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Graphical 3D Printing: Challenges, Solutions and Applications

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Abstract

Graphical 3D printing is a relatively novel field of 3D printing focusing on reproducing the visual material appearance of an object in addition to its shape. Applications can be found in traditional prototyping, patient-individual surgery planning, fabricating prosthetic eyes, movie and entertainment industry as well as creating replicas in the field of cultural heritage. This paper gives a rough overview on the major challenges as well as solutions in graphical 3D printing focusing on imaging and computational aspects. It also gives an outlook to future research directions and new applications.

Figure 1. 3D printed partly-textured artificial eye. Model was printed with Cuttlefish® [1] on a Stratasys J750 3D printer.

Introduction

Graphical 3D printing describes the layer-wise fabrication of objects and their visual attributes (spatially-varying color, translucency, gloss) or optical material properties (spatially-varying Bidirectional Reflectance Distribution Function svBRDF or Bidirectional Surface Scattering Reflectance Distribution Function svBSSRDF) [2]. This requires 3D printing technologies able to combine multiple materials with different visual or optical properties in a single print with a very high resolution. Various 3D printing technologies are able to do this, such as Material Jetting (also called Polyjetting), Binder Jetting, Multi-Jet Fusion, Layer Laminated Manufacturing, Fused Deposition Modeling with inkjet coloring. All these 3D printing techniques use ink jetting to either color the layers during manufacturing or to directly jet colored material.

Applications

Graphical 3D printing has a large variety of applications that go far beyond the initial purpose of prototyping, for which 3D prints are created to mimic the appearance of end-products fabricated with traditional manufacturing methods. Prototyping is widely used in the consumer goods industry, automobile industry or architecture. In this paper, just a few other very interesting applications shall be mentioned:

1. Printing surgery planning models: Patient-individual models can be created from CT and MRI data at which color and/or translucency can be annotated based on a priori knowledge on the optical properties of the scanned tissue. Furthermore, regions of interest (such as tumors) can be visualized with false colors and transparencies can be used to visually remove occlusions without changing shape. For various indications, planning surgeries using anatomically accurate 3D printed models have shown a significantly shorter duration and higher success rates of surgeries as well as a reduction of costs for hospitals [3]. It is expected that the market for patient-individual surgery planning models (incl. just shape models) will grow to US$ 1.5 billion in 2027 [4].
2. Printing prosthetic eyes: Patients who lost an eye in an accident or due to a disease use commonly a prosthetic eye that is supposed to visually match the healthy eye. Today, manufacturing such artificial eyes is handcrafted work conducted by ocularists. This is time consuming and costly and lacks reproducibility. Graphical 3D printing is already able to create high-fidelity artificial eyes (see e.g. Fig. 1) and it is expected that this technology will disrupt the ocular prosthetic industry for the benefit of approx. 5 million patients.
3. Film making and entertainment: Graphical 3D printing is used in the movie industry to create props or for replacement animation [5]. Also in the growing computer game industry, graphical 3D printing is used to fabricate individual game characters.
4. 3D portraits: In many cities service providers offer already full-body 3D scans and a 3D printing service to create individual 3D portraits and figurines.
5. Replicas in the field of cultural heritage: Various museums create digital archives of their collections via color 3D scanning, allowing virtual exhibitions on the internet. This data can be used for 3D printing, which does not only aid restoration work but can also democratize the tangible access to such collections. Furthermore, it is possible to exhibit very realistic replicas instead of originals, which can be necessary because of climate and safety reasons. Finally, such replicas can also show simulations of objects before aging or (with transparencies) inner structures and hidden surfaces.

Challenges

Graphical 3D printing emerged in the early 2000s with the first binder jetting printers from ZCorp able to print in full color.

Figure 2. *3D printed artistic anatomy model. Model was printed with Cuttlefish® [1] on a Stratasys J750 3D printer.*

In the last decade many other printing technologies were introduced. Particularly Polyjetting allows the reproduction of appearance beyond color e.g. spatially-varying translucency or gloss. Even though today's printers are capable of creating a wide variety of appearance effects, many imaging and computational challenges must still be solved to exploit the full potential of this technology to reliably reproduce objects with given material appearance:

