Elimination of Apparent Image on Single-Pixel-Imaging by Use of High-Frame-Rate Display With Latent Random Dot Patterns

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ABSTRACT

Single-pixel-imaging in which random patterns for illumination are latent in the apparent image have the problem that the apparent image remains on the reconstructed image. By using negative-positive inversion of the apparent image as the illumination pattern, the influence of the apparent image on the reconstructed image was reduced.

1 Introduction

Single-pixel-imaging is a method for imaging by photodetector and randomly changing illumination pattern, without image sensing device such as camera. Image is reconstructed by the use of correlation between fluctuation of detected intensity and fluctuation of illumination intensity. Single-pixel-imaging has attracted attention because of its ability to capture images at wavelengths other than visible light and in low light. However, single-pixel-imaging used to have problems with low reconstruction quality and time-consuming data acquisition. It takes a lot of time to acquire the same level of data as images taken with a typical camera [1]. There have been studies using Hadamard transforms and Fourier transforms for efficient reconstruction [2], as well as deep learning to reduce the time required to take pictures [3].

We focus on the privacy considerations of single-pixel-imaging. Single-pixel-imaging enables privacy-aware imaging by capturing shadow pictures. Our previous studies include privacy-aware gesture recognition, improving computational methods to reduce the number of measurements for single-pixel-imaging, and using deep learning to restore reconstructed images and classify reconstructed images [4]. As an implementation, single-pixel-imaging using a high-frame-rate display as a light source has been proposed [5]. By high-speed modulation of the random pattern in which the apparent image is latent, observer can recognize the apparent image. However, the image reconstructed by this method retains the influence of the apparent image. We propose the use of negative-positive inversion of apparent images to eliminate the influence of apparent images. By merging the reconstructed image with the apparent image and the reconstructed image with the negative-positive inversion of the apparent image, it is expected to cancel out the influence of each other's apparent image.

The purpose of this paper is to verify the elimination of the apparent image on the reconstructed image by using negative-positive inversion of the apparent image. We examined whether the influence of Eliminating the apparent image by proposed method changes depending on the number of times of illumination used for reconstruction of single-pixel-imaging.

2 Principle

2.1 Single-Pixel-Imaging

The basic principle of single-pixel-imaging used in this paper is shown in Fig. 1. A randomly generated mask is used to modulate the illumination for the subject at an arbitrary number of times, and the measurement is conducted by use of a single-pixel detector. The information obtained from the measurements is converted into a matrix and calculated by an intensity correlation function. The calculation gives the restored image as a result of a floating-point operation that takes a range from -1 to 1. In order to obtain a clear restored image, a large number of measurements are required. The restored image with a small number of measurements contains a lot of noise. The intensity correlation function can be expressed as:

$$\begin{aligned} G(x,y,n) &= \langle \Delta I(x,y,n)\Delta A(n)\rangle \\ &= \langle [I(x,y,n)-\langle I(x,y,n)\rangle][A(n)-\langle \Delta A(n)\rangle]\rangle \\ &= \langle I(x,y,n)A(n)\rangle - \langle I(x,y,n)\rangle\langle A(n)\rangle \end{aligned} \tag{1}$$

where $\Delta I(x,y,n)$ is the deviation between the light intensity $I(x,y,n)$ and the mean $\langle I(x,y,n)\rangle$ of the n-th randomly patterned mask in the coordinates (x,y). $\Delta A(n)$ is the deviation of the average value of the light intensity pixel detector. $A(n)$ can also be given by

$$A(n) = \iint T(x,y)I(x,y,n)dxdy \tag{2}$$

where $T(x,y)$ denotes the transmission function [6–7].

The Reconstruction results for each number of measurements is shown in Fig. 2.

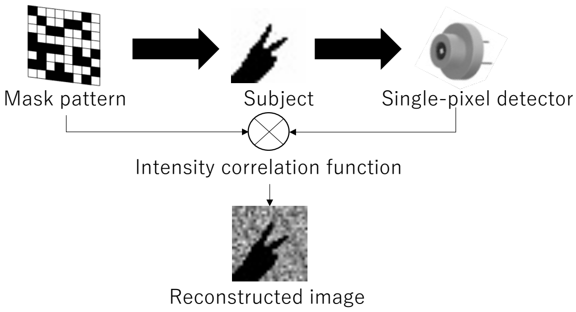

Fig. 1 Schematic diagram of single-pixel-imaging to detect shadow picture.

