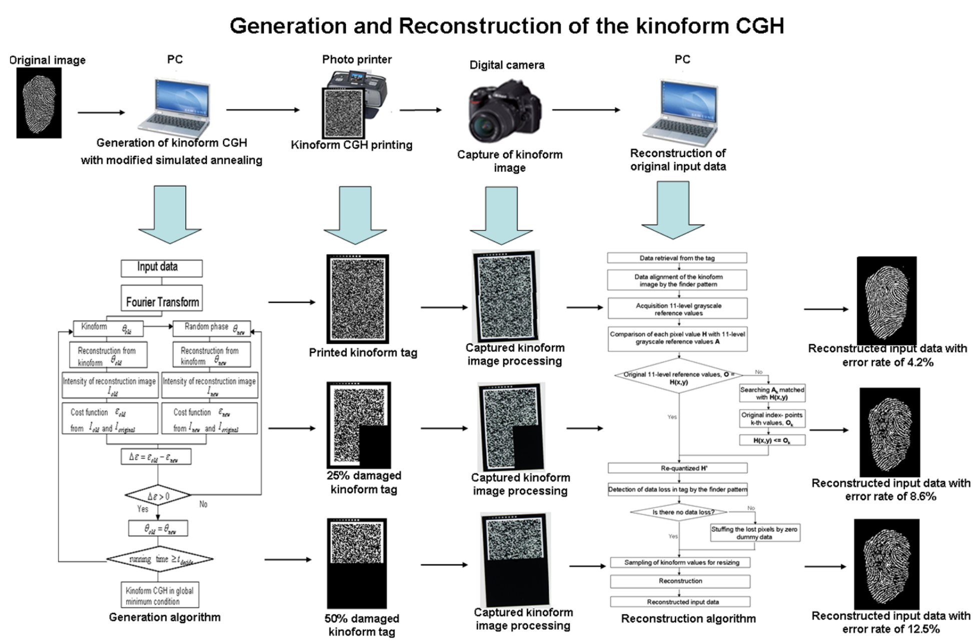
IEEE Photonics Journal
An IEEE Photonics Society Publication

Application of Kinoform CGHs to an ID Tag System

Volume 2, Number 4, August 2010

Hye-Rim Kim
Ki-Mun Pak
Ki-Woo Jun
Hyun-Whan Choi
Ji-Song Lim
Yong-Hyub Won



DOI: 10.1109/JPHOT.2010.2050872
1943-0655/$26.00 ©2010 IEEE

IEEE photonics SOCIETY
IEEE

Application of Kinoform CGHs to an ID Tag System

Hye-Rim Kim, Ki-Mun Pak, Ki-Woo Jun, Hyun-Whan Choi, Ji-Song Lim, and Yong-Hyub Won

Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-732, Korea

DOI: 10.1109/JPHOT.2010.2050872
1943-0655/$26.00 ©2010 IEEE

Manuscript received March 18, 2010; revised May 13, 2010; accepted May 13, 2010. Date of publication May 20, 2010; date of current version June 18, 2010. This work was supported by the IT R&D program of Korea Evaluation Institute of Industrial Technology (KEIT) under Grant 2008-F-049-01. Corresponding author: Y.-H. Won (e-mail: yhwon@kaist.ac.kr).

Abstract: In this paper, we successfully apply multilevel kinoform computer-generated hologram (CGH) patterns, which are recorded on a fine texture paper by a photo printer, into the hologram identification (ID) tag system. The 11-level kinoform CGH images are generated on our tag samples by a modified simulated annealing method at a low quantization error rate of 0.4% compared with the original data and then retrieved by a commercial digital camera and reconstructed in the computer to the original data with about 4% reconstruction error rate. The low reconstruction error is accomplished by suitable pattern recognition and image processing. We also propose a kinoform reconstruction algorithm that can considerably reduce reconstruction errors occurring when the tag is damaged. It is shown that the original image of a fingerprint can be reconstructed at a low error rate of about 12%, although nearly half of the tag data are lost.

Index Terms: Kinoform, computer-generated hologram, simulated annealing, optical ID, hologram ID.

