Binarization of gray-scale hologram

Project of ECE 533

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1. Introduction

Since Gabor's first hologram, the meaning of this term have grown with increased use of the invention. This rapidly growing is also because the hologram can be generated by computers. Computer generated holograms (CGH) have been investigated intensively in recent years owing to their wide application range and their advantages in terms of flexibility, accuracy, size, weight and cost. Applications can be found, e.g., in optical information processing, in which CGH's are used as filters to generate a required wave front, or in optical neural networks, in which they are used to accomplish complex synaptic interconnections.

But, what is hologram? Hologram is a kind of mask that created by the diffraction wave of the object target and a reference beam. So in the hologram, information of the phase of the target is recorded. After reconstruction, the object can be recovered easily. In this project, the diffraction theory I used is Fraunhofer diffraction, which is just the Fourier Transform of the object.

There is a rough process about making hologram and reconstruction in the figures below. Here the reconstruction is from the gray-scale hologram. One of the images is original image; while the other one is the conjugate image.

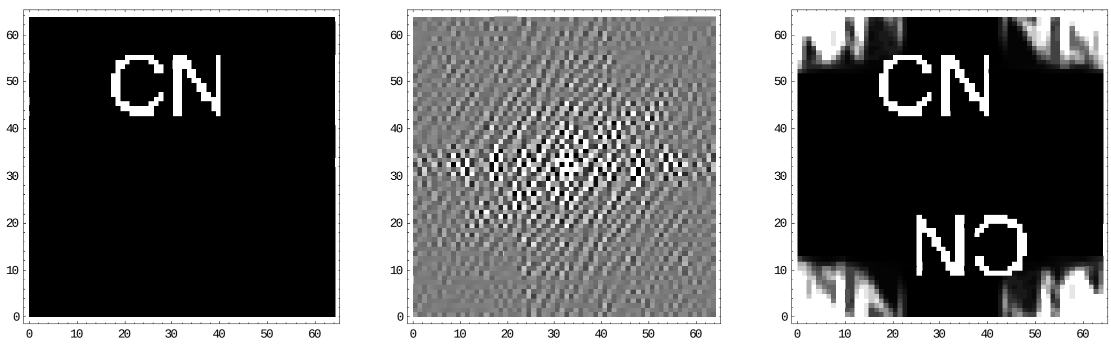

Figure 1: Object (Target) → Hologram (gray-scale) → Reconstruction.

One can generate a hologram with computer very easily, but after the calculation for a hologram, the picture is gray-scale. However, since the limitation of the lithography, we can only record binary information on the photo resist, which means, the intensity of the hologram can only contain 0 and 1. So we need to take care of the binarization process for the gray-scale hologram. There are a lot of papers about the binarization methods for hologram. And in this project, I will use the threshold as the key for the binarization and compare 3 different binarization processes.

2. 3 different methods for binarization

The essential point for binarization is the threshold. If the intensity of the gray-scale is higher than threshold number, the binary hologram will have 1 for this point; otherwise, the number in the binary hologram will be 0. According to this idea, the production and the reproduction of binary holograms is simple. However, one has to take care of the binarization error because this error can cause enormous errors in the reconstruction with respect to the original object. So here, I have 3 different methods for binarization. They all have the threshold as the key part, but the threshold will be calculated in different way, or there will be post-processing in the binarization. I will show all the results of the binary hologram, and use the reconstruction result to be the comparison.

2.1 Approach 1: Simple threshold

As said above, using a simple threshold can create a binary hologram. In the textbook of this course, we know how to choose the threshold is very important in the conversion. And all the optimal thresholds are depending on the histogram of the picture. It is said, in the histogram, we need to first clarify the object part and the background part. In the figure below, it's the histogram of the hologram.