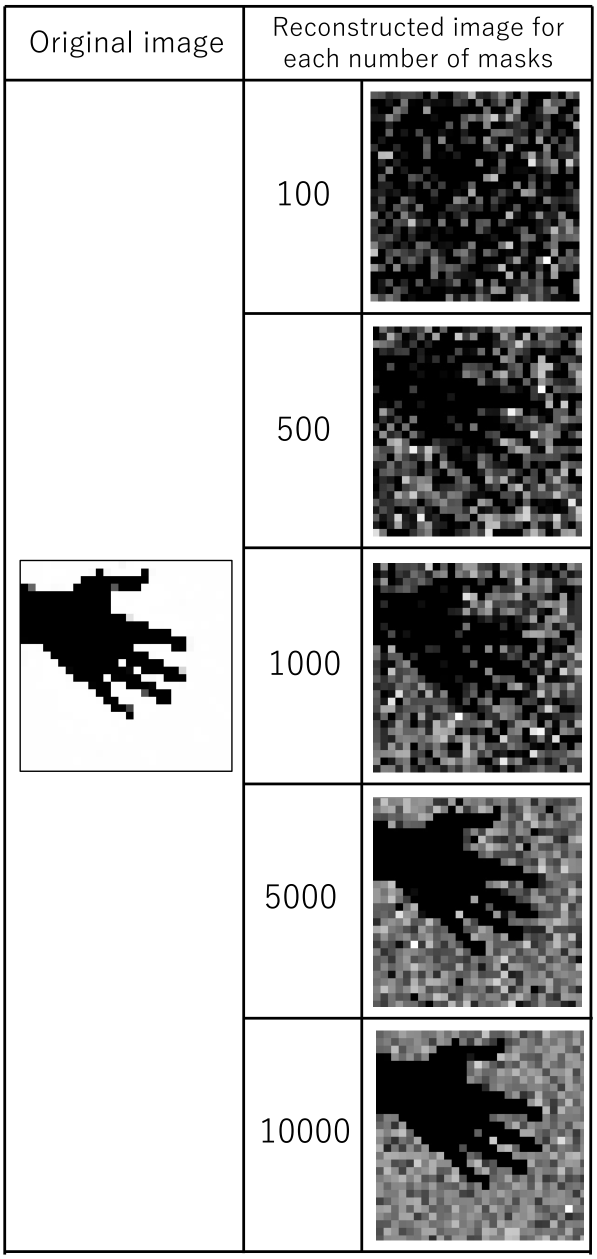

Fig. 2 The reconstruction results for each number of measurements.

2.2 Encoding of Apparent Images

Schematic diagram of the spatial-temporal codes with an apparent image is shown in Fig. 3. The LED display is updated at a sufficiently high frame rate so that the observer perceives an integrated image of latent random patterns. This principle has been confirmed with LED displays at 960 fps [8].

Encode m frames in order to latent random patterns in the apparent image. The latent random pattern satisfies:

$$V(x,y) \equiv \sum_{n=1}^{m} E(x,y,n) \tag{3}$$

where $V(x,y)$ be the pixel value of the apparent image at coordinate (x,y) and $E(x,y,n)$ be the pixel value of the nth coded image. The order in which these are displayed is random for each pixel. By displaying them at high speed, they are perceived by the observer in the same way as apparent images.

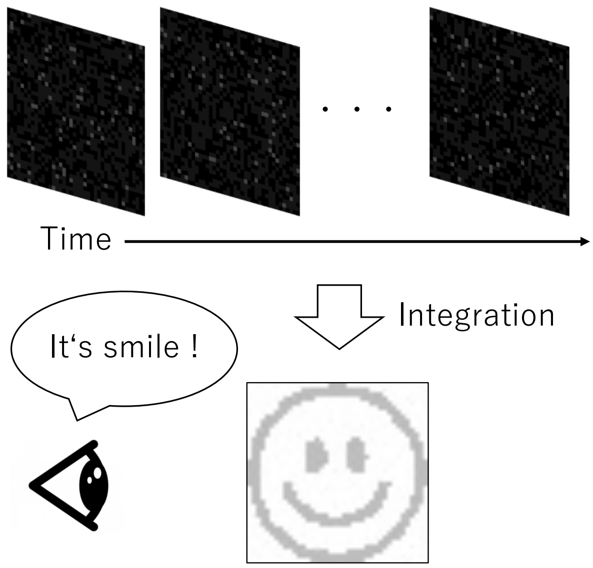

Fig. 3 Schematic diagram of the spatial-temporal codes with an apparent image.