1. Introduction

The proposed hologram ID tag system in Fig. 1 is expected to improve the weakness of a conventional 2-D barcode system [1]. Compared with a 2-D barcode, the hologram ID tag provides a larger amount of data storage with higher security. However, generating various kinds of hologram data on the ID tags are not easy tasks because of the limitations of real objects. It can be then solved using the computer-generated holograms (CGHs). The CGH is a flexible hologram-making process through which it can generate the hologram patterns of any objects without any physical entities [2]. The CGH pattern can be generated via pure mathematical manipulations based on the simulations of interference fringes between two beams (object and reference beams).

Kinoform CGHs, which encode interference patterns, simulate two beam interference patterns in terms of spatial variance in phase with their amplitudes restricted to be constant [3], [4]. The recording of the kinoform CGHs is typically made on a photosensitive material by laser beams, and the recorded kinoform images can be in turn retrieved by a construction beam and then reconstructed optically to the original data through a Fourier Transform lens [5]. This kind of an optical recording and reconstruction process has been a conventional research topic so far in the field of kinoform CGHs. In this paper, however, our kinoform tag samples are prepared by minutely printing kinoform patterns on the fine texture papers, and the reconstruction process is accomplished electrically in the computer. This new scheme offers some advantages for an ID

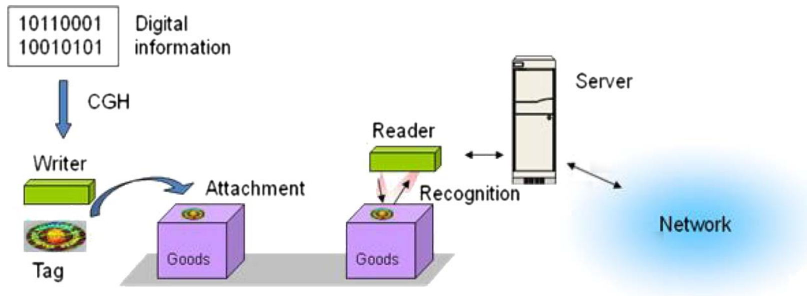


Fig. 1. Schematic diagram of a hologram ID tag system.

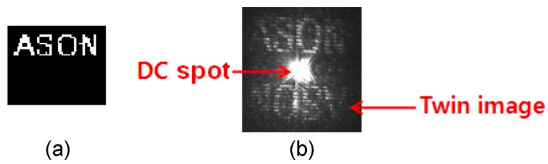


Fig. 2. Reconstructed image from (a) computational reconstruction method and (b) optical method.

tag application over the conventional optical methods: 1) There is no need for elaborate optical setups or equipment to write holographic data on the optical materials; 2) the printed kinoform patterns on the tag are captured relatively easily and accurately under natural light by a normal charged-coupled device (CCD) camera or a scanner, as shown in our experiments in Section 3, which makes it possible to implement a small and cheap hand-held type tag reader; and 3) the reconstructed data are not spoiled by DC spots or conjugate images, which is the most important advantage. As shown in Fig. 2, DC spot or conjugate images appear in the reconstructed data obtained from conventional optical method, which increase error rate.

When the kinoform images on the tag are retrieved, the grayscale value of each pixel may deviate from place to place due to the spatial non-uniformity of a light source and kinoform CGH ID tag can be exposed to danger of data loss, thus resulting in some errors in the retrieved data. In order to reduce the errors, the proposed reconstruction method uses the reference value index and dummy data. In the following sections, we will discuss a generation method for a kinoform CGH ID tag with modified simulated annealing and propose a reconstruction method for error reduction. We will also show and analyze the experimental results from the proposed reconstruction method.

2. Generation of Kinoform Images

Simulated annealing is often used to reduce the reconstruction error occurring in synthesis of kinoform images from original input data [1], [6]. This error inevitably occurs in kinoform CGHs since their amplitude components are restricted to be constant, and their phase components are quantized into a finite number of discrete levels. In the simulated annealing method, the kinoform image has minimal errors when it reaches an optimized condition for the global minimum of a cost function which measures a mean-square error between the input data and the reconstructed data from the kinoform image [1], [6]. The cost function, ε, is then defined as

$$\varepsilon(\theta) = \sum_{x=1}^{N}\sum_{y=1}^{M} |I_0(x,y) - I(x,y)|^2 \tag{1}$$

where N and M are row and column sizes of the input data, respectively, $I_o(x,y)$ is the intensity of the input data, $I(x,y)$ is the intensity of the reconstructed data, and α is a scale factor [6]. The scale

