Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# Multiple-image hiding using super resolution reconstruction in high-frequency domains

Xiao-Wei Li, Wu-Xiang Zhao, Jun Wang, Qiong-Hua Wang *

*School of Electronics and Information Engineering, Sichuan University, Chengdu 610065, China*

ARTICLE INFO

*Keywords:*
Multiple-image hiding
Super-resolution
Computer-generated integral imaging

ABSTRACT

In this paper, a robust multiple-image hiding method using the computer-generated integral imaging and the modified super-resolution reconstruction algorithm is proposed. In our work, the host image is first transformed into frequency domains by cellular automata (CA), to assure the quality of the stego-image, the secret images are embedded into the CA high-frequency domains. The proposed method has the following advantages: (1) robustness to geometric attacks because of the memory-distributed property of elemental images, (2) increasing quality of the reconstructed secret images as the scheme utilizes the modified super-resolution reconstruction algorithm. The simulation results show that the proposed multiple-image hiding method outperforms other similar hiding methods and is robust to some geometric attacks, e.g., Gaussian noise and JPEG compression attacks.



## 1. Introduction

Images are widely used in multimedia communications via public network as well as private network, whose security has drawn increasing attention with the fast development of Internet. Image hiding is one of the effective measures to ensure the security of private image information. In recent years, a large number of image encryption algorithms have been developed [1–9].

Multiple-image security can be applied to some scenarios such as clinical information exchange, wireless sensor networks and electronic commerce systems. Multi-image security algorithms have been studied increasingly due to their higher efficiency and flexibility [10–14]. Most of these algorithms encrypt the multiple-image into one image. Recently, multiple-image encryption based on multiplexing techniques has received increasing interest in the field of image security, since it not only advances the encryption capacity but also facilitates the transmission and storage of the ciphertext [15–18]. One of the vital issues in multiple-image encryption is cross-talk noise due to recording multiple ciphertexts on a single medium, which degrades the quality of the decrypted images and consequently restricts the multiplexing capacity severely. To prevail over this issue, a multiple-image security method based on interference and wavelet transform has been developed [19]. This scheme provides high image quality of the recovered images, but has poor robustness. To solve this problem, a multiple-image watermarking method using the computational integral imaging method has been proposed [20]. In this scheme, the multiple secret images are first recorded into the elemental image array (EIA) [21,22], and the recorded EIA is embedded into the low frequency of cellular automata transform (CAT) domain. In this scheme, before embedding, the secret image needs to be pre-processed by the computer-generated integral imaging technique. This technique is divided into two parts: computational pickup part and computational integral imaging reconstruction (CIIR) part [23–31]. In the pickup part, a set of elemental images are generated by the computer mapping algorithm instead of using a lenslet array. Reconstruction of plain images is a reverse process of pickup by propagating the rays coming from EIA through the same pinhole array. The detailed description of the computer mapping algorithm can be found in [32–36].

However, CIIR also yields low-resolution images because there are intensity irregularities with a grid structure at the reconstructed image plane, which is a result of insufficient overlapping of the elemental images.

In this paper, a new multiple-image hiding method using computer-generated integral imaging and the modified super-resolution reconstruction algorithm is proposed. In this work, a color host image is separated onto R, G, and B three channels, and each channel is decomposed by CAT into four frequency domains LL, HL, LH, and

* Corresponding author.
*E-mail address:* qhwang@scu.edu.cn (Q.-H. Wang).

http://dx.doi.org/10.1016/j.optcom.2017.06.014
Received 31 March 2017; Received in revised form 25 May 2017; Accepted 3 June 2017
Available online xxxx
0030-4018/

HH. The frequency domains labeled HL, LH and HH represent high-frequency information, which provide better imperceptibility. The frequency domain LL represents the low-frequency information which contains important data of the original image. The information embedded into the frequency domain LL degrades the quality of the stego image. Each secret color image is preprocessed by computer-generated integral imaging and is encoded by CA. Each of three channels of the encoded secret image is embedded into the high frequency domains HL, LH, and HH, respectively. The reconstruction of secret images is implemented by the modified super-resolution reconstruction algorithm. The proposed method has two significant advantages: (1) robustness to geometric attacks because of the memory-distributed property of EIA, (2) increasing quality of the reconstructed secret images via the modified super-resolution reconstruction algorithm.

## 2. Theoretical analysis

### 2.1. Modified super-resolution reconstruction algorithm

To improve the limited resolution of CIIR, a new super-resolution reconstruction technique is to be applied for the integral imaging system. We investigate the iterative back-projection (IBP) super resolution reconstruction technique [37–40] as a potential and useful digital super-resolution technique to be used in 3D visualization, image recognition and image watermarking with the integral imaging system. In this technique a high resolution image can be produced with an iterative of error estimation and an inference of a low-resolution image. If we define $f^{(n)}$ as the inferred super-resolution image produced after $n$ iterations and the iterative process is briefly presented as follows:

1. Inferring the simulated sub-images, the simulated image $G^{(n)}_{sx,sy}$ after $n$ iterations is generated by using

$$G^{(n)}_{sx,sy} = \left[T_{sx,sy}(f^{(n)})\right] \downarrow s \tag{1}$$

where $T_{sx,sy}$ denotes the geometric transformation between the sub-image and the target image at position $(sx, sy)$, $\downarrow s$ is the down-sampling operator. The sub-images are generated from elemental images by the following transform process:

If an elemental image array (EIA) is composed of $X \times Y$ elemental images, each elemental image (EI) with the size $M \times N$ and the $x$-line and $y$- column EI can be calculated by

$$\mathrm{EI}_{x,y}(m,n) = \mathrm{EIA}(xM + m, yN + n) \tag{2}$$

where, $M \times N$ represents the size of each of EIs, $m = 0, 1, 2, \ldots, M-1$. $n = 0, 1, 2, \ldots, N-1$. Hereby, the $m$-line $n$-column sub-image (SI) can be obtained from

$$\mathrm{SI}_{m,n}(x,y) = \mathrm{EIA}(xM + m, yN + n) \tag{3}$$

where $x = 0, 1, 2, \ldots, X-1$. $y = 0, 1, 2, \ldots, Y-1$. From Eq. (3), we can see that the new generated sub-image array contains $M \times N$ sub-images and each image with the size of $X \times Y$.

2. Estimating the error function between the observed and the simulated sub-images is defined as

$$e^{(n)} = \left[(1/N^2)\sum_{sx=0}^{N-1}\sum_{sy=0}^{N-1}(G_{sx,sy} - G^{(n)}_{sx,sy})^2\right]^{1/2} \tag{4}$$

where $G_{sx,sy}$ is the observed sub-image at position $(sx, sy)$. If the calculated $e^{(n)}$ is less than the given threshold value $\eta$ and the iteration is terminated. Otherwise, the inferred super-resolution image is updated by

$$f^{(n)} = f^{(n-1)} + (1/N^2)\sum_{sx=0}^{N-1}\sum_{sy=0}^{N-1} T^{-1}_{sx,sy} \times \left\{\left[(G_{sx,sy} - G^{(n-1)}_{sx,sy}) \uparrow s\right]\right\} \tag{5}$$

where $T^{-1}_{sx,sy}$ is the inverse of $T_{sx,sy}$, $\uparrow s$ denotes up-sampling.

However, in the iteration process, the $n$-iteration inferred image $f^{(n)}$ exists ringing artifacts due to the high-frequency difference between the simulated sub-image and the observed sub-image.

To reduce the ringing artifacts of the inferred high resolution image, in this paper, the Laplace operator is employed to extract the high-frequency components of the simulated sub-image and the observed sub-image. Therefore, the updated equation can be revised as

$$f^{(n)} = f^{(n-1)} + (1/N^2)\sum_{sx=0}^{N-1}\sum_{sy=0}^{N-1} T^{-1}_{sx,xy} \times \left\{\left[\left((G_{sx,sy} - G^{(n-1)}_{sx,sy}) - (\Delta G^{(n-1)}_{sx,sy} - \Delta G_{sx,sy})\right) \uparrow s\right]\right\} \tag{6}$$

where $\Delta$ is the Laplace operator.

### 2.2. Secret images embedding algorithm

The embedding algorithm of secret images mainly consists of three stages:

(1) Converting the host image from the spatial domain to the frequency domain by using CA transform.
(2) Preprocessing the secret image by the computer-generated integral imaging algorithm.
(3) Embedding the secret image data into the CA transform domains (HL, LH, and HH).

To improve the imperceptibility of the proposed multiple-image hiding method, the secret images are embedded into high-frequency domains of the host image. The four different transform domains are shown in Fig. 1, the domains of HL, LH, and HH represent the high frequency domains of the host image.

Next, in order to improve the robustness of the proposed method, the secret images need to be preprocessed by the computer-generated integral imaging algorithm and the obtained EIAs are shown in Fig. 3(a)–(c). The sub-image arrays can be generated from the obtained EIAs by Eq. (3). Then, to further improve the security of the secret images, the sub-image arrays are encrypted by CA. The encrypted results as the final data are used for embedding. We embed the three color channels of the secret image into HL, and LH, and HH domains of one channel of the host image.

### 2.3. Secret images extraction algorithm

The secret images extraction process, similar to the secret image embedding process, consists of three stages:

(1) Re-decomposing the stego-image into frequency domains by CA transform;
(2) Extracting the secret image information from the CA transform domains;
(3) Reconstructing the secret images by the modified super-resolution reconstruction algorithm.

## 3. Results and discussion

The goal of the experimental part has twofold. Firstly, we aim at illustrating the resolution of the secret image via the modified super-resolution algorithm. Secondly, we access the computer-generated integral imaging to improve the robustness against external noise attacks.

To evaluate the performance of our method, we conduct experiments on a color image 'Monkey' of size 480 × 480 as the host image is shown in Fig. 2 (a). Three color image 'yellow car', 'green car', and 'dice' with the same size of 240 × 240 as the secret images are shown in Fig. 2(b)–(d), respectively. The EIA is generated from the secret image by the computer-generated integral imaging algorithm, a virtual pinhole array is composed of 30 × 30 pinholes is used and located at $z = 0$ mm, the



Please cite this article in press as: X.-W. Li, et al., Multiple-image hiding using super resolution reconstruction in high-frequency domains, Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.06.014.