case. Any shift from the starting position can have a compounding effect, causing colors to appear in the wrong places on a model. This issue only becomes worse with larger models. E-steps must also be well calibrated, ideally to two significant figures. If the expected extrusion differs from the true amount extruded, color shifting can occur as described in Sec. 4.2. To preserve colors in the object, color transitions must be contained in the purge tower. Ideally, color bleeding would not appear outside of the purge tower. Due to shifted filament, color bleeding will gradually appear in a model the longer a print goes on. A larger purge tower can mitigate this issue, however this would be undesirable due to the large quantity of material being used.

As mentioned in Sec. 4.1, color reproduction can vary depending on the coloring agent used in a permanent marker. There are plenty of color options available for permanent markers, though there is no guarantee that the applied color will appear in the final object. A workaround for this is applying multiple inks of known color outputs to the filament in order to mix colors. This would require testing and precise control over the ink dispensed to achieve high color accuracy.

5.5 Improvements and Future Work

We believe that lowering the cost barrier to multi-color printing will enable integration with projects such as p5.fab [53] to add a dimension of color for users to interact with, or reduce the need for post-processing expertise in works such as producing replicas of historical artifacts [49]. Our solution currently matches the capabilities of higher cost filament switching solutions to promote the use of color in designs for 3D printing. Development of tools for creating files for multi-color printing, such as Autodesk's Meshmixer [3], have ceased or are few and far between. We hope in providing an open source multi-color printing solution that researchers consider novel approaches to color processing or color editing tools for FFF 3D printing. Our web interface uses the popular React framework in order to accommodate new plugins and feature improvements to expand user interaction with color in fabrication.

To address the calibration dependency and PC.4 in our current solution, we can take aim at the open loop stepper motor. Integrating a closed loop stepper motor to accurately detect the position of the filament would help mitigate the need for precise calibration and potential for color shifting. In solving this problem, 3D printers would additionally benefit from detecting underextrusion and layer shifting.

As explained in Sec. 4.4, there is potential in expanding the CMYK color mixing capabilities to create a full color 3D printing system for FFF 3D printers. We currently use a binary approach to activating servo motors in engaging the coloring process. By varying the angle of the servo motor and consequently the pressure applied by the marker onto the filament, the ink dispensed can likely be changed. Modulating in this way would better allow control over the outputted color. Full color printing with our filament inking approach would have to address ink bleeding from permanent markers resting on the same side. Currently, cyan would pick up yellow ink if green were to be created from the two. This occurs due to the permanent markers covering half the filament in the corresponding color. Another approach to adding color options would be expanding the number of permanent markers available on the device. The servo motor driver we use can handle up to 16 motors, allowing for a total of 16 permanent markers to be installed with modification to our design. Furthering the available color palette with our approach has implications for producing objects with varying internal colors when using translucent material, similar to the work presented by Bader et al. [4]. With FFF 3D printing in its current form focused on surface features, users may find it novel to work with the internal features of their model.

PLA was the primary material used in developing this system. We plan to continue testing with other rigid plastics such as PETG and ASA to better determine material compatibility with our approach. It has yet to be seen how different materials would react to inking. It may be possible for permanent marker inks to better stain certain plastics, producing more consistent color results. Since the coloring process requires the inked filament to maintain its shape, our device is likely not compatible with flexible materials. As the market availability for niche materials is smaller, the price of each spool tends to be higher than their PLA counterparts. This could be a future improvement for users wanting to customize niche materials that have reduced color varieties. Further testing with ink varieties such as metallic and fluorescent markers have the potential to further expand the visual properties of fabricated objects.

6 CONCLUSION

We introduced a low-cost system for multi-color 3D printing, compatible with existing single extruder 3D printers on the market. A

[6] Prusa Specific GCODE

pre-processing approach is used to ink filament with minimal need for user intervention. Our approach meets the requirements laid out in Sec. 1 with, however, only incomplete success for R.1. While certain permanent markers produce unexpected color outcomes, the majority of colors tested fulfill this criteria. In keeping with the practical considerations, our system fulfills all but PC.4, minimal calibration. The extent to which a 3D printer needs to be calibrated for this technique to work was well underestimated. While we aid users in this process with the addition of calibration calculators in our web interface, we acknowledge this can still pose a barrier for users. Though this being the case, we remain optimistic in our pre-processing approach to increase FFF 3D printer compatibility over custom solutions for individual devices. Our web interface provides a simple way for users to generate color profiles for a 3D print, further acting as a framework for others to improve user interaction in multi-color 3D printing. We believe users will benefit from the increased accessibility to fabricating with color.

