

An Interactive Fabrication System that Allows Users to Edit a 3D Model during 3D Printing

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INTRODUCTION

Digital fabrication (including 3D printing) is becoming increasingly common, and is having a significant impact on current manufacturing methods. 3D printers that can form high-precision 3D objects are being utilized in a wide variety of applications, from personal fabrication projects to commercial product prototyping.

However, in current 3D printing process, 3D printers are utilized in the final stage of printing to produce the completed 3D model. The 3D models are designed with modeling software during the pre-printing stage (as shown in Figure 1, top). Currently, 3D printers are not used in the initial design stage, because 3D models are typically incomplete at this stage owing to lack of clear goal. In addition, it is often necessary to use trial and error (i.e., modifying the 3D model) to improve a design after an object is printed; in this case, users must remove already printed objects from the printer platform and reconfigure printing parameters.

In this paper, we present an interactive fabrication system that allows users to edit a 3D model during the printing (Figure 1, bottom). Our technique allows users to edit non-printed areas of a 3D model during printing by intervening in the communications between the 3D printer and the host application controlling the printer (Figure 2). This system provides a new fabrication environment that integrates printing with 3D modeling; it not only speeds up the trial and error process, but also allows users to create 3D models during printing. We describe the mechanism in our system in detail and discuss the capability of this technique.

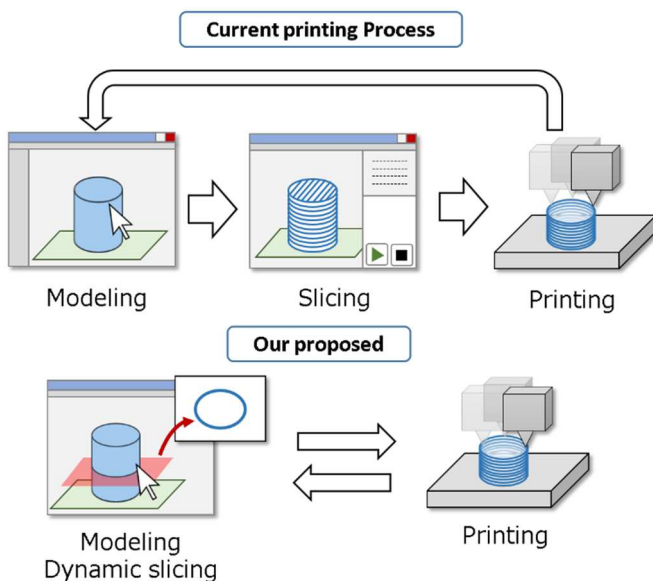


Figure 1. Comparison between current 3D printing process and our proposed.



Figure 2. Editing during printing

RELATED WORK

Willis et al. [1] use the term *Interactive Fabrication* to describe a fabrication environment that allows users to edit the design of object while it is being printed. *Interactive Fabrication* is characterized by the capability to accommodate real-time input/output from user; this allows users to interact directly with the material via fabrication machines, similar to the manner in which brushes or chisels are used to paint or sculpt. Therefore, users can establish a closer relationship with materials and reflect their creativity while printing objects. Willis et al. present a series of prototype devices that accept real-time input/output to fabricate physical forms, and investigate the capability of *Interactive Fabrication* [2]. In a similar vein, *Interactive Construction* [3] can interactively control a laser cutter. Using a laser pointer, users directly create cutting instructions for materials placed on a laser cutter platform. Traditional 3D printers do not have this interactivity, and each part of the process is separate; 3D models must be modified before/after printing. Our technique allows trial and error during printing, and uses a 3D printer as a part of an interactive system for early stages of design.

In the field of human-computer interaction, there is a significant amount of research on the 3D printing speed. Muller et al. studied the feasibility of increasing 3D printing speed and reducing printing time by lowering the fidelity of 3D models [4]; this system reduces the 3D printing area by replacing a portion of the 3D model with bricks or acrylic material cut by a laser cutter. Our technique does not aim to reduce printing time; however, if users can effectively edit a 3D model during printing (to modify a modeling error, for example) it is possible to reduce overall processing time, including the time required for trial and error.

SYSTEM

In this section, we describe the mechanism used by our technique, and discuss the prototype system we implemented to demonstrate it. This system is implemented as a host application to control 3D printers. We employ the visual language vvvv¹ to implement our system, and we practically apply this to ATOM², a 3D printer based on fused deposition modeling.

Methods that allow 3D model to be edited during printing

A host application converts inputted 3D model data (i.e., an STL file) into commands by slicing models into print head movement path layers. These commands are written in *Gcode*, which is the most widely used numerical control programming language. *Gcode* is used mainly in computer-aided manufacturing to control automated machine tools. A host application sends the code to 3D printers sequentially, and printing is completed step by step. We leverage this mechanism to allow 3D models to be edited in the middle of printing.

However, in a general host application, we cannot access a 3D model or *Gcode* when printing begins, because 3D models are converted into *Gcode* all at once. In contrast, our system writes each printed layer as a partial 3D model; only the parts required for printing are sliced into *Gcode*.

Process Pipeline

The pipeline of our technique is shown in Figure 3. First, the system calculates the points where the 3D model intersects with two plates: a lower plate placed at the current printed position, and an upper plate positioned one layer above the lower plate. A partial 3D

¹ <http://vvvv.org/>

² <http://genkei.jp/atom2/>

model is generated from these intersection points and written to the specified STL file. This process is repeated from the lowest to the highest point of the 3D model (where no additional intersection points exist).