3 Single-Pixel-Imaging with Apparent Images

3.1 Experiment

The apparent image is a binary image with pixel values of 190, 255 as shown in Fig. 4(a), and Fig. 4(b) is a negative-positive inversion of Fig. 1(a). To latent a random pattern in the apparent image, it is encoded in 20 frames. The example of encoding images is shown in Fig. 5. This paper consists of one frame with pixel values of 0 or 65, 10 frames with pixel values of 19, and 9 frames with pixel values of 0. The 20 encoded images are added together to obtain the apparent image.

The subject image is 40x40 pixels with pixel value 0,255 as shown in Fig. 6. Reconstruction of the subject image is performed with the coded image of the apparent image and the coded image of the negative-positive reversal of the apparent image, respectively. The number of masks for single-pixel imaging is 100, 500, 1000, 5000, and 10000.

(a) (b)

Fig. 4 (a)Apparent images and (b) its negative-positive inversion.

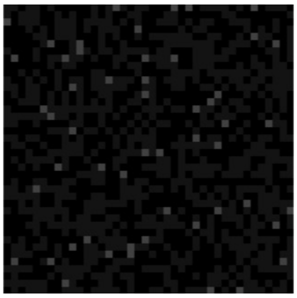

Fig. 5 Example of encoding images.

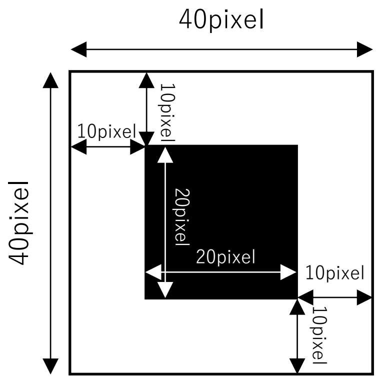

Fig. 6 Size of subject image.

3.2 Results

The Reconstruction results using apparent images and negative-positive inversion of apparent images are shown in Fig. 7. In the reconstructed images with 5,000 and 10,000 masks, the subject image is clearly reconstructed, but the reconstructed image is influenced by the apparent image. In the reconstructed images with less than 1000 masks, the reconstructed images are noisy, and the subject image cannot be reconstructed well, and some influence of the apparent image can be seen in the reconstructed images.

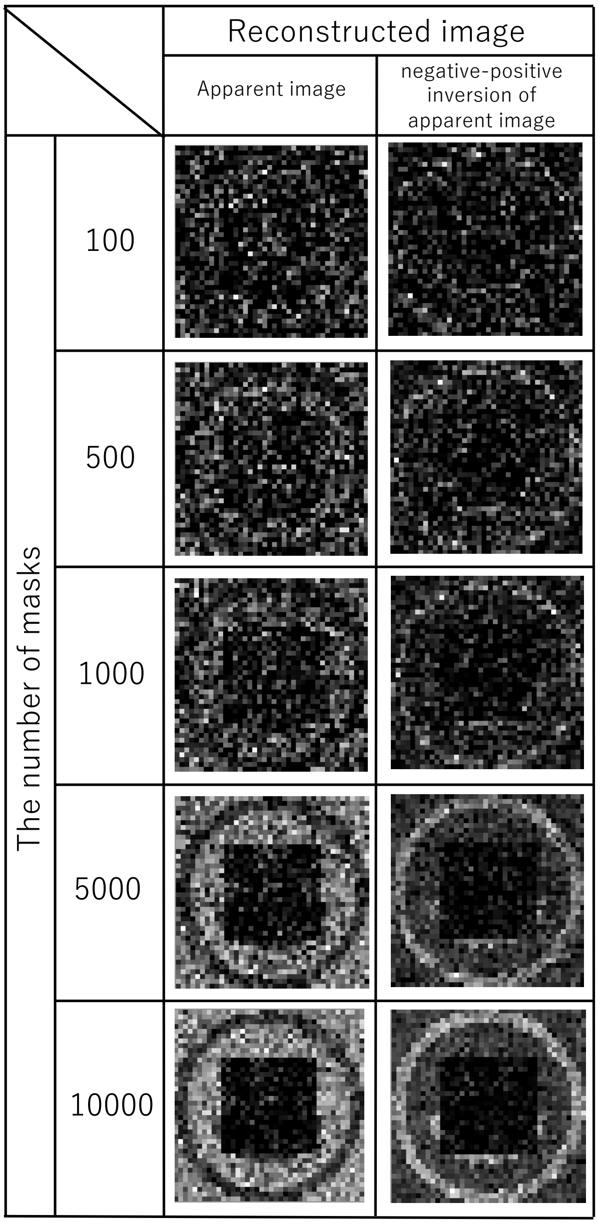

Fig. 7 The reconstruction results using apparent images and negative-positive inversion of apparent images.