7 ACKNOWLEDGMENTS

This work was partially supported by NSF award 1844538.

REFERENCES

[1] Co Print 3D. 2022. Co Print 3D Printing Technologies. https://coprint3d.com/
[2] adlughmin. 2014. 'Ultimate Filament Colorer': Sharpie marker colors 3D printer filament prior to extruding. https://3dprint.com/3340/ulimate-filament-colorer/
[3] Inc Autodesk. 2020. Meshmixer. https://www.meshmixer.com/
[4] Christoph Bader, Dominik Kolb, James C. Weaver, Sunanda Sharma, Ahmed Hosny, João Costa, and Neri Oxman. 2018. Making data matter: Voxel printing for the digital fabrication of data across scales and domains. *Science Advances* 4, 5 (2018), eaas8652. https://doi.org/10.1126/sciadv.aas8652 arXiv:https://www.science.org/doi/pdf/10.1126/sciadv.aas8652
[5] P. Cignoni, E. Gobbetti, R. Pintus, and R. Scopigno. 2008. Color Enhancement for Rapid Prototyping. In *Proceedings of the 9th International Conference on Virtual Reality, Archaeology and Cultural Heritage* (Braga, Portugal) *(VAST'08)*. Eurographics Association, Goslar, DEU, 9–16.
[6] ColorFabb. 2022. ColorFabb. https://colorfabb.com/
[7] Creality. 2018. Ender 3 3d Printer. https://www.creality3dofficial.com/products/official-creality-ender-3-3d-printer
[8] Cults. 2022. Cults 3D. https://cults3d.com/
[9] DasMia. 2019. DIY Rainbow 3D printing filament. https://www.instructables.com/DIY-Rainbow-3D-Printing-Filament/
[10] E3D. 2017. Kraken documentation. https://wiki.e3d-online.com/Kraken_Documentation#Assembly_Guidelines
[11] Oskar Elek, Denis Sumin, Ran Zhang, Tim Weyrich, Karol Myszkowski, Bernd Bickel, Alexander Wilkie, and Jaroslav Křivánek. 2017. Scattering-Aware Texture Reproduction for 3D Printing. *ACM Trans. Graph.* 36, 6, Article 241 (nov 2017), 15 pages. https://doi.org/10.1145/3130800.3130890
[12] 3DMaker Engineering. 2020. Flow Rate Calibration Guide. https://www.3dmakerengineering.com/blogs/3d-printing/flow-rate-calibration
[13] Machael Feygin, Alexandr Shkolnik, Michael N Diamond, and Emmanuil Dvorskiy. 1998. Laminated object manufacturing system.
[14] Atomic Filament. 2022. Atomic Filament High Precision 3D Printer Filament. https://atomicfilament.com/
[15] DAS FILAMENT. 2022. Filament - refill. https://www.dasfilament.de/filament-refill/?p=1
[16] Jack Forman, Mustafa Doga Dogan, Hamilton Forsythe, and Hiroshi Ishii. 2020. *DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion.* Association for Computing Machinery, New York, NY, USA, 1222–1233. https://doi.org/10.1145/3379337.3415876
[17] Emmett Grames. 2022. Extruder calibration: 6 steps to calibrate your extruder. https://all3dp.com/2/extruder-calibration-6-easy-steps-2/
[18] Jean Hergel and Sylvain Lefebvre. 2014. Clean Color: Improving Multi-Filament 3D Prints. *Comput. Graph. Forum* 33, 2 (may 2014), 469–478. https://doi.org/10.1111/cgf.12318
[19] Mirjam Hintz. 2019. Hand-Painting 3D Prints with Acrylics. https://justpaint.org/hand-painting-3d-prints-with-acrylics/
[20] Andreas Iliopoulos and Jackson O'Connell. 2021. Silk Pla filament: The best brands of 2021. https://all3dp.com/2/silk-3d-printing-filament-brands-compared/
[21] ORD Solutions Inc. 2022. Rova4D Full Color Blender 3D Printer. https://www.ordsolutions.com/rova4d-full-color-blender-3d-printer-pre-order/
[22] XYZprinting Inc. 2022. da Vinci Color 3D Printer. https://www.xyzprinting.com/en-US/product/da-vinci-color
[23] MakerBot Industries. 2022. Digital designs for physical objects. https://www.thingiverse.com/
[24] Yuhua Jin, Isabel Qamar, Michael Wessely, and Stefanie Mueller. 2020. Photo-Chromeleon: Re-Programmable Multi-Color Textures Using Photochromic Dyes. In *ACM SIGGRAPH 2020 Emerging Technologies* (Virtual Event, USA) *(SIGGRAPH '20)*. Association for Computing Machinery, New York, NY, USA, Article 7, 2 pages. https://doi.org/10.1145/3388534.3407296
