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Ozdemir, Mehmet; AlAlawi, Marwa ; Dogan, Mustafa Doga ; Martinez Castro, Jose Francisco ; Mueller, Stefanie ; Doubrovski, Zjenja

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Demonstrating Speed-Modulated Ironing: High-Resolution Shade and Texture Gradients in Single-Material 3D Printing

Mehmet Ozdemir
Delft University of Technology
Netherlands
mehmet.ozdemir@tudelft.nl

Marwa AlAlawi
MIT CSAIL
Cambridge, MA, US
malalawi@mit.edu

Mustafa Doga Dogan
MIT CSAIL
Cambridge, MA, US
doga@mit.edu

Jose Francisco Martinez Castro
Delft University of Technology
Netherlands
j.martinezcastro@outlook.com

Stefanie Mueller
MIT CSAIL
Cambridge, MA, US
stefanie.mueller@mit.edu

Zjenja Doubrovski
Delft University of Technology
Netherlands
e.l.doubrovski@tudelft.nl

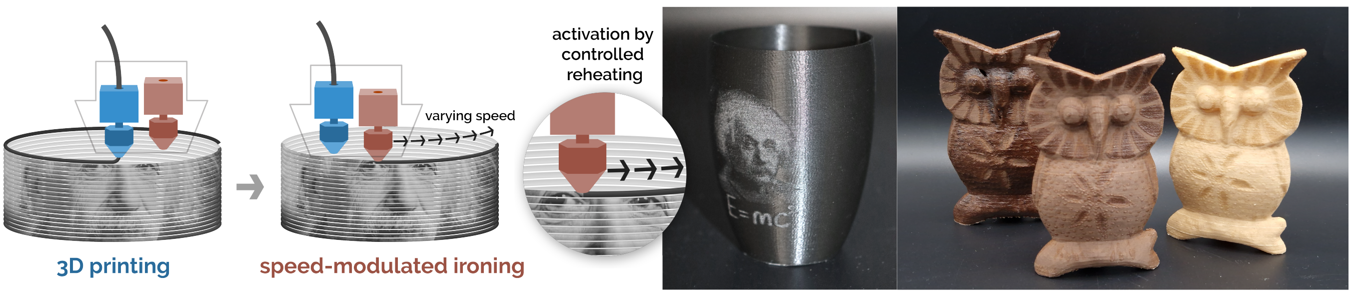

Figure 1: Speed-Modulated Ironing is a novel 3D printing technique for FDM 3D printers to continuously program temperature-responsive filaments at a high resolution. It works by using one print head to lay down the filament, followed by the second print head that activates the temperature response of the material by "ironing" the printed layer at varying speeds, changing the achieved property. Our method can be used with different temperature-responsive filaments.

Abstract

We present Speed-Modulated Ironing, a new fabrication method for programming visual and tactile properties in single-material 3D printing. We use one nozzle to 3D print and a second nozzle to reheat printed areas at varying speeds, controlling the material's temperature-response. The rapid adjustments of speed allow for fine-grained reheating, enabling high-resolution color and texture variations. We implemented our method in a tool that allows users to assign desired properties to 3D models and creates corresponding 3D printing instructions. We demonstrate our method with three temperature-responsive materials: a foaming filament, a filament with wood fibers, and a filament with cork particles. These filaments respond to temperature by changing color, roughness, transparency, and gloss. Our method is able to achieve sufficient resolution and color shade range that allows surface details such as small text, photos, and QR codes on 3D-printed objects. Finally, we provide application examples demonstrating the new design capabilities enabled by Speed-Modulated Ironing.

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CCS Concepts

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

Keywords

3D printing, multi-property printing, gradients, personal fabrication, rapid prototyping, temperature-responsive filaments

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1 Introduction

Material extrusion 3D printing is becoming a widespread technology that is being used for an increasing number of applications. With the ultimate goal of fabricating 3D objects in one go, researchers and makers aspire towards the ability of 3D printers to process parts with multiple properties [1]. Printing parts with different colors, textures, and other visual properties and doing so at a high resolution is essential for many applications.