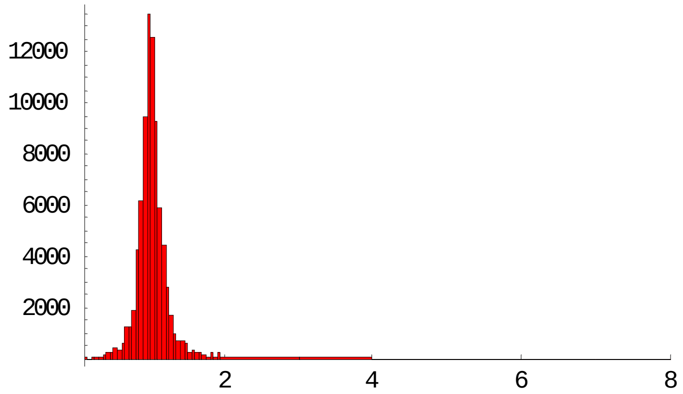

Figure 2: Histogram of the gray-scale hologram
(max. is 7.3916; min. is 0.11108)

As seen in the figure, it is impossible to separate the object and the background. So in this case, we just use the median number of all the intensity data in the hologram as the threshold so that the binary hologram will have 50% black and 50% white.

Run the Mathematica to find the median number, which is 1.228. And convert the gray-scale hologram to binary hologram. Here is the result.

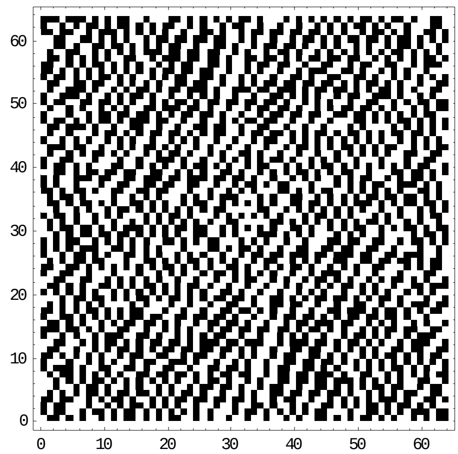

Figure 3: Binary hologram created using approach 1.

2.2 Approach 2: Random binarization

According to "*Gradual and random binarization of gray-scale holograms*", it is said most of the binarization error should be the random error. Hence, if we can binarize the n (n < total pixel number in the hologram) random pixels using their own threshold each time, and repeat this process until all the pixels are binarized, then we can reduce this kind of random error.

Using this idea, the algorithm is shown in the next page.

Since I used different address for each pixel, and created n pseudorandom for the key to pick up the pixels, the pixels will be chosen randomly. And the threshold will be the median number of these n random pixels. So in each round, the chosen pixels cannot all be the same, hence the threshold for each round will be different. After all the pixels are binarized, the process ends.