[25] Tim Kuipers, Willemijn Elkhuizen, Jouke Verlinden, and Eugeni Doubrovski. 2018. Hatching for 3D prints: Line-based halftoning for dual extrusion fused deposition modeling. *Computers & Graphics* 74 (2018), 23–32. https://doi.org/10.1016/j.cag.2018.04.006
[26] 3D Chameleon LLC. 2021. 3D Chameleon - Automatic Color Changer. https://www.3dchameleon.com/
[27] M3D. 2019. The QuadFusion Print Head. https://www.kickstarter.com/projects/m3d/the-quadfusion-print-head-making-color-3d-printing
[28] Mosaic Manufacturing. 2020. Multi-color kidney model. https://www.thingiverse.com/thing:4655812
[29] Mosaic Manufacturing. 2022. Palette 3 pro. https://www.mosaicmfg.com/products/palette-3-pro
[30] MatterHackers. 2022. Fluorescent filament. https://www.matterhackers.com/store/c/fluorescent-3d-printer-filament?ref=mh-nav-tree
[31] MatterHackers. 2022. Matterhackers quantum dual-color pla. https://www.matterhackers.com/store/c/matterhackers-quantum-pla
[32] Martin Mayer. 2022. Are 3D filament spools recyclable? What to do with them! https://3dsolved.com/are-3d-filament-spools-recyclable-what-to-do-with-them/
[33] Devin Montes. 2018. Colorful 3D prints on a single extruder printer // artistic phone cases. https://youtu.be/KV2AjyowXX4
[34] Devin Montes. 2019. Single extruder multicolor in Cura Tutorial // multipass 3D printing. https://youtu.be/D7FiT5VqLSg
[35] Devin Montes. 2020. 3D Printing Custom Colors with Markers?! https://youtu.be/yQwkHDDed0o
[36] MosaicManufacturing. 2017. Multi-Color World with Stand. https://www.thingiverse.com/thing:2242946
[37] MosaicManufacturing. 2018. Multi-Color Mini Plant Cell. https://www.thingiverse.com/thing:2811554
[38] nervoussystem. 2014. 2-color tree frog. https://www.thingiverse.com/thing:329436
[39] Jackson O'Connell. 2020. Rainbow Pla filament: The best brands of 2021. https://all3dp.com/2/rainbow-filament-pla-brands-compared/
[40] Polymaker. 2022. Polymaker. https://polymaker.com/
[41] Parinya Punpongsanon, Xin Wen, David S. Kim, and Stefanie Mueller. 2018. ColorMod: Recoloring 3D Printed Objects Using Photochromic Inks. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173787
[42] Tim Reiner, Nathan Carr, Radomír Měch, Ondřej Šťava, Carsten Dachsbacher, and Gavin Miller. 2014. Dual-Color Mixing for Fused Deposition Modeling Printers. *Comput. Graph. Forum* 33, 2 (may 2014), 479–486. https://doi.org/10.1111/cgf.12319
[43] Prusa Research. 2018. Original Prusa i3 MMU2S upgrade kit (for Mk2.5S & Mk3s/+). https://www.prusa3d.com/product/original-prusa-i3-mmu2s-upgrade-kit-for-mk2-5s-mk3s-org/
[44] Prusa Research. 2019. Colorprint. https://blog.prusa3d.com/color-print_3993/#:~:text=You%20can%20easily%20add%20color,estimate%20until%20each%20color%20change.
[45] Prusa Research. 2022. Original Prusa MMU1. https://help.prusa3d.com/en/tag/mmu1
[46] Prusa Research. 2022. Printables by Josef Prusa. https://www.printables.com/
[47] Prusa Research. 2022. Prusaslicer. https://www.prusa3d.com/page/prusaslicer_424/
[48] Sakati84. 2021. Sakati84/3DPrintColorizer: Software & hardware to do multi color printing with sharpies. https://github.com/Sakati84/3DPrintColorizer
[49] R. Scopigno, P. Cignoni, N. Pietroni, M. Callieri, and M. Dellepiane. 2017. Digital Fabrication Techniques for Cultural Heritage: A Survey. *Computer Graphics Forum* 36, 1 (2017), 6–21. https://doi.org/10.1111/cgf.12781 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.12781
[50] Liang Shi, Vahid Babaei, Changil Kim, Michael Foshey, Yuanming Hu, Pitchaya Sitthi-Amorn, Szymon Rusinkiewicz, and Wojciech Matusik. 2018. Deep Multispectral Painting Reproduction via Multi-Layer, Custom-Ink Printing. *ACM Trans. Graph.* 37, 6, Article 271 (dec 2018), 15 pages. https://doi.org/10.1145/3272127.3275057