For multi-color or multi-property printing, the standard workflow is to use multiple materials, each with their own properties [2].

However, in this approach, a material can only be assigned to a discrete region in the 3D print, making it impossible to assign values "in-between" and to fabricate graded transitions. Other methods include a pre-processing of the filament prior to 3D printing [3] or mixing materials in the nozzle [6], all of which require additional hardware or printer modifications.

Alternatively, the temperature response of some specific filaments has been used to locally vary appearance or other properties in 3D prints [4] [5]. Existing work uses the printing nozzle temperature to vary, for example, the color or roughness of the printed part. However, nozzle temperature cannot be rapidly changed, which significantly limits the resolution of the achievable property variations. Besides, this varying nozzle temperature method results in a much longer print time and more material waste.

Eliminating the dependency on the slow nozzle temperature change and allowing high-resolution, fine-grained control of visual and tactile properties, we present ***Speed-Modulated Ironing***.

2 Method: *Speed-Modulated Ironing*

Speed-Modulated Ironing is a novel fabrication technique to achieve high-resolution shade and texture gradients by continuous fine-grained programming of temperature-responsive filaments. In our method, every layer is first printed and then re-heated by a second nozzle, which irons over the layer at a constant temperature but at precisely controlled speeds, see Figure 1. By separating the printing step from the programming step, we address the inability of a printing nozzle to change temperature rapidly. This allows us to locally vary the applied heat with precision and thus, to change properties of temperature-responsive filaments at an unprecedented resolution.

2.1 Temperature-Responsive Filaments

Our method utilizes the ability of some materials to obtain varying color shade, texture, and translucency when exposed to different levels of heat. In this paper, we present our work on three off-the-shelf 3D printing filaments; however, in principle, our approach can be used for other temperature-responsive materials as well. The first filament is a foaming filament, which contains a foaming agent that causes the filament to convert into a closed-cell structure when heat is applied. The higher the applied heat, the more the foam expands, leading to larger cells. The type of foaming filament used in this work is LW-PLA[1]. As the second and third material, we use PLA filled with wood fibers (Woodfill[2]) and with cork fibers (Corkfill [3]) respectively. The last two filaments have a comparable temperature response, they obtain a progressively darker color shade when exposed to higher temperatures due to pyrolysis [4].

2.2 Programming Through Ironing

Working principle: We separate the 3D printing and re-heating for programming into two consecutive steps using an unmodified dual-nozzle 3D printer. The first nozzle is dedicated to the primary task of 3D printing the filament at a relatively low nozzle temperature that does not cause any temperature response of the material (see Figure 1). The second nozzle is empty (i.e., does not have any filament loaded into it) but is used for programming the properties by *re-heating* the already printed layer of material. The re-heating is done by moving the empty heated nozzle over the print while slightly touching, *"ironing"*, the top of the printed layer. The temperature increase in the layer triggers a temperature response of printed material, such as change in color shade. We keep the ironing nozzle temperature constant and modulate the applied heat through variations in ironing speed. Slow ironing causes the layer to heat up more than when ironing at a faster speed. The separation of the 3D printing and programming into two steps allows us to leverage the accurate motion control of the printing head since the speed of the ironing nozzle can be rapidly and precisely changed within a layer, unlike nozzle temperature.

Ironing workflow: The main input to our workflow is the gcode of a sliced geometry for a single-nozzle 3D print prepared by the user. Gcode instructions for the ironing by the second nozzle are inserted into this input gcode while all 3D printing instructions and features, such as inner walls, infills, and support structures, remain unchanged. This workflow also preserves the user preferences of slicing, machine, and material-related settings for 3D printing. A schematic overview of the workflow is shown in Figure 2.

Since we are interested in the color shade and textures of 3D objects in this work, our method applies the ironing step only to the outer contour in each layer. For each layer of the 3D print, we extract the contour geometry of the outer wall from the input gcode. To this contour, we apply sampling points at a distance that we tested as short as 0.2mm. For each point, we then sample the intended property value (color shade, texture, translucency). The property values can be defined via an image, such as the color texture image of a 3D mesh file, or the user can project an image onto a 3D geometry directly in our tool (see Section 3).