1. Handling erroneous input 3D models: For 3D printing, models have to possess distinct geometric properties for unambiguously determining whether a distinct point is part of the model or outside the model. One important property is watertightness, which means that the inner part of the model is completely enclosed by the mesh defining the surface. Every path from an inner point of the model to the outside has to intersect the surface. A model should also not posses non-manifols edges or corners. Many graphical 3D models have not been made with the purpose of printing, but for rendering and displaying, or are 3D scans for which occlusions result in holes in the model's surface. This causes also missing texture that needs to be inpainted. Some models might be suitable for 3D printing but have too thin structures for the particular 3D printer. These structures must be detected and removed or thickened for printing. In graphical 3D printing these geometric issues must be mostly manually corrected today because of the lack of algorithms ensuring printability in combination with esthetic consideration (smooth filling of holes, inpainting, etc.).
2. Optical modeling 3D printers: Optical printer models are predicting functions of reflectance and/or light transport properties, such as BRDFs or BSSRDFs, from given material arrangements and/or print process parameters. Models successfully used in 2D printing to predict reflectances, such as the Yule-Nielson spectral Neugebauer Model, show a poor prediction performance for translucent materials used in 3D printing. Cellular models require many cells to reach acceptable error rates and thus many prints and measurements. Models derived from approximations of the Radiative Transfer Equations (RTE), such as the Kubelka-Munk [6, 7], the Four-Flux Model [8] or Monte Carlo Path Tracing [9] were proposed.
   Furthermore, for highly-translucent printing materials, color measurements cannot be made with commercial spectrophotometers used in 2D printing due to edge-loss effects [10]. Thus, not only optical models but also measurement devices must be reconsidered for characterizing graphical 3D printers.
3. Sheer amount of data: The resolution of today's graphical 3D printers is very high, resulting in up to 10^{12} addressable voxels which can be filled, in case of the Stratasys J850, with up to eight available printing materials. Even small models contain dozens of billions of voxels. Storing this amount of data in memory at once is mostly impossible and a streaming architecture is necessary. A particular challenge is to consider global effects such as reproducing objects with optically thin (almost transparent) materials. In this case the translucency signal on the surface impacts the material placement of voxels far away from the surface and the sheer number of voxels makes it difficult to consider these long range effects accurately.
4. Defining a suitable appearance connecting space: Reproducing physical quantities, such as BRDFs or BSSRDFs, is mostly impossible in 3D printing due to the limited number of materials and their limited optical properties. Furthermore, it is very difficult and time consuming to measure such quantities and there is no metric in physical space that can be used to measure the perceived quality of a reproduction. Therefore, it is important to identify easy-measurable physical quantities relevant for our perception and to develop transformations that map these quantities into an (if possible low-dimensional) appearance space that can serve as a device-independent connection space between capturing devices and graphical 3D printers (similar approach as in color management). Such developments are still in its infancy and just a few approaches have been proposed, such as a low-dimensional joint color and translucency space [11].
5. Appearance gamut mapping: For color, various heuristic methods have been proposed for gamut mapping [12]. Also methods that use image difference metrics have been used to optimize color gamut mapping [13]. Combining color gamut mapping with gamut mapping of additional appearance attributes, such as translucency, is still an active research field and just a few approaches have been proposed [14]. Particularly, the interaction between appearance attributes is not fully understood yet and investigating potential cross-contamination (changing one attribute changes also another attribute) is necessary. Furthermore, research on the understanding of the impact of shape on material appearance is still in its infancy and just little quantitative data suitable for technical use has been published so far [15].

Solutions

A graphical 3D printing pipeline loads a textured 3D model and computes the material arrangements as well as print process parameters for controlling a multimaterial 3D printer to reproduce shape and appearance of the model. This requires multiple signal processing steps shown in Fig. 3:

1. In a preprocessing step the model is oriented and/or nested with other models in the print tray maximizing print speed

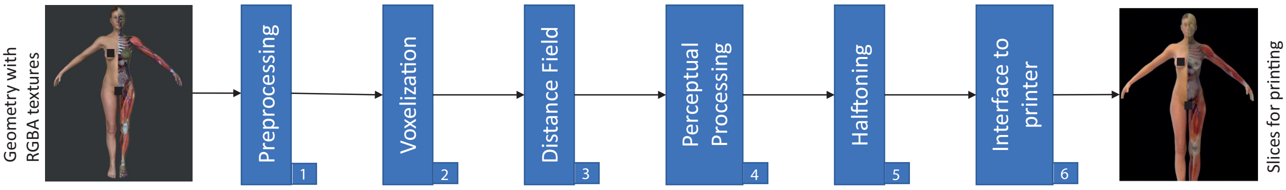

Figure 3. *Graphical 3D printing workflow*

and/or quality (the quality of reproducing fine details might depend on the orientation due to stair-casing artifacts or anisotropic print resolution) or minimizing support material consumption. Many pipelines also perform a mesh repair in a preprocessing step required for subsequent voxelization algorithms.