4 Elimination of Apparent Image Influence

4.1 Experiment

Use reconstructed images with negative-positive inversion of the apparent image to eliminate the influence of the apparent image. These two reconstructed images are added and averaged together to eliminate the influence of the apparent image.

4.2 Results

The result of adding and averaging the reconstructed image using the apparent image and the reconstructed image using the negative-positive inversion of the apparent image. is shown in fig. 8.

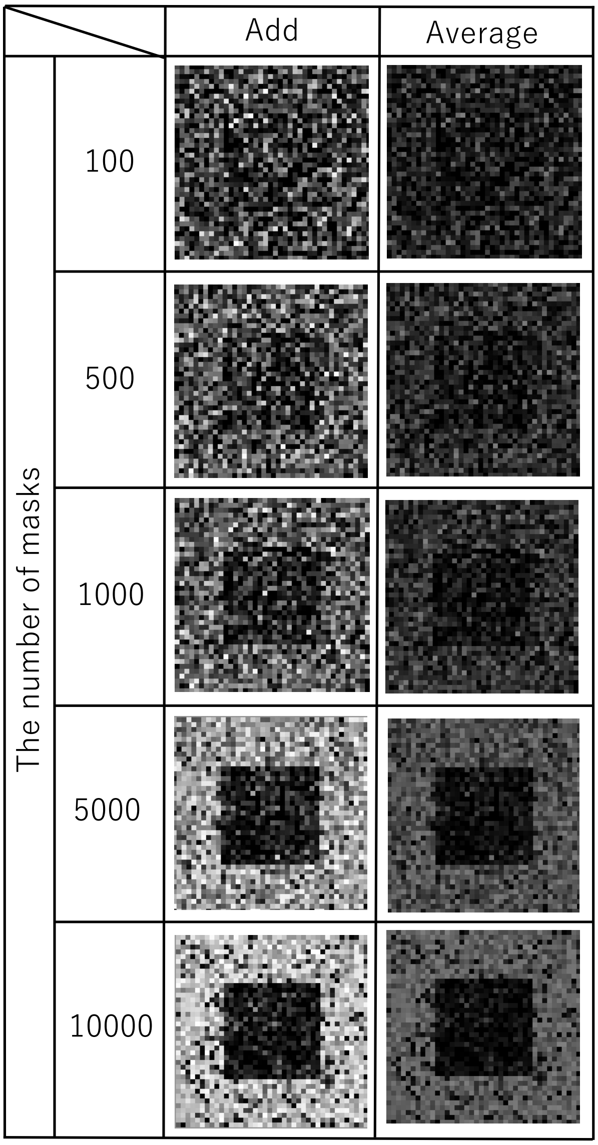

Fig. 8 The result of adding and averaging the reconstructed image using the apparent image and the reconstructed image using the negative-positive inversion of the apparent image.

5 Discussion

In Fig. 7, the effect of the apparent image is more apparent. In this paper, 20 images were encoded, but it is necessary to find a number of images that reduces the influence of apparent images. However, if the number of encoded images is increased, the image may become darker when viewed by the viewer, so it is necessary to examine the encoding process to ensure good visibility and to reduce the influence of apparent images. It is also thought that deep learning can be used to eliminate the influence of apparent images.

In Fig. 8, the influence of the apparent image was removed by combining the reconstructed image using the apparent image and the reconstructed image using the negative-positive inversion of the apparent image. Comparing the added image and the average image, the added image is brighter, and the shape of the subject is more recognizable. Therefore, the added image is considered to be suitable.

6 Conclusions

Single-pixel-imaging was performed with random patterns latent in the apparent image. The reconstructed image is influenced by the apparent image. The influence of the apparent image was successfully removed by adding up the reconstructed images using negative-positive inversion of the apparent image to remove the influence of the apparent image.

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