Each sampled value, for example, target color shade, is then mapped to an ironing speed that will yield the required re-heating and, therefore, corresponding color change in the material. Using these modulated speeds, we create ironing toolpaths and insert these into every layer of the input gcode, together with the printer instructions for the nozzle changes. The final gcode file can be sent to the 3D printer for fabrication.

Ironing parameters: For each of the used materials, we determined the ironing parameters that yield the desired results. We aimed for a maximum difference in the property (color shade, texture, translucency) while keeping the structural and 3D detail integrity of the 3D printed shape. For example, a too-high ironing temperature or too-slow ironing speed may be able to trigger a response of the material but at the same time damage the printed structure. Possible damages include an unintended roughening of the surface or even holes in the printed part. This means that the ironing parameters need to be well-balanced. Table 1 presents the ironing parameters we use in our method.

3 *Speed-Modulated Ironing* Tool

We developed a tool with a user interface that allows users to apply our method in their 3D printing workflow[4]. It provides an

[1]https://colorfabb.com/lw-pla-black
[2]https://colorfabb.com/woodfill
[3]https://colorfabb.com/corkfill

[4]https://github.com/zjenjad/speed-modulated-ironing

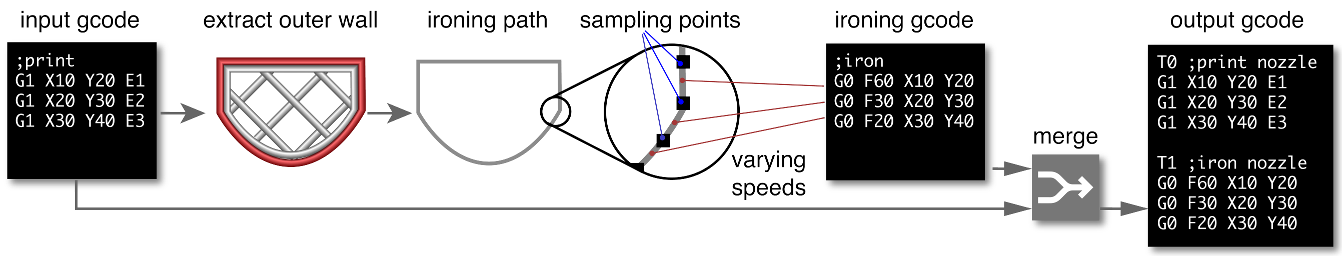

Figure 2: *Speed-Modulated Ironing* workflow. Starting with a gcode for a single-nozzle print, we extract the toolpaths of the outer wall for every layer. This contour is then subdivided at the sampling length (0.2 mm) and used as the ironing path. The gcode for the ironing operations is merged with the input gcode, and the merged output can be sent for 3D printing.

