Position estimation through scattering medium by using digital twin based on Gaussian splatting

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Abstract: In this study, we propose a method for estimating positions of objects through scattering media using a digital twin. Use of digital twins generated through data assimilation enables the emulation of real-world phenomena through model analysis and prediction. By emulating scattering process as convolution of point spread function and optimizing a digital twin consisting of Gaussian clouds with rendered images, three dimensional space behind a scattering medium can be reproduced. Experimental result shows that the position of LED behind scattering medium can be estimated by reconstructing a three-dimensional space as a digital twin.

***Keywords**: computational imaging, Three-dimensional image processing*

Introduction

Estimating the position of light source through scattering media is an important technique in fluorescence imaging to observe deep tissues, which shows unique opportunities for studying cellular dynamics and interaction. Confocal microscopy and two-photon microscopy enable to detect fluorescence in biological tissue and identify position and shape of target through selective excitation of the fluorophore. However, these methods require scanning the focusing point three-dimensionally, which take significant time. A digital twin constructed through data assimilation can reveal behaviors of objects and phenomena in real-world by modeling and emulating them in cyber space [1]. We aim to implement three-dimensional scattering imaging by using a digital twin constructed with measurement data. In this study, we construct a digital twin using three-dimensional Gaussian splatting (3DGS) to represent the positions of point light sources beyond a scattering medium. 3DGS represents three-dimensional space as an ensemble of opaque ellipsoids [2]. Using this method, LED light sources positioned behind the scattering medium were reconstructed through a 3DGS algorithm involving the scattering process. We evaluated the performance of the digital twin by estimating the positions of the LEDs.

Construction of digital twin based on Gaussian Splatting involving scattering process

3DGS is a method for representing three-dimensional space using Gaussians with adjustable opacity. To achieve position estimation of an object by using the digital twin, scattering process is involved in images rendered from the digital twin consisting of Gaussians. Figure 1 shows a procedure of 3DGS algorithm involving scattering processing to construct the digital twin behind scattering medium. First, randomly distributed point clouds are generated. Each point is converted into a set of Gaussians with opacities following Gaussian distribution by adding parameters including 3D covariance matrix, opacity and spherical harmonic coefficient which represent its color. By projection and differentiable tile rasterizer, the digital twin of the 3D space, which is represented by Gaussians is rendered into images based on the camera pose. Each pixel value in the rendered image is calculated through the alpha-blending of N ordered:

$$I_{pix} = \sum_{i}^{N} c_i \alpha_i^{2D} \prod_{j}^{i-1} \left(1 - \alpha_j^{2D}\right),$$

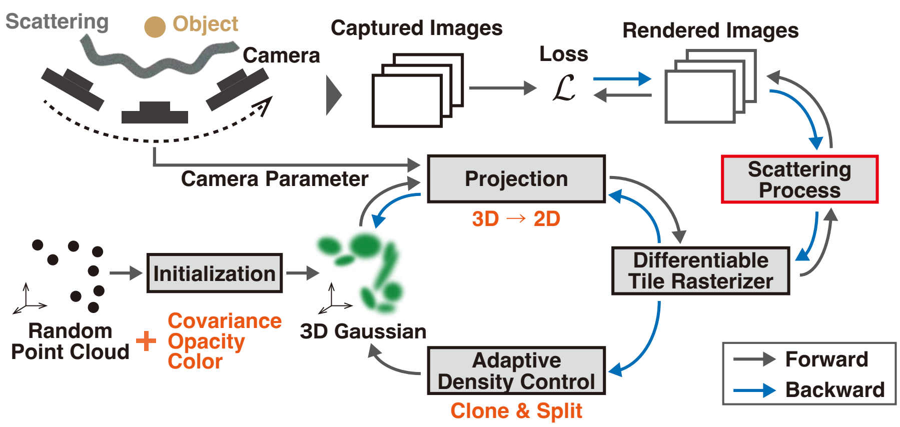

Figure 1 Procedure of digital twin construction involving scattering process.

where α_i^{2D} represents opacity of the i-th Gaussian weighted by 2D Gaussian covariance. In our method, the rendered images are degraded using convolution with pre-measured point spread function (PSF). By involving convolution with PSF, the scattering process can be reproduced in the algorithm for constructing the digital twin. By minimizing loss values between actually and virtually captured image, the parameters of each Gaussian are optimized using stochastic gradient descent technique. In addition, the number of Gaussians are adjusted based on cloning and splitting. Through iterative processing, the digital twin representing 3D space without scattering can be constructed, and objects and its position behind scattering media can be estimated.