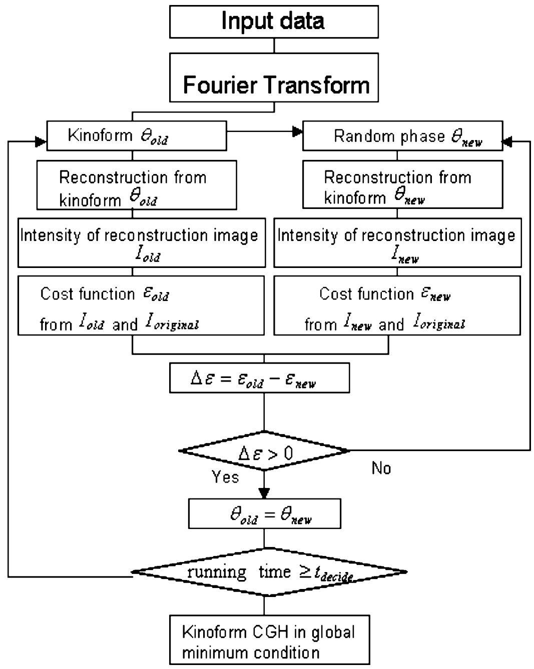


Fig. 3. Flowchart for kinoform CGH image generation using our modified simulated annealing.

factor is also given by

$$\alpha = \frac{\sum_{x=1}^{N}\sum_{y=1}^{M} I_0(x,y)}{\sum_{x=1}^{N}\sum_{y=1}^{M} I(x,y)}. \tag{2}$$

We have proposed a modified simulated annealing technique for the kinoform CGH generation, as shown in Fig. 3. As represented in the flowchart of the proposed modified simulated annealing, the initial reconstructed images are obtained through the kinoform CGH data with a random phase, unlike the conventional method starting with a zero phase. The modified simulated annealing chooses the phase values of kinoform CGH among the quantized values randomly for effective phase change. On the other hand, the conventional method chooses a zero phase at first and then selects increased phase values in serial order [3].

Fig. 4 shows a comparison of cost functions for a 100×50 pixel fingerprint input between the conventional algorithm [3] and the new algorithm in which the modified method significantly improves convergence and computational speed in kinoform synthesis at the same quantization level. The kinoform CGHs obtained from our modified algorithm yield much lower cost values than those from the conventional simulated annealing at the saturation region. The error rate is also calculated to be as low as 0.4% for our modified method while as relatively high as 10% for the conventional one. Here, the error rate for kinoform CGHs is defined as a relative number of pixels that are different each other when each pixel value between the original input and the reconstructed input from its kinoform image is compared, that is

$$\text{Error rate} = \frac{\text{Total Number of pixels different from those of the original input}}{\text{Total pixel number of the reconstructed data}}. \tag{3}$$

Our proposed simulated annealing method is based on the phase-optimization scheme previously suggested by Nozaki in [6]. In the Nozaki's method, the initial kinoform distribution is obtained by Fourier

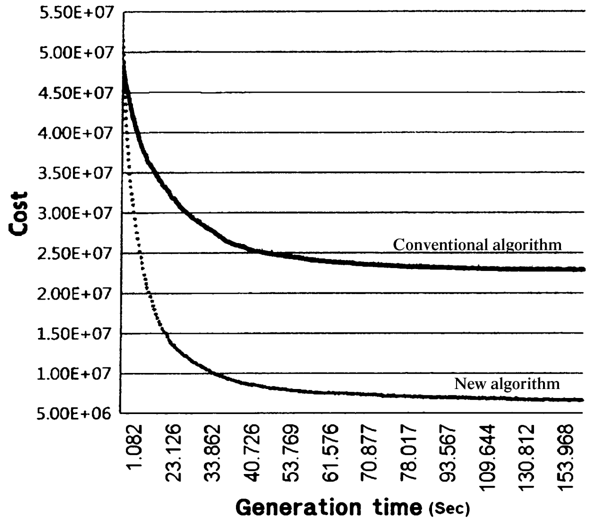


Fig. 4. Comparison of cost functions between the conventional [3] and our modified algorithm at the same (100 × 150 pixels of a fingerprint input).

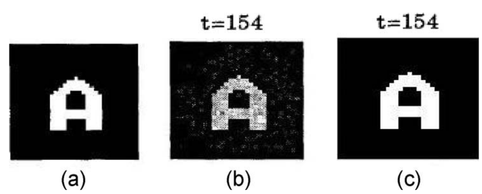


Fig. 5. (a) Original image, reconstructed images from (b) Nozaki's method [6], and (c) our method.

