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SwissVAMyKnife.jl: an open-source package for tomographic volumetric additive manufacturing

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Abstract. We introduce an optimization framework for ray and wave optical tomographic volumetric additive manufacturing (TVAM). In TVAM, tomographic patterns are projected with a light modulator onto a photocurable resin from different angular directions. Once an energy dose threshold is crossed, the resin starts polymerizing. Current approaches assume a ray optical model for light propagation, using the Radon transform as backbone, which breaks down for small features in the region of 20 µm. In this work we describe how a wave optical framework allows to optically print smaller feature sizes. The optimization framework is written in the programming language Julia and allows for high-performance optimization of ray or wave optical based patterns for volumetric additive manufacturing.

1 Introduction

Tomographic volumetric additive manufacturing (TVAM) is an emerging 3D printing technique because it allows to print millimeter to centimeter scale objects within tens of seconds [1, 2]. It is based on the tomographic principle which projects patterns from different angular directions onto a glass vial containing the photosensitive resin. Because it can only project a non-negative light dose the whole volume receives light intensity. Therefore, it is important that the resin polymerizes only when a certain deposit energy is reached. A lot of work has been contributed to solve the question which is the optimal set of patterns such that object voxels cross this threshold whereas void pixels should stay below that threshold [2–4]. The general setup of TVAM is shown in Fig. 1.

2 Optimization Formulation

The key ingredient for the optimization problem to find the optimal patterns is the following loss function which is inspired by [5]:

$$\mathcal{L} = \underbrace{\sum_{v \in \text{object}} |\text{ReLu}(T_U - I_v)|^2}_{\text{force object polymerization}} + \underbrace{\sum_{v \notin \text{object}} |\text{ReLu}(I_v - T_L)|^2}_{\text{keep empty space unpolymerized}}$$

$$+ \underbrace{\sum_{v \in \text{object}} |\text{ReLu}(I_v - 1)|^2}_{\text{avoid overpolymerization}} + \underbrace{\kappa \cdot \sum_{j \in \text{patterns}} |P_j|^D}_{\text{enforce non-sparse patterns}}$$

I_v is the normalized received intensity at a voxel v after propagation of the patterns. The first term ensures that object voxel receive more intensity than T_U to polymerize. The second term ensures that void voxels stay below a threshold of T_L to not polymerize. The third term introduces a penalty if some object voxels receive more intensity than 1 which avoids overpolymerization. Typical values are $(T_L, T_U) = (0.9, 0.97)$. The last term controls the sparsity of the patterns. P_j is the j-th pattern (e.g. corresponding to different angles). κ is the weighting factor of this term. Suitable values for D are 2,3 or 4. The optical propagator $\mathcal{P}$ propagates the pattern into the volume filled with photosensitive resin. $\mathcal{P}$ can be ray or wave optics based. The ray optical assumption is commonly used in literature; recently a wave-optical model with amplitude modulation has been introduced [6]. Our group also utilized a Lee-hologram to print samples in a Fourier space phase modulation configuration [7]. However, the theoretical model in printing space is still a hybrid ray and wave optical approach. Li et al. have rigorously simulated the wave optical propagation based on a Fourier-space modulation [8].

3 Numerical results

Our source code is written in the programming language Julia [9] and allows to optimize patterns based on ray or wave optical assumptions. It can run on GPUs or CPUs and corrects for light absorption of the resin (following Beer-Lambert's law) or refraction from the air-glass-resin interface. Fig.1 shows the optimized results. Importantly, i) shows the distributed intensity at a small length scale optimized with the wave optical propagator. After thresholding a perfect print can be seen in j). However, if we take ray optical optimized patterns (from a)), the ignored diffraction effects severely degrade the printing quality (see k)).

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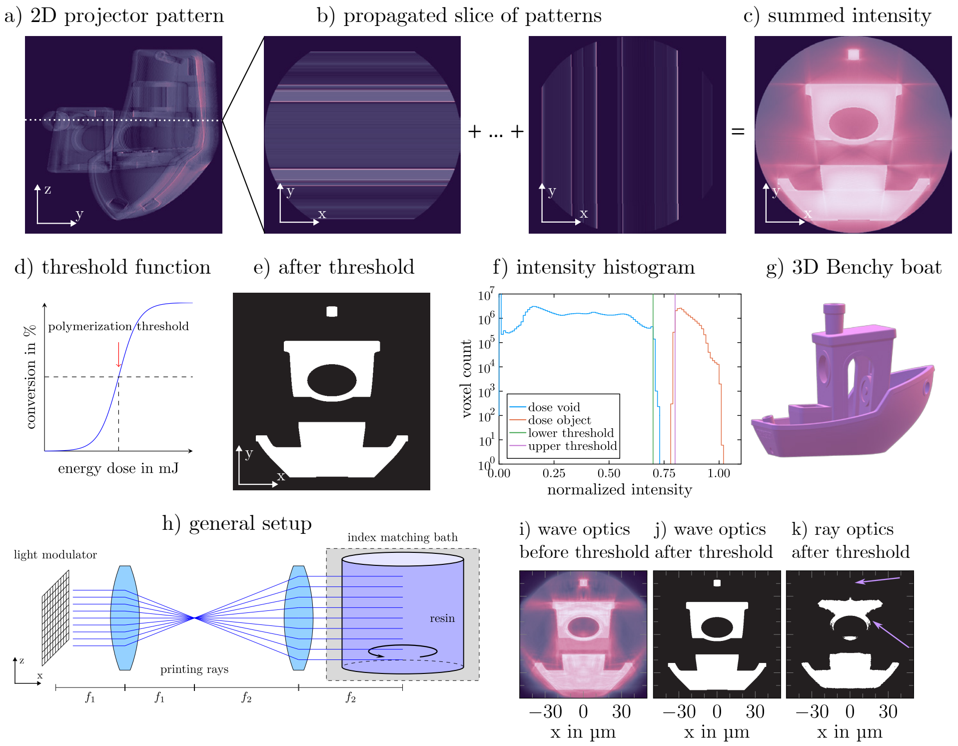

Figure 1. The general principle behind TVAM. a) a set of 2D projection patterns is propagated into space. b) shows how a slice of the pattern propagates through the volume and c) how the incoherent sum results in a total energy dose. d) the object polymerizes if it reaches an energy threshold. e) polymerization threshold results in a printed slice. f) is the intensity histogram of b). g) is the 3D view of the Benchy boat. h) is the general amplitude setup. i) is a wave optical optimization result at a small length scale. j) is the printed region after thresholding. k) is a ray optical optimization result propagated with the wave optical propagator.

4 Conclusion

SwissVAMyKnife.jl is able to optimize wave optical and ray optical patterns for Tomographic Volumetric Additive Manufacturing. This packages demonstrates that the optical patterns allow for micrometer scale TVAM.

5 Backmatter

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Data Availability All source code for the optimization is available over the `SwissVAMyKnife.jl` package on GitHub: github.com/EPFL-LAPD/SwissVAMyKnife.jl

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