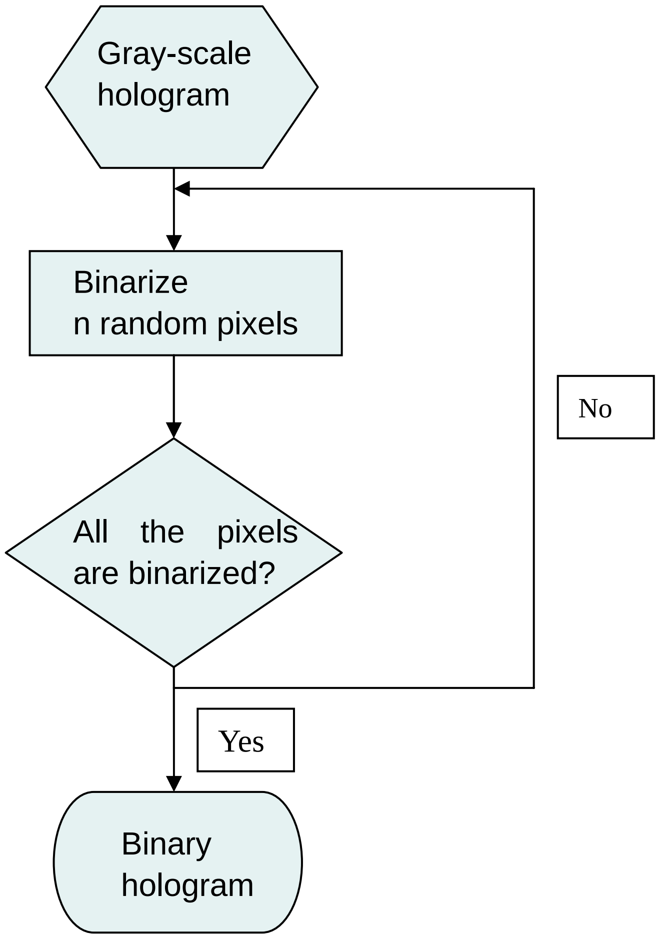

Figure 4: Algorithm of random binarization

As a result, we should see that the histogram of the hologram gradually change to contain only the intensity of 1 and 0. (Figure 5)