Transform of the original image with a random phase. This method adds the random phase to the "original image" before Fourier transform, which calculates the Fourier transform of the input image repeatedly. However, our modified simulated annealing method chooses the phase values of the kinoform CGH randomly after the Fourier Transform, which calculates the Fourier transform of the input image only once, which means that our simulated annealing method can reduce the generation time. Fig. 5 shows the simulation results using Nozaki's method and our method. The input image is a letter "A" with 32 × 32 pixels. When the generation time is 154 s, the Nozaki's method has the reconstruction result with cost value of 10^7; on the other hand, our method has a lower cost value of 2×10^6 with same generation time, which means that our method conducts more iteration at same time and spends less time conducting one cycle of the algorithm.

Using our algorithm, several cost functions are plotted as a generation time at different quantization levels, as shown in Fig. 6. Since the cost function is directly proportional to error rate (arriving at saturation of the cost function), there is a general tradeoff between these two variables, as indicated in the plot. With a choice of higher quantization levels, lower error rates of kinoform images can be obtained at the expanse of longer computational time [7]. All our kinoform samples were made at 11-quantization levels in consideration of both generation time and error rate for the experiments. The quantization levels can be chosen depending on the degree of importance for data in real ID tag applications.

3. Experiments

3.1. Configuration of the Kinoform Tag Samples

The tag samples are designed for their kinoform images to be correctly read and reconstructed, although they are put under a tag reader at a slant. The right position of the tag data is located by

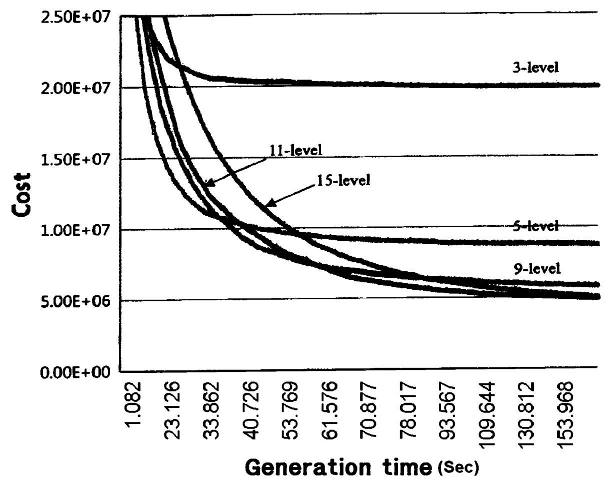


Fig. 6. Cost function versusl number of stage changes at different quantization levels (100 × 150 pixels of a fingerprint input).

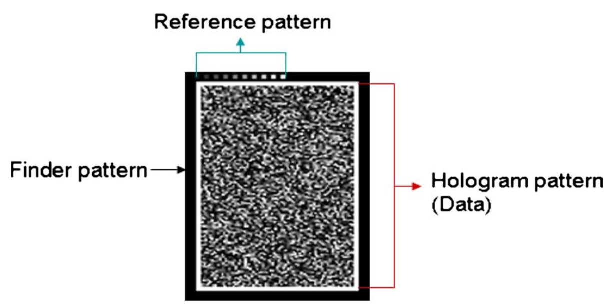


Fig. 7. Configuration of an 11-level grayscale CGH kinoform tag sample.

a finder pattern, which is a bold frame line in Fig. 7. When the kinoform images are captured by a CCD camera or a scanner, the captured images may not be spatially uniform because of non-uniformity of scattered light illumination; therefore, the grayscale value of each pixel deviates from place to place. In order to reduce this spatial uncertainty of grayscale values, the 11 index-points for reference values are used to differentiate the 11 different grayscale values more confidentially. Based on these index-points, each with one of 11-level grayscale values, the captured kinoform images are compared pixel by pixel and re-quantized into 11-levels for reconstruction errors to be reduced. The reference points are recorded on the left top corner of the tag, as shown in Fig. 7.

3.2. Reconstruction of the Kinoform Images

The kinoform image on the tag is optically retrieved and reconstructed to the original input data through a reconstruction process in the computer. Mathematically, the reconstructed input data are expressed by Inverse Fourier transform of the kinoform image, that is

$$I(x,y) = \left| \sum_{u=1}^{N} \sum_{v=1}^{M} W_{\text{phase}}(u,v) e^{-j2\pi\left(\frac{ux}{N}+\frac{vy}{M}\right)} \right|^2 \qquad (4)$$

where $I(x,y)$ is the reconstruction intensity, and $W_{\text{phase}}(u,v)$ is the phase of the kinoform image [8].