[51] M. A. Skylar-Scott, J. Mueller, C. W. Visser, and J. A. Lewis. 2019. Voxelated soft matter via multimaterial multinozzle 3D printing. *Nature* 575, 7782 (11 2019), 330–335.

[52] Haichuan Song, Jonàs Martínez, Pierre Bedell, Noémie Vennin, and Sylvain Lefebvre. 2019. Colored Fused Filament Fabrication. *ACM Trans. Graph.* 38, 5, Article 141 (jun 2019), 11 pages. https://doi.org/10.1145/3183793

[53] Blair Subbaraman and Nadya Peek. 2022. p5.fab: Direct Control of Digital Fabrication Machines from a Creative Coding Environment. https://doi.org/10.48550/ARXIV.2205.00323

[54] Haruki Takahashi, Parinya Punpongsanon, and Jeeeun Kim. 2020. *Programmable Filament: Printed Filaments for Multi-Material 3D Printing.* Association for Computing Machinery, New York, NY, USA, 1209–1221. https://doi.org/10.1145/3379337.3415863

[55] tardani95. 2019. Mini Lizards MMU2S test. https://www.printables.com/model/3561-mini-lizards-mmu2s-test/comments

[56] Creative Tools. 2020. Benchy Boat. https://www.3dbenchy.com/download/

[57] Ultimaker. 2022. Ultimaker 3D printers. https://ultimaker.com/3d-printers

[58] Joshua Vasquez, Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2020. *Jubilee: An Extensible Machine for Multi-Tool Fabrication.* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376425

[59] Kiril Vidimče, Szu-Po Wang, Jonathan Ragan-Kelley, and Wojciech Matusik. 2019. OpenFab: A Programmable Pipeline for Multimaterial Fabrication. *Commun. ACM* 62, 9 (aug 2019), 97–105. https://doi.org/10.1145/3344808

[60] Yizhong Zhang, Chunji Yin, Changxi Zheng, and Kun Zhou. 2015. Computational Hydrographic Printing. *ACM Trans. Graph.* 34, 4, Article 131 (jul 2015), 11 pages. https://doi.org/10.1145/2766932

A FILAMENT INKING DURING A PRINT

A.1 Octoprint Approach

We previously ran an inking system in tandem with a 3D print, utilizing Octoprint to control the inking mechanism. Conceptually, inking filament while 3D printing would work by continuously coloring until a tool change command is encountered in the GCODE. Ideally, the Raspberry Pi would capture the tool change and control the inking process to change colors. In practice, a few roadblocks prevented the realization of this approach. Though the Prusa i3 MK3 runs on the Marlin firmware, modifications to the firmware have been made due to the memory limitations of the microcontroller used on the printer. As a result, the GCODE command "M118", used for sending messages over serial communication, has been removed. This prevents modifying GCODE directly to add custom M118 commands to signal to Octoprint when a color change should occur.

Other options for adding custom commands with Octoprint include Action Commands and @ Commands. Modifying the python files in Octoprint's Action Command and @ Command folders allows for the creation of functions that run when a custom command is read. Lines of GCODE are read in a queuing system where these custom commands are captured. An Action Command can be specified to run when the custom GCODE is in queuing, sending, or sent to the printer. Due to the way Octoprint processes GCODE, the timing of when a custom command is run differs throughout a 3D print even upon specifying in the callback function. This issue creates inconsistent results and affects the reliability of the system.

Another obstacle when running an inking system during a 3D print is the drying of the markers over time. Even small 3D prints can last hours given the detail and complexity of the model. As a result, a permanent marker can dry when left exposed for the duration of the print. With multiple markers left exposed, the potential for inconsistent coloring results only increase. An approach to solving this issue is creating an enclosed device that protects the permanent markers from drying. Upon implementing this, we have found that the ink has very little time to dry, causing ink to accumulate in the nozzle and bleed into other parts of the object.