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Monocular Vision for Online Feedback Control in Volumetric 3D Printing

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Abstract
Volume 3D printing, also called volumetric additive manufacturing or computed axial lithography, is a new way to create objects in which the entire 3D shape forms at once inside a liquid resin, rather than being built layer by layer. Currently, this system operates in an open-loop mode, where adjustments can only be made by trial after printing is complete, which limits further improvement in printing accuracy and production. To address this issue, this work proposes a method for monitoring and feedback through multi-angle light scattering image acquisition based on monocular vision: the foreground image of the light scattering image is extracted via background subtraction and threshold calibration, and then the 3D reconstruction of the printed model is achieved by combining filtered back-projection, edge extraction, and volume rendering algorithms. Meanwhile, the projected light dose is adjusted based on the forming status to achieve closed-loop control. Experimental results show that this method effectively addresses excessive curing in large features.

Keywords: volumetric printing; monocular vision; 3D reconstruction; feedback adjustment; closed-loop control

1. Introduction

Volumetric 3D printing (V3DP) borrows from computed tomography (CT) imaging, decomposing the target's three-dimensional light dose field into multi-angle two-dimensional projection patterns using Radon transform, and then sequentially projecting these patterns onto a photosensitive material [1]. When the accumulated light dose in the target area exceeds the curing threshold, the structure solidifies entirely within the material, achieving rapid prototyping. This paradigm avoids layer-by-layer stacking, thus possessing advantages such as speed, no layering, no support required, and high structural freedom, showing potential applications in biomedicine, flexible electronics, ceramics, and optical devices [2, 3].

However, V3DP is still constrained by problems such as insufficient repeatability, light scattering, difficulty in quantitative process monitoring, and limited precision for small features. Existing work has improved forming quality through offline light dose correction or post-printing reconstruction, but these rely on the results of the previous round to correct the next round of the process, making it difficult to suppress error accumulation in a timely manner [4, 5]. To address this, this paper constructs an online monitoring and feedback system. It uses a CCD to acquire formed images and extract the foreground sequence, combining filtered backprojection and geometric reconstruction to achieve three-dimensional reconstruction and quantitative process monitoring. Based on this, it adjusts the projected light dose in a closed loop, thereby improving the forming precision of small features and printing repeatability.

2. Methods and materials

In this study, to achieve online monitoring of the volumetric 3D printing process, we designed a photocuring system that undergoes phase separation during polymerization/gelation, forming a polymer-rich phase and a polymer-poor phase. The microscopic inhomogeneity caused by phase separation significantly enhances light scattering during the gelation stage; therefore, the cured region appears milky white with high scattering, while the uncured region remains clear and transparent.

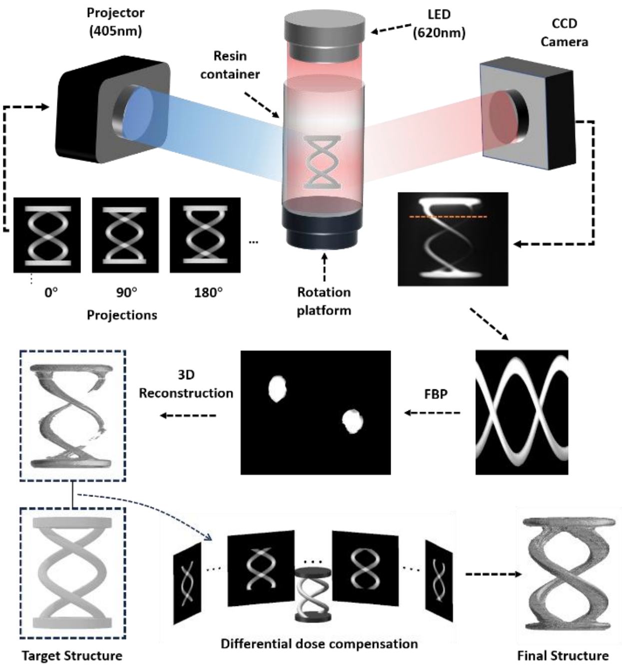

Figure 1. Schematic diagram of an online monitoring and feedback system for volumetric 3D printing

As shown in Figure 1, after extracting the foreground image, the forming process of the forming region can be observed after eliminating background interference. When a new feature is formed in the forming region, the projection is stopped and the rotary table is rotated one revolution to obtain light scattering data of the forming model at different angles. By analyzing the scattering data at different angles within one cycle, the lateral scattered light of the forming model can be analyzed to construct the projection sine curve of each two-dimensional cross-section of the model. Back-projection of these projection sine curves can construct the two-dimensional cross-sectional image of each layer of the model. However, since the two-dimensional cross-sectional image obtained by direct back-projection is the projection value of each angle back-projected onto the image plane, the reconstructed two-dimensional cross-sectional image will have problems such as blurred edges, radial artifacts in high-contrast areas, and low-frequency information redundancy. To counteract this distortion and correct the frequency characteristics of the projection data, a filtering function is introduced during back-projection to obtain the filtered back-projection (FBP) cross-sectional image. After obtaining the two-dimensional cross-sectional images of each layer of the formed model, the three-dimensional model can be reconstructed by stacking these cross-sections in the Z direction.