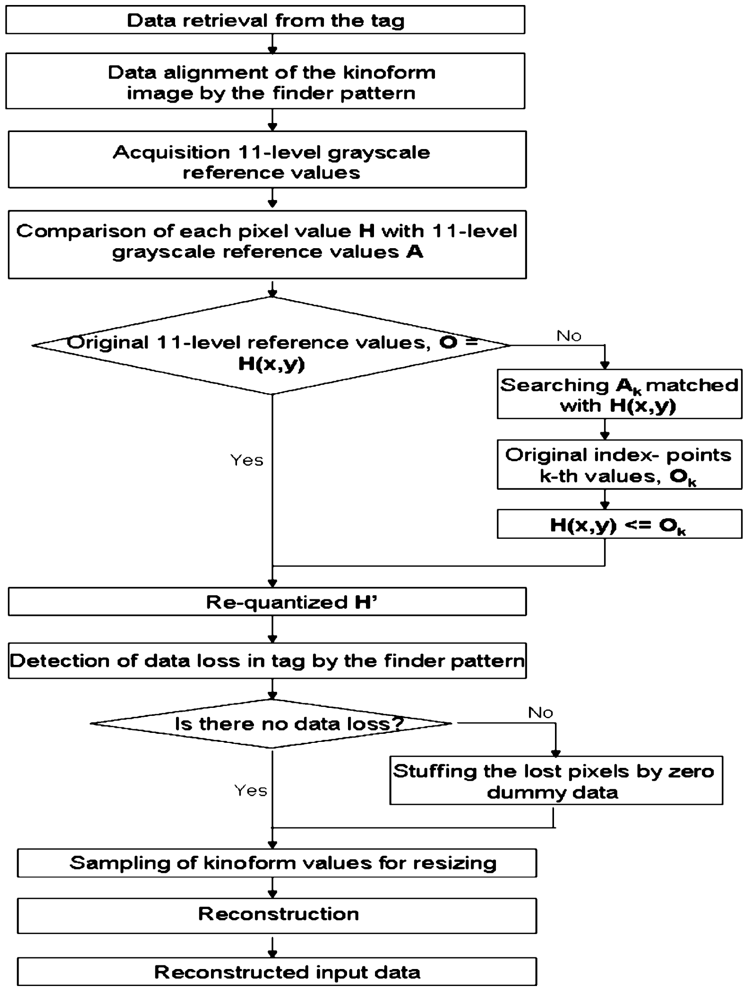


Fig. 8. Flowchart for a reconstruction process of kinoform images.

Fig. 8 shows a flowchart in which a reconstruction process is illustrated step by step to produce the original input data. First, the kinoform image is isolated from the captured whole data by the finder pattern and aligned correctly to be compared pixel by pixel with 11 reference values. Next, each pixel is re-quantized to have a new value which is closest to any one of 11 discrete reference values. Then, the new kinoform image is estimated by the finder pattern again if there are any lost pixels in it. With no lost pixels, the original input data are reconstructed from the new kinoform image. If there are any lost pixels, they are forced to be stuffed by 0's. Last, the modified kinoform image partly stuffed by 0's is used to reconstruct the original input data. The reconstructed input images of a fingerprint are compared for two cases; with and without re-quantization of the kinoform image, as shown in Fig. 9. The two images exhibit a considerable difference in error rate, i.e., approximately more than 10%, which implies that the re-quantization technique using the reference patterns can enhance the reconstruction performance of the kinoform images significantly.