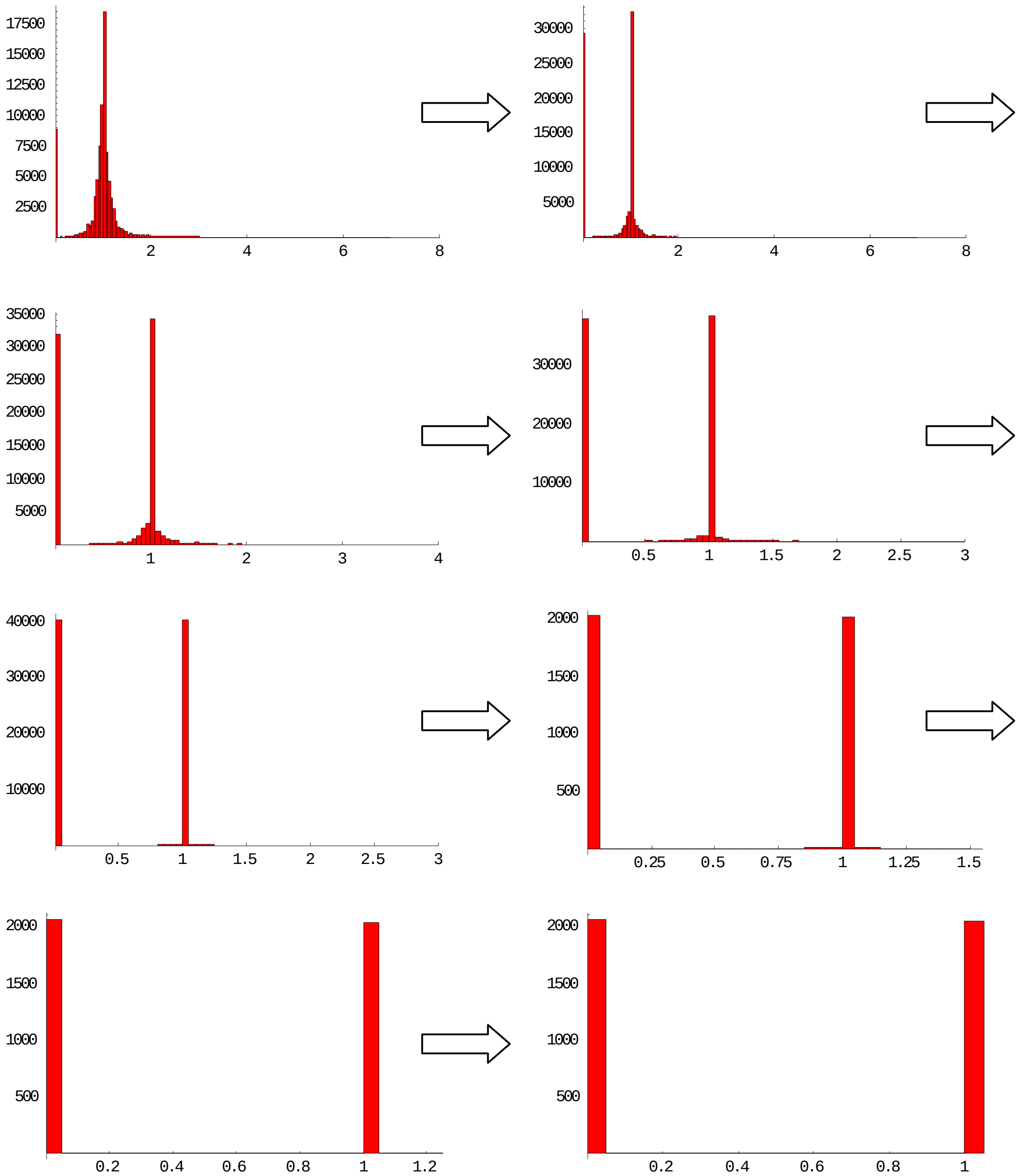

Figure 5: Histogram changes with the increasing rounds: After the 1st round; after the 10th round; after the 11th round; after the 20th round; after 30th round; after the 31st round; after the 50th round; after the last (61st) round.

And the final result of the binary hologram is shown below.

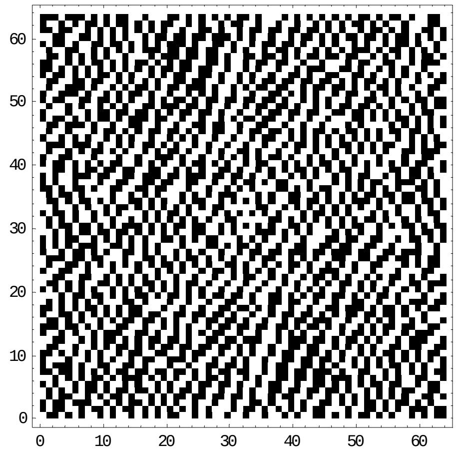

Figure 6: Binary hologram created using Approach 2.

2.3 Approach 3: High frequency binarization

This binarization is created by our group. Here, we still use one threshold to convert the gray-scale hologram. But after this simple conversion, we have a post-processing. During this process, we picked up the maximum points under the threshold in the gray-scale hologram, and changed their intensity from 0 to 1 in the binary hologram. Similarly, we also picked up the minimum points above the threshold in the gray-scale hologram, and changed their intensity from 1 to 0 in the binary hologram. So far, all the peaks in the gray-scale hologram will have 1 in the binary hologram; while all the valleys in the gray-scale hologram will have 0 in the binary hologram. And these numbers are independent with the threshold. Hence all the rapid changes in the gray-scale hologram can be saved in the binary hologram. Since rapid changes are the high frequency information in the picture, so we call this method as high frequency binarization.

There is one 1-D example to explain this method on the next page.

The above one is the gray-scale hologram of a 1-D object; while the bottom one is the binary hologram created by the high frequency binarization. And the horizontal line in the gray-scale hologram is the threshold in the conversion. Look at the blue point in the ray-scale hologram. It is above the threshold, but it is the valley respect to its neighbor points. So in the binary hologram, this pixel will have 0 intensity, as shown at the blue point in the binary hologram. And the red points are the opposite situation. In gray-scale hologram, it is a peak but under the threshold. In binary hologram, it still has 0 value. And all the peaks in gray-scale hologram have 1 in the binary hologram; while all the valleys in gray-scale hologram have 0 in the binary hologram. As a result, the binary hologram has save most of the high frequency information.