After 3D reconstruction of the forming effect, the forming status of the printed model during the printing process can be further analyzed, and this can be used as a basis to determine whether printing is complete. If only some feature areas of the printed model are formed, and printing is not complete, the light dose can be adjusted based on the actual forming status of the printed model, as shown in Figure 1. This feedback method overcomes the problem that volumetric 3D printing systems cannot perform dynamic mode correction, and also solves the problem of over-curing caused by the continued accumulation of light dose in already formed areas during subsequent printing processes. This further improves the forming accuracy of the printed model and establishes a closed-loop control system that adjusts the light dose based on the forming status during the printing process.

3. Results

Figure 2 illustrates the forming evolution of the double-helix structure model during the printing process. The reconstructed 3D model shows that before light dose feedback adjustment, the larger feature (the two flat cylindrical features at the top and bottom) appears first, followed by the smaller feature (the middle helical structure). Upon completion of printing, the larger feature underwent over-curing, with the light-receiving side over-curing to the bottle wall, resulting in significant forming errors.

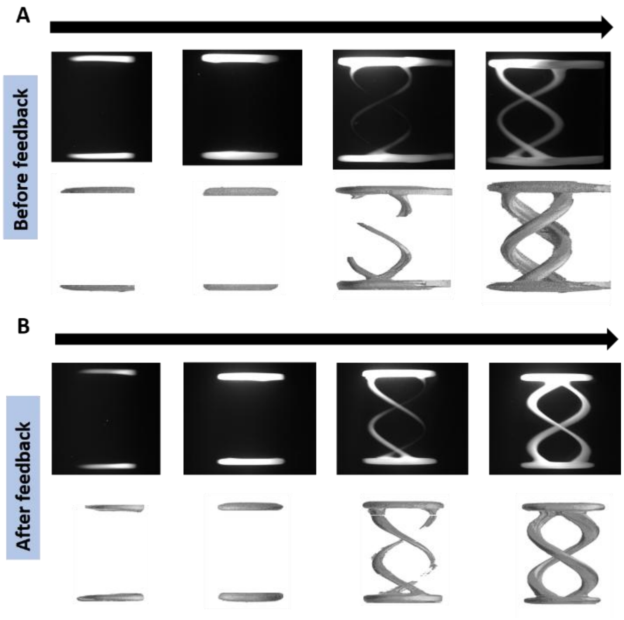

Figure 2. Diagrams of the printing model forming process before and after feedback

After feedback adjustment, when the larger feature (the two flat cylindrical features) was fully formed, the light dose projection of that feature was stopped, while the unformed portion (the middle helical structure) maintained its projection. This reduced the impact of inconsistent curing times for features of different sizes within the target area, improving the forming accuracy of the smaller feature area while preventing over-curing of the larger feature area, effectively enhancing the forming accuracy of the printed model.

Furthermore, Figure 3 shows the molding results of the microchannel structure and boat model printed under the designed volumetric additive manufacturing monitoring and feedback system, and provides the corresponding 3D reconstruction model. The results demonstrate that the system can perform non-contact 3D measurement of the molded body during the printing process, and achieve closed-loop feedback adjustment of the light dose based on the measured shape deviation, thus avoiding the accuracy degradation caused by the difficulty in dose correction based on the actual molding state in traditional printing. Using this method, the shape error of the printed model is controlled within ±200 μm, significantly improving the printing accuracy.

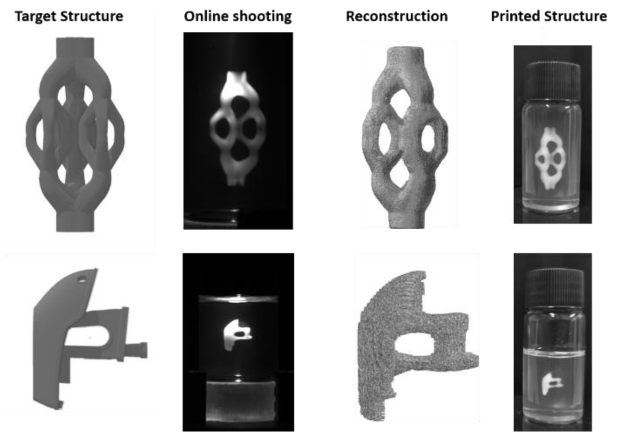

Figure 3. Other structural model printing and 3D reconstruction

4. Conclusion

This paper constructs an integrated monitoring and feedback scheme for volumetric 3D printing and verifies its effect on improving forming accuracy and process stability. First, a 3D reconstruction method is proposed to achieve non-contact 3D measurement of the forming process during printing. Second, a photometric dose feedback strategy is proposed to address the problems of under-curing/distortion of small features and over-curing of large feature areas. This strategy achieves adaptive dose adjustment based on the forming state, effectively improving the forming quality of detailed features and suppressing local over-curing, providing system-level methodological support for high-fidelity, repeatable volumetric 3D printing.

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