3.3. Experimental Results

The kinoform tag samples have been made very fast and easily using a normal photo printer. Each pixel of the kinoform patterns measures about 100 μm $\times$ 100 μm and has one of 11 grayscale values. The optical equipment to capture the images is a commonly used digital camera with approximately

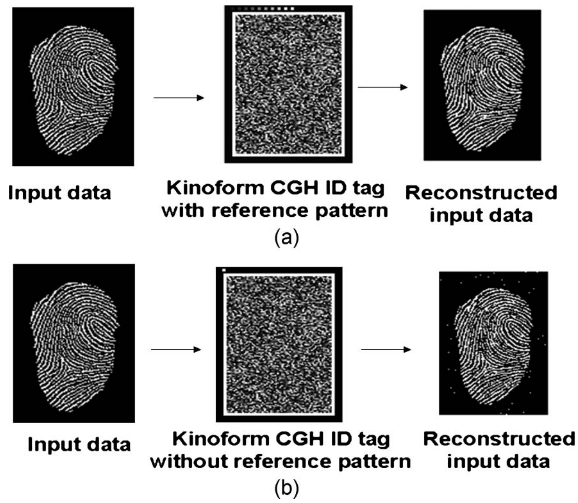


Fig. 9. Comparison of reconstructed input images of a finger print. (a) With and (b) without re-quantization of the captured kinoform image.

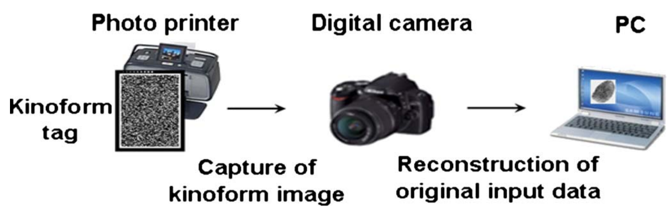


Fig. 10. Equipments for reconstruction experiments on the kinoform tags.

4 Mega pixels. The captured kinoform tag images captured by the camera in the white light are transferred into the computer and there reconstructed to the original input data, as depicted in Fig. 10.

For the reconstruction experiments, we used a fingerprint and a text file as input data which are typical examples of images and characters, respectively. These input data are transformed into kinoform CGH patterns which are in turn detected optically in white light and converted to the original data through our reconstruction algorithm. As for the text file, it is expressed as a binary image before being transformed into the kinoform image. Each character in the text file is changed into particular 8-bit binary number which consists of 1 and 0. Then, it is converted to the kinoform CGH by using the generation algorithm. The original text file can be obtained from the reconstructed binary image through matching the 8-bit binary numbers and characters. Fig. 11 shows reconstruction results for the experiments on the undamaged kinoform tags in which both of the reconstructed input data have low error rates of approximately 4%, as compared with the original document and fingerprint, respectively.

One advantage of the kinoform tag is to recover most part of the original data from the damaged tag, although it loses more than 50% of its total pixels, as plotted in Fig. 12. Since the kinoform image is formed by Fourier transform of the original input data, it has a unique property in which all the data information is spread over each pixel of the kinoform image. In Fig. 12, the error rates of the simulation results are different from one of the experiments. The simulation values have been obtained through reconstruction process directly from the kinoform tag data, while measurement data involve one more step of the camera-capturing process. A few percent deviations of the error rates between the real experiments and the simulations may be caused by the limitation of the camera resolution and quantization errors in the camera-capturing process, compared with the

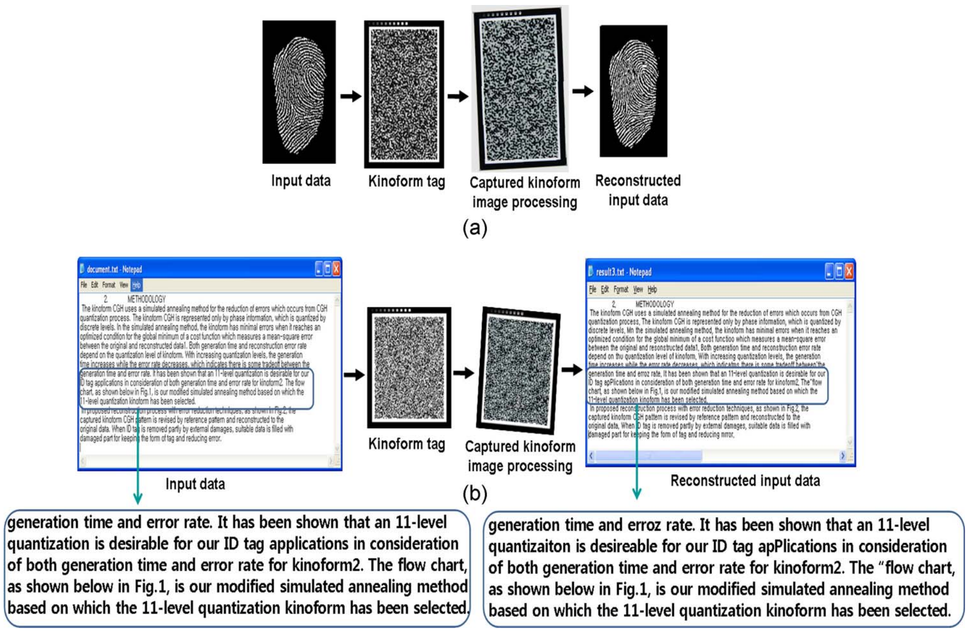


Fig. 11. Reconstruction experiments on the kinoform tags with no lost pixels (a) for a fingerprint image and (b) for a text.