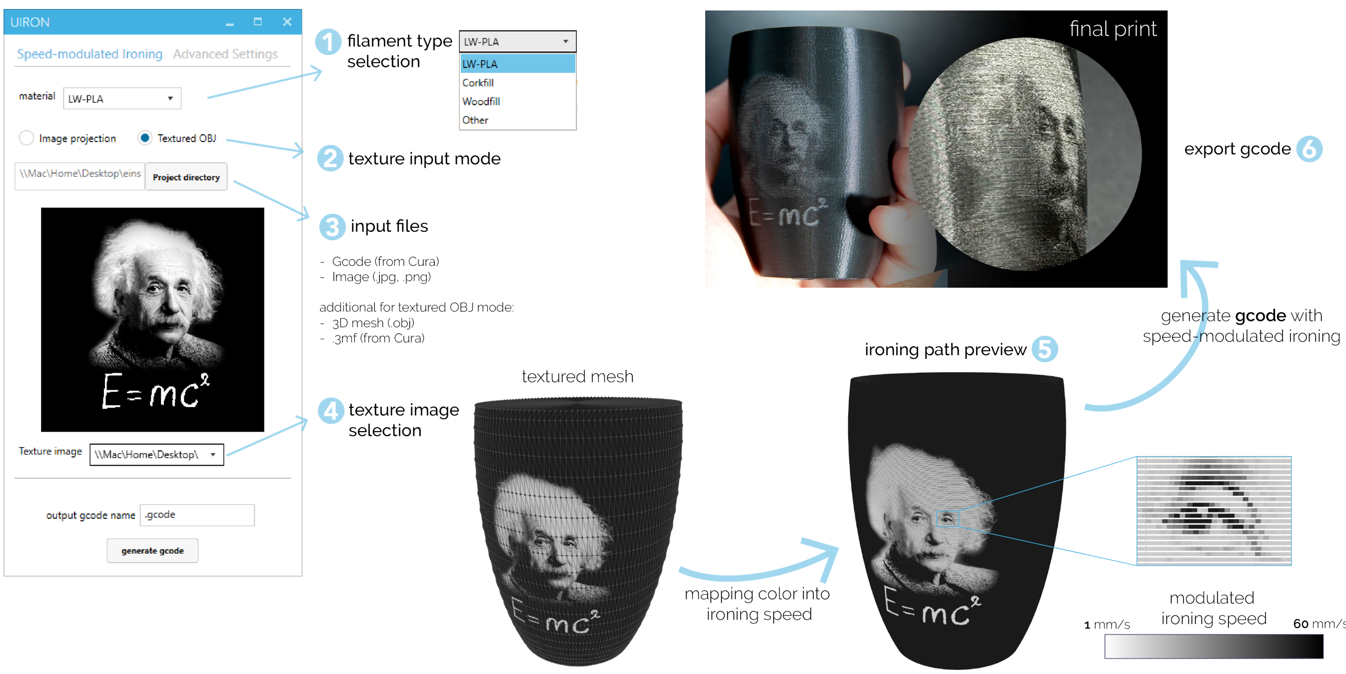

Figure 3: User interface of the *Speed-Modulated Ironing* tool with the main interface to generate a gcode and the steps to follow by users. First, the user selects the material and chooses the input mode. Then, the user points to the project directory that contains the input files. When using Textured OBJ mode, the textured mesh in converted to ironing paths and a preview image of the generated gcode is shown. After selecting "generate gcode", the printing file is exported and can be fabricated.

	nozzle temperature [°C]	min speed [mm/s]	max speed [mm/s]
LW-PLA	300	1	60
Woodfill	325	1.5	10
Corkfill	325	1	20

Table 1: Ironing nozzle temperature and ironing speed ranges for the three materials used in our method.

accessible way for makers to create locally varying shades, textures, and translucency with a single material using their unmodified 3D printers. In the recommended mode, the tool currently supports the three materials we have used in this paper without the need to modify any settings. For advanced users or for users who want to apply the method to not-yet-tested materials, we also provide the option to change the ironing parameters and other settings of our tool. The tool and the interface are implemented in *Rhinoceros 3D Grasshopper* and can be considered as a gcode post-processor since it generates and adds the computed ironing printer instructions to existing gcode files.

File preparation and gcode generation: The user interface and the steps to use the tool are presented in Figure 3.

Prior to using the tool, the user needs to slice the geometry for their printer with standard slicer software. Our current implementation assumes the file is sliced using *Cura*[5] slicer. The first step in our tool is to choose the material to be used, which defines the ironing settings (step 1 in Figure 3). This is followed by selecting the texture input mode, which is either *image projection* or *textured OBJ* mode (step 2 in Figure 3). Next to the pre-sliced gcode, the required input files depend on the selected input mode. The textured OBJ mode, requires a textured mesh file (in the Wavefront OBJ file format) and a 3MF file (exported from *Cura* along with the gcode). All the input files need to be stored in a project directory, and this folder has to be selected on the interface (step 3 in Figure 3). The texture or projection image should be included in the same folder, which can be selected and viewed on the interface (step 4 in Figure 3).