Digital twin of LED array behind scattering medium and position estimation

To demonstrate the effectiveness of a digital twin, we captured images of LEDs behind a scattering medium and estimated their positions. Three LEDs were placed in three-dimensional space and illuminated (Fig. 2). A scattering medium was positioned in front of the image sensor, and the LED array was captured from various angles. Figure 3 shows the LEDs captured from a viewpoints. Compared to the image captured without the scattering medium [Fig. 3 (a)], the virtual images obtained using the primitive GS algorithm appeared blurred [Fig. 3 (b)]. In contrast, the images obtained with the proposed method successfully reproduced the shape of the LEDs [Fig. 3 (c)]. To investigate that the digital twin reproduces the three-dimensional space, the centroid of the Gaussian ensemble representing each LED was calculated to estimate the positions of the LEDs [Fig. 3 (d)]. The centroid positions of each Gaussian ensemble were estimated from the digital twin corresponded to those derived from the parallax of images taken from multiple angles, with an estimation error of 2.0 mm. We confirmed that construction of a digital twin based on GS involving scattering process estimated the position of light sources accurately. Our method contributes to identify the positions of fluorophores inside scattering media.

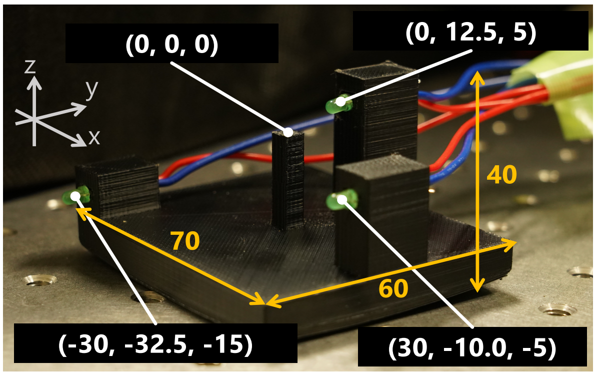

Figure 2 LED array placed in three dimensional space. The coordinates units are in millimeter.

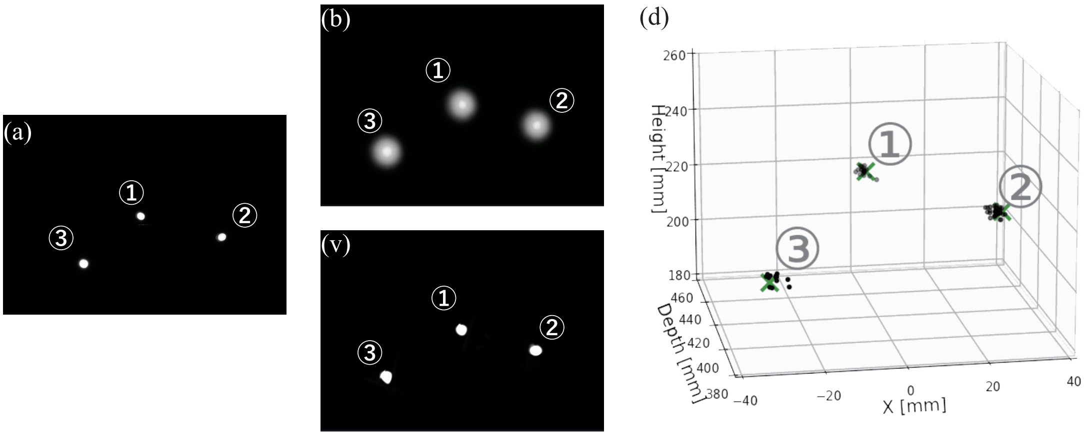

Figure 3 (a) Captured image of the three LED from a viewpoint without a scattering medium. Virtually captured images obtained using (b) the primitive GS method and (c) our proposed method. (d) Scatter plot showing the center positions of Gaussians (black dots) and the estimated LED positions (green crosses).

Acknowledgments

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References

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