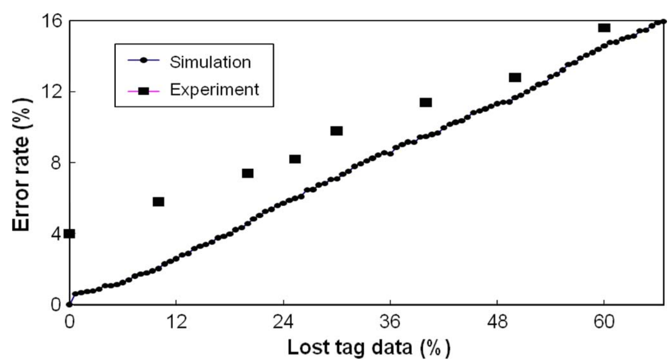


Fig. 12. Error rate as a function of damaged portion of the tag data.

simulations, which are in ideal condition. The quantization errors are caused by matching the pixel values with the quantized reference values.

We used kinoform CGH tags in which one has 25% damage, and the other has 50% damage physically. Both tags are detected optically and recovered on the same condition, have the same light intensity, the same camera angle, and so on. The recovered data are compared in terms of error rates with the original data. Fig. 13 shows that the fingerprint kinoform reconstructs original data at an error rate of 8.6% for the 25% tag loss and 12.5% for the 50% tag loss in the experiments.

Also, as shown in Fig. 14, the character kinoform has low error rates of 8.7% for the 25% tag loss and 13% for 50% tag loss, which are quite consistent with those of computer simulations. The lost pixels of the damaged tags were stuffed by 0's because of no contribution of the lost pixels to the original image reconstruction.

4. Conclusion

The kinoform tag samples were experimentally demonstrated to reconstruct the original input data. All the equipment used in the experiments are commonly used appliances in daily life with normal

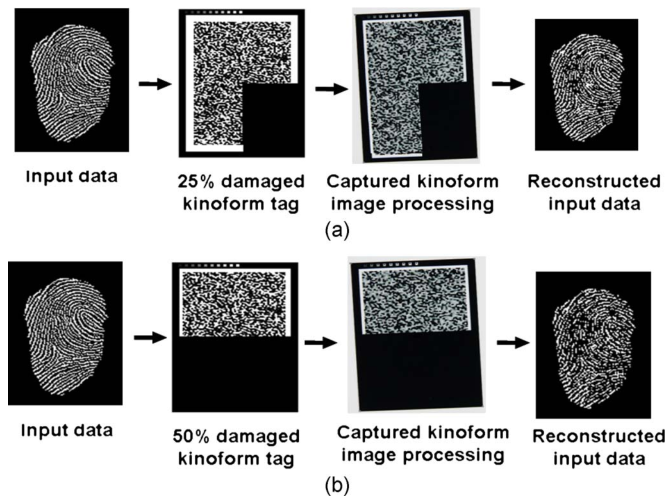


Fig. 13. Original input data and its reconstructed data for a fingerprint kinoform tags with 25% damage and (b) with 50% damage.