Our design tool reads all the documents from the folder and processes them as follows: First, the gcode file is used to extract the outer wall toolpaths for every layer, which are used as the contour path for the ironing. This contour is subdivided into segments of 0.2mm to get the sampling points (Figure 2). In the textured OBJ mode, the mesh is automatically aligned with the gcode by using the transformation matrix from the 3MF file. Then, using the UV mapping values from the OBJ mesh, for every sampling point, the color values from the OBJ texture file are extracted and converted to grayscale values. In the image projection mode, the grayscale values of a user-selected 2D image are projected through the 3D model over one axis using parallel projection. Then, for every sampling point, the corresponding grayscale value from the 2D image is used to obtain the ironing velocities.

Finally, choosing the *generate gcode* on the tool, the print-ready output file is saved to the project directory. The user can see the preview of the generated file (step 5 in Figure 3), where the preview shows the gradients on the object surface. Depending on the chosen material, the preview shows the expected color values that will be obtained in the print. After exporting the gcode (step 6 in Figure 3), the file can be sent for fabrication. Figure 3 also shows the final printed object in comparison to the preview. The combination of material-specific mapping of the ironing speeds and high sampling rate, the tool allows the fabrication gradients that appear smooth and linear to the human eye.

Advanced mode: For users to experiment with the process or test additional materials, we provide advanced settings in the tool. These include both ironing and printing settings. In the ironing settings, the users may control the sampling length (resolution of the speed variations), ironing temperature, speed interval, and nozzle Z-offset. Lowering the sampling length provides finer texture details while resulting in a longer processing time and a larger output file. The other settings here can be fine-tuned for new materials. We also provide the option to change several print settings that are also material-dependent. For instance, standby temperature (printing nozzle temperature while inactive) and retraction settings are helpful to avoid material oozing out of the printing nozzle while ironing with the second nozzle.

[5]https://ultimaker.com/software/ultimaker-cura/

4 Applications

4.1 Color Shade

Our method can also be used to fabricate 3D-scanned objects. A textured mesh of a color-scanned owl figurine[6] was imported into our tool (Figure 5a). The model with the texture details was reproduced using Corkfill filament, (Figure 5b and c), Woodfill filament (Figure 5d), and green foaming filament (Figure 5e).

Figure 4: Examples showing local shade variations. Each object was printed using a single material; either Corkfill or Woodfill was used.

Figure 5: Example of a scanned figurine processed using our method and fabricated with local shade variations. A) The mesh file with texture. B) A print made with Corkfill. C) Another print with Corkfill but with reversed brightness values. D) Print with Woodfill. E) Print with green LW-PLA.

[6]Owl Ornament Statue 3D Scan by 3DRstudio https://sketchfab.com/3d-models/owl-ornament-statue-3d-scan-a2ef1344af5143b9b0a214f969640a15

4.2 Translucency

Our method enables the creation of 3D-printed objects with regions of varying translucency. As an example, Figure 6 shows a transparent liquid container with opaque design features printed using "natural color" LW-PLA.

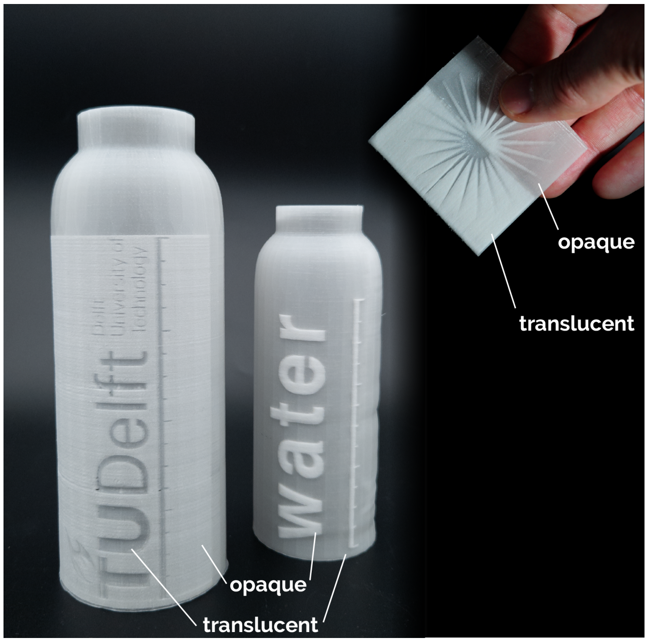

Figure 6: Liquid containers printed using "natural color" LW-PLA. Regions ironed at a low speed become opaque, while regions ironed at a high speed remain translucent.