2. In the voxelization step the model is decomposed into a set of voxels corresponding to the print resolution. The voxel size represents the smallest geometric volume the printer can fill with a distinct material or fixed material mixture (in case the printer can jet multiple droplets with variable dot-size into one voxel). Typically the voxel is anisotropic with a much smaller size in Z (orthogonal to the slice plain) than in X or Y. Common ΔZ sizes of a voxel are between $14-30\mu$m and $\Delta X, \Delta Y$ between $40-80\mu$m. Particularly interesting are voxelization approaches robust to holes or other mesh errors, such as the one proposed by Jacobson et al. [16]. They are based on approximations of the generalized winding number and may directly determine whether a voxel is inside or outside the object even for complex self-overlapping meshes with holes.
3. In the next step a signed distance field to the surface voxels is computed, i.e. for each voxel the minimal distance to the surface is determined. This is necessary because the appearance information (such as color and translucency) is given just on the surface defined by texture mapping or per-vertex-colors. Particularly for global effects, such as translucency/transparency, every voxel in the volume must possess this information. Using the distance field the appearance signal of the nearest surface voxel can be assigned to every voxel. Brunton et al. [14] show how to efficiently compute such distance fields employing slice-wise distance transforms using the algorithms proposed by Felzenzwalb and Huttenlocher [17].
4. The next step called *Appearance Processing* in Fig. 3 transforms the device independent appearance information into material ratios and/or print process parameters required to reproduce the given appearance. This is done typically on a voxel level using a precomputed look-up table. This table combines appearance gamut mapping and the inverted optical printer model and must be smooth to avoid banding artifacts. Brunton et al. proposed a method to create such a table for joint color and translucency reproduction [14]. Fig. 4 shows an example print made with this approach.
5. At this stage of the pipeline, each voxel contains a ratio of printing materials and/or print process parameters. The print process parameters can be directly applied but a voxel can just be filled with only one material or a ratio of materials with a very small bit depth (for printers allowing variable dot size voxel fillings). A volumetric halftoning algorithm must be applied to quantize the material ratio into the desired bit depth (mostly just one material per voxel). Since the contrast sensitivity of the human visual system is particularly high for low-frequencies, i.e. to errors caused by agglomerations of materials, a halftoning algorithms creating material arrangements with blue-noise characteristic produces visually pleasing results, in particular preserving the smoothness of appearance gradients. Error-diffusion algorithms applied per slice or adapted to the 3D geometry [18] as well as 3D halftoning matrices [19] were proposed for this purpose.
6. In the final stage of the pipeline print control data, i.e. material arrangements and (local/global) print process parameters are send to the printer's firmware for fabrication.

Some pipelines also contain components to correct physical effects, such as texture blurring caused by subsurface light transport, [20, 9]. Fig. 1 shows a 3D printed artificial translucent eye with very fine texture details for which a correction method for light transport blurring was used (not published so far).

Due to the high resolution of printing systems a 3D printing pipeline is supposed to be based on a streaming architecture, i.e. that just a few slices are computed and stored in memory at each point of time.

In the case the input data is already in a voxel format, such as in medical applications as color/translucency annotated CT or MRI data, the preprocessing and voxelization step must be replaced by a voxel resampling from the medical device resolution to the almost always much higher resolution of the 3D printer.

Outlook and Future Research Directions

Two ongoing developments are particularly interesting to shape the future of graphical 3D printing:

1. The Multi-Jet-Fusion technology can create full-color parts with a mechanical durability similar to parts fabricated with injection molding. This allows a large spectrum of applications of highly customized real world parts, such as eyeglass frames. Due to the powder bed approach the visual quality, in particular the texture quality, is not as high as in Polyjetting and it is also not possible to create translucencies/transparencies so far. New advances in this technology might improve quality and add more visual effects.
2. Polyjetting can create full-color parts possessing an extremely high visual quality with spatially-varying translucencies, transparencies and gloss. Due to the use of low-viscose photopolymers the mechanical durability was not high enough for many applications. This limitation will be strongly reduced in future because of new high-speed print head developments, allowing to jet high-viscose photopolymers, able to create durable parts sufficient for various applications. Furthermore, these high-speed print heads combined with new 3D printer designs with rotary-trays can reduce printing time drastically.

Today's graphical 3D printers, in particular Polyjetting, can create color, translucency and gloss effects. Some appearance effects, such as spatially-varying goniochromatic or metallic appearance, are not reproducible today. New 3D printing materials may change this in near future requiring an adaptation of the

Figure 4. *3D printed head model possessing color and translucency of human skin. Model was printed with Cuttlefish® [1] on a Stratasys J750 3D printer.*

3D printing pipeline and more effort into designing an appropriate appearance connection space. The new EU Marie-Curie ITN project *ApPEARS* [21] is focusing on developing solutions to many of the challenges stated in this paper.

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