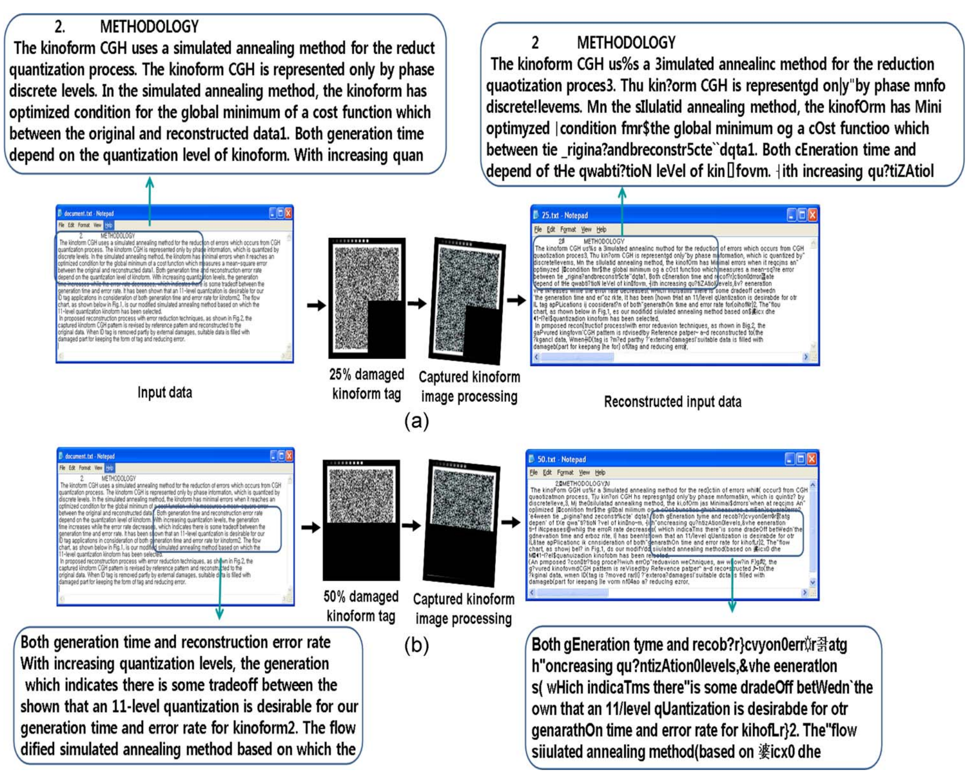


Fig. 14. Original input data and its reconstructed data for text kinoform tags (a) with 25% damage and (b) with 50% damage.

characteristics and performances, which enables us to easily implement a cheap tag reader and kinoform ID tags. The kinoform CGHs were generated using a modified simulated annealing scheme for ID tag applications at the 11-level grayscale in which the result shows less than 0.5% of the quantization error. The kinoform CGH tags generated from the images of a fingerprint were optically captured and successfully reconstructed using a conventional digital camera and appropriate image-correction algorithms with low error rate of about 4% compared with the original image. We also proved our reconstruction algorithm to be robust to external damages. The original image of a fingerprint and characters were reconstructed at a low error rate of about 12% based on our proposed algorithm, although half of the tag data were lost. We believe that this ID tag technology is very promising for future applications with its excellent capabilities of the large data storage, user-friendliness, and robust damage recovery.

References

[1] H. J. Yang, J. S. Cho, and Y. H. Won, "Reduction of reconstruction errors in kinoform CGHs by modified simulated annealing algorithm," *J. Opt. Soc. Korea*, vol. 13, no. 1, pp. 92–97, Mar. 2009.
[2] L. B. Lesem, P. M. Hirsch, and J. A. Jordan, Jr., "The kinoform: A new wavefront reconstruction device," *IBM J. Res. Develop.*, vol. 13, no. 2, pp. 150–155, Mar. 1969.
[3] N. Yoshikawa and T. Yatagai, "Phase optimization of a kinoform by simulated annealing," *Appl. Opt.*, vol. 33, no. 5, pp. 863–868, Feb. 1994.
[4] B. R. Brown and A. W. Lohmann, "Computer-generated Binary Holograms," *IBM J. Res. Develop.*, vol. 13, no. 2, pp. 160–168, Mar. 1969.
[5] A. Cable, P. Mesh, and T. Wilkinson, "Production of computer-generated holograms on recordable compact disc media using a compact disk writer," *Opt. Eng.*, vol. 42, no. 9, pp. 2514–2520, Sep. 2003.
[6] S. Nozaki, Y. W. Chen, and Z. Nakao, "A new approach based on simulated annealing to kinoform optimization," *Proc. SPIE*, vol. 3956, pp. 160–166, 2000.
[7] N. C. Gallagher and B. Lui, "Method for computing kinoforms that reduces image reconstruction error," *Appl. Opt.*, vol. 12, no. 10, pp. 2328–2335, Oct. 1973.
[8] M. Ekberg, M. Larsson, and S. Hard, "Multilevel phase holograms manufactured by electron-beam lithography," *Opt. Lett.*, vol. 15, no. 10, pp. 568–569, May 1990.