Next, the system converts the partial 3D model in the STL file into Gcode. For this process, we used CuraEngine³, which is open-source slicing software operated by our system (via command line execution). CuraEngine can import a configuration file containing runtime arguments; through this file, we can specify parameters such as printed layer height, internal structure configurations, and printer head speed. Users can modify this configuration file as needed; for example, the top and bottom layer defined by the Gcode can be changed to solid (to achieve a structure density of 100%). We removed the start and end codes returned by CuraEngine from the Gcode. These codes are useful for regular printing, but caused layer-shifting errors in our system. We also added a movement command to the end of the Gcode. This movement prevented printed objects from being melted by the heat of the printer head.

Finally, the system sends this Gcode to the 3D printer sequentially, and the 3D printer begins printing. When the printing of a layer is complete, the system generates and slices the next layer, increasing the height of the two plates. In the middle of this printing process, the system allows users to edit 3D model areas above the printed layers, which avoids interference with the printing process.

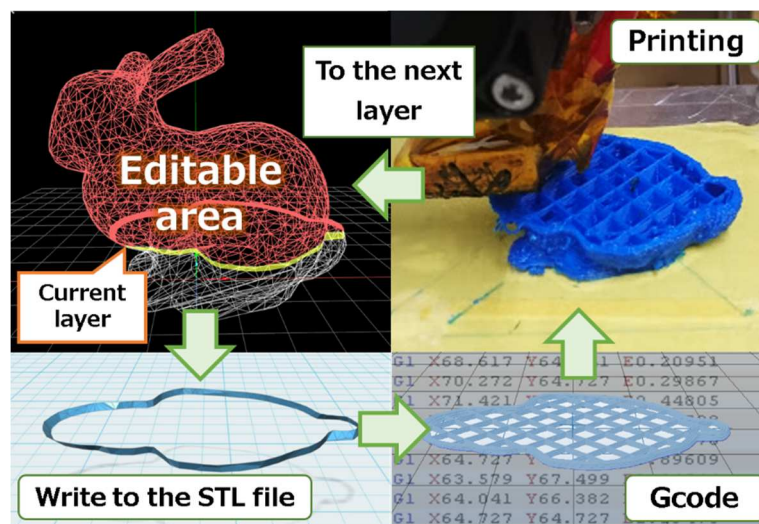


Figure 3. Process pipeline

DISCUSSION

Using our technique, an improved 3D printing process and fabrication environment are realized. Our technique allows users to begin printing with a view toward editing during printing; thus, it is possible to modify a 3D model in the middle of printing or create a 3D model while printing. This printing process is expected to improve printing efficiency. For example, if 3D models have a common lower part (such as the base seat shown in Figure 4a), users start printing first, and then create the upper area of the 3D model during printing.

In general, 3D modeling is an iterative process and users are able to repeatedly modify 3D models using digital software. In our technique, an object that is already printed has an irreversible character, and the non-printed area is created in consideration of previously printed layers. When our system is used to print entire objects, it is possible to engage in

³ <http://reprap.org/wiki/Cura>

creative activities that could be characterized as improvised modeling (Figure 4b). Of course, users can use traditional 3D modeling software to print an object and switch the 3D model during printing (Figure 4c).

There are a couple of limitations in our system and the process that allows editing during printing. The support structure for stable printing cannot be pre-calculated prior to the printing process. It is well-known that 3D models with overhanging parts cannot be printed without support structures. In our technique, however, these overhanging parts may be created during printing. To address this case, we may need to add support material dynamically during printing, or set up a modeling constraint that prevents the generation of overhanging parts.

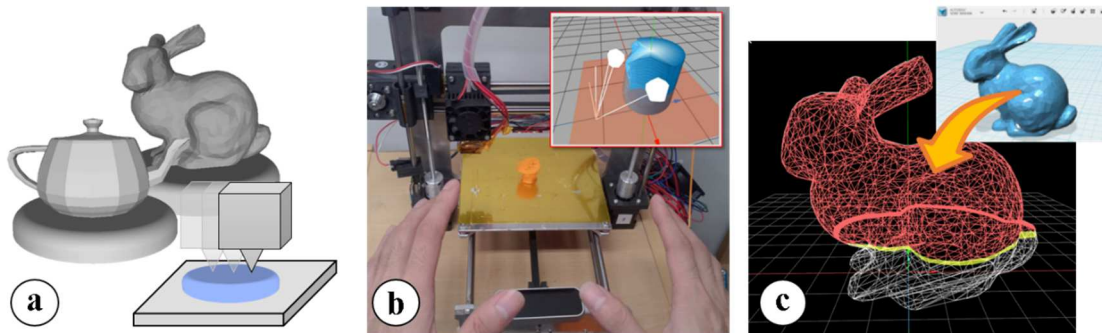


Figure 4. System usage. (a) 3D models with a common lower part. (b) Improvised modeling. (c) Switching the printed object while using traditional 3D modeling software.

CONCLUSION

In this paper, we presented an interactive fabrication system that allow users to edit a 3D model during printing. We described our system's mechanism in detail and discussed the capability of this technique.

We regard 3D printers not as machines that produce completed 3D models but as an interface for creating designs. Therefore, we believe that developing good relationships between people and 3D printers is vitally important. Our technique provides opportunities to integrate design into the fabrication process, and contributes to the discovery of new 3D printing capabilities. In future work, we plan to improve the user interface of our system, and conduct a user study to further evaluate our 3D printing techniques.

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