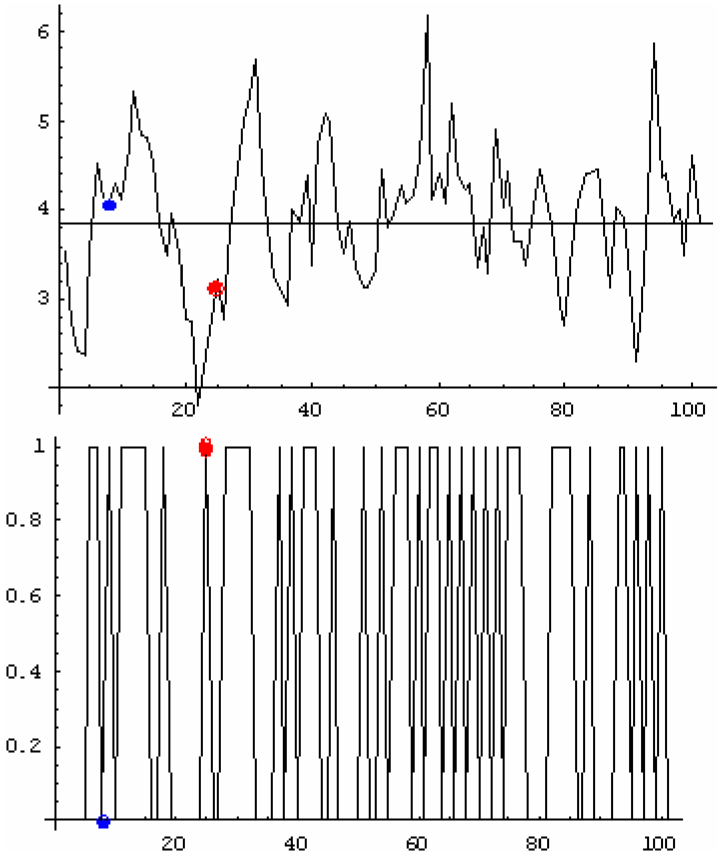

Figure 7: High frequency binarization example in 1-D.

And the result of this binary process is shown below.

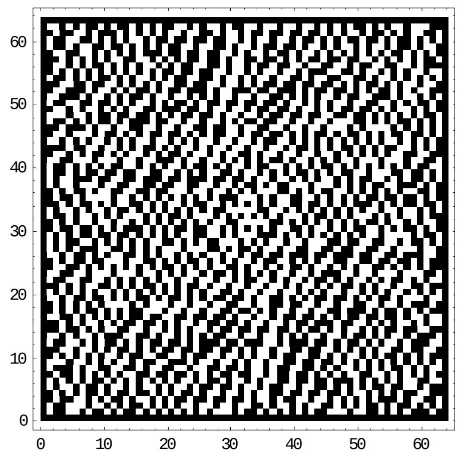

Figure 8: Binary hologram created using Approach 3.

3. Comparison among the results from the 3 methods.

So far, we have got the binary holograms from the 3 methods. In this section, we will compare the quality of these 3 binary holograms.

3.1 The reconstruction of the binary hologram

As mentioned before, we can easily reconstruct the target object using the hologram. Now we can compare the reconstruction results from 3 different methods.