4.3 Tactile Texture

Our method enables the incorporation of diverse textures into 3D-printed objects. This includes textured handles for tools and appliances or ergonomic grips for sports equipment, e.g., the bike handle example in Figure 7.

Figure 8 shows a speaker enclosure with touch buttons which are smoother to the touch compared to the rest of the housing. These areas also visually signal the tactile, "touchable" nature of the buttons. This part was printed using regular PLA (i.e. without special additives) and is, therefore, an example of our method being applied using a commonly used printing material.

5 Demonstration

For the interactive session, we demonstrate *Speed-Modulated Ironing*in three key ways. First, we allow visitors to interact with the Speed-modulated ironing tool, creating designs with varying visual properties. Then, a dual nozzle 3D printer is available to fabricate the resulting designs using our method. Visitors will be able to see the separate steps of printing and ironing in action. Finally, we exhibit a collection of 3D printed results, demonstrating the capabilities and applications of *Speed-Modulated Ironing*.

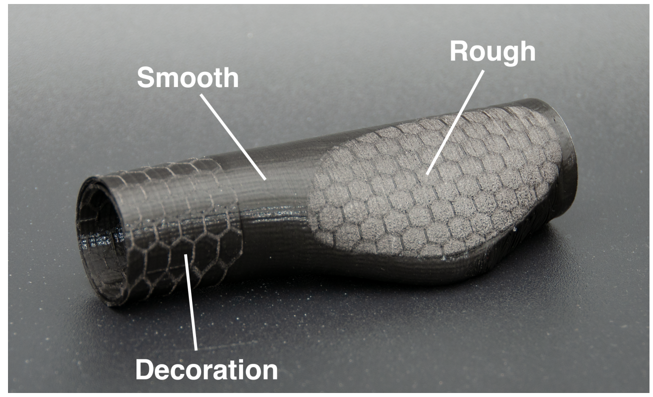

Figure 7: Bike handle fabricated using black LW-PLA. Our method was used to apply varying roughness for grip and decoration.

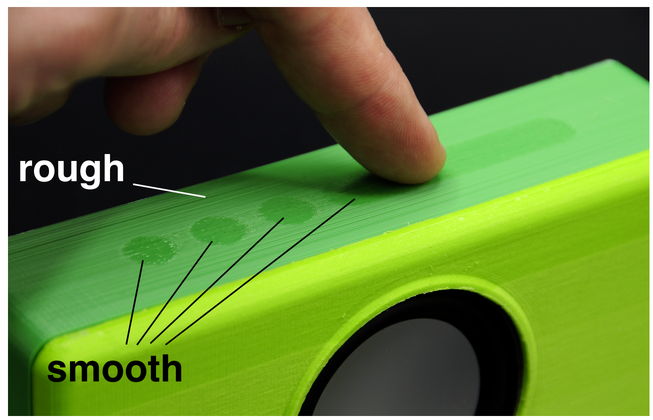

Figure 8: Touch buttons on a speaker. The touch regions have a smoother and glossier finish compared to the surrounding area. This part was printed using regular PLA.

6 Conclusion

In this work, we introduced *Speed-Modulated Ironing*, a novel method that expands the capabilities of single-material 3D printing by enabling high-resolution control over visual shade and tactile texture gradients. This approach, leveraging dual-extruder printers, allows for the intricate activation of temperature-responsive filaments, such as wood, corkfill, and foaming filaments. Using our software tool, users can achieve high-resolution fabrication of objects with graded shades, textures, and translucency, without necessitating multiple materials or complex hardware modifications.

We demonstrated the capability of our approach to create objects with fine textures and graphics using a single material. We hope that our work represents a step toward a more versatile, expressive, and sustainable form of 3D printing and will enable further explorations into leveraging the inherent properties of materials.

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