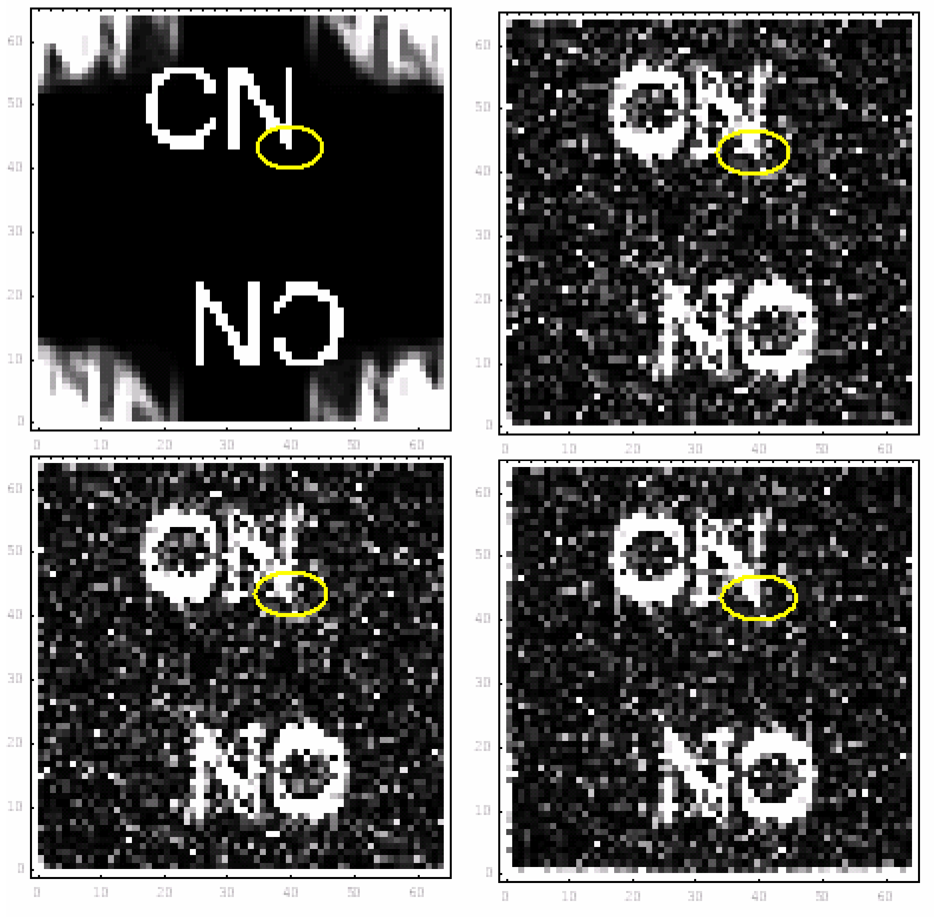

Figure 9: Compare the reconstruction results from the binary holograms.

Left, up: reconstruction of gray-scale hologram;

Right, up: reconstruction of binary hologram of method 1;

Left, bottom: reconstruction of binary hologram of method 2;

Right, bottom: reconstruction of binary hologram of method 3.

The 3 reconstructions of the binary hologram look almost the same. But if compare the region in the yellow circle, we can see the result from method 3 will be better than the results from method 1 and 2.

3.2 Mean-square Error

Since we cannot say which result will be better, method 1 or method 2, just looking at the reconstruction from the binary holograms, so we need to find another way to consider the quality of the binary hologram. Here, we us the mean-square error (MSE). Suppose f_{xy} to be the original signal and g_{xy} to be the reconstruction of the hologram; then the MSE is computed by

$$MSE = \frac{1}{M^2} \sum_{xy \in W} \left| \frac{f_{xy} - \bar{f}}{\sigma_f} - \frac{g_{xy} - \bar{g}}{\sigma_g} \right|^2$$

where $M \times M$ is the total pixel number of the hologram, W is the whole reconstruction region, and

$$\bar{f} = \frac{1}{M^2} \sum_{xy \in W} f_{xy} , \qquad \bar{g} = \frac{1}{M^2} \sum_{xy \in W} g_{xy} ,$$

$$\sigma_f^2 = \frac{1}{M^2} \sum_{xy \in W} \left| f_{xy} - \bar{f} \right|^2 , \qquad \sigma_g^2 = \frac{1}{M^2} \sum_{xy \in W} \left| g_{xy} - \bar{g} \right|^2$$

Using this parameter, we can then compare the difference between the real target and our reconstruction result.

Here are some results of MSE. MSE for gray-scale hologram is only 0.01. MSE for binary hologram of the 1st method is as big as 1.021; while MSE for the binary hologram of the 2nd method is 1.019. So it seems that the 2nd one is a little better than the 1st one. That also satisfies our theory: because the 2nd one has reduced some of the random errors in the binarization. MSE for the 3rd one is 0.81. So the improvement of the 3rd method is obvious compare to the first two methods.

4. Conclusion

I used 3 different binarization processes in this project. All of the binarization processes are based on threshold. I compared the results in this project. The high frequency binarization can have the best results among these three methods. But all of the results are still far from the reconstruction of gray-scale hologram, which should be almost lossless reconstruction. Maybe the main problem is using threshold in the conversion. There are other methods for binary hologram instead using a threshold in the conversion, and that should be the future work of this topic.

Reference:

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