Computer generated holograms for optimized laser pattern formation

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Abstract:
Holographic light shaping has a myriad of applications. But the occurrence of coherent artifacts (speckle) hampers its use for the reconstruction of continuous laser intensity profiles, such as images. Therefore, the reduction of speckle in holographically reconstructed images is a very active research topic, and a vast number of approaches are currently investigated. In this work, several speckle reduction methods based on intensity averaging and iterative algorithms were implemented. Simulations and experimental results were obtained and compared against regarding perceived image quality, speckle contrast and reconstruction speed. The results show that the investigated methods allow the reconstruction of precise and high quality images.

I. INTRODUCTION

Digital holography is a powerful method to sculpt a laser wavefront into an arbitrary intensity pattern through spatial modulation of the optical amplitude or phase. The modulation information is called a hologram in this context and it is commonly displayed on a spatial light modulator(SLM). The image information is usually carried by both amplitude and phase of the light electric field, so that the modulation of both properties is necessary for the precise reconstruction of intensity patterns. However, commercially available SLMs are either amplitude or phase modulators, but not both. So the hologram needs to be approximated as either phase or amplitude information. In general, phase modulation is preferred because phase-only SLMs have the advantage that they redistribute the light instead of blocking it, which means that they achieve substantially higher light efficiencies than amplitude modulators. That makes them suitable for power-sensitive applications such as optical micro-manipulation, laser scanning microscopy, material processing or holographic displays [1]. Phase-only holograms are commonly approximated with iterative Fourier transform algorithms, such as the Gerchberg-Saxton (GS) algorithm [2], which gradually shift more of the image information into the phase of a hologram with each iteration until it converges.
However, in this process, the optical phase of the reconstructed wavefront is used as a degree of freedom, which leads to abrupt phase changes between neighboring image points. Since there is an overlapping of their electric field, they interfere and unwanted intensity variations appear that degrade the reconstructed image. These coherent artifacts are also called speckle in the context of holography and are a major obstacle for the holographic reconstruction of intensity patterns [9].
Several speckle reduction techniques were developed which are based on different approaches[8]. A promising group of methods is based on sequentially displaying different holograms that each reconstruct the same intensity pattern, albeit with different overlaying speckle patterns. Through an integration of the various reconstructed patterns over time an averaging effect is achieved which reduces speckle.
In this work, few averaging methods were implemented and the experimental and simulated results were compared against regarding reconstruction speed, image quality and speckle contrast.

■ Holographic image reconstruction

A lens properly placed (2f system) relates the field of two planes by a Fourier transform operation. Figure 1 shows the relation between the two planes of interest, the hologram plane (HP), where the SLM diffracts the incident beam, and the reconstruction plane (RP), where the image is reconstructed. This allows to calculate the hologram $h(x,y)$ with a simple inverse Fourier transform of a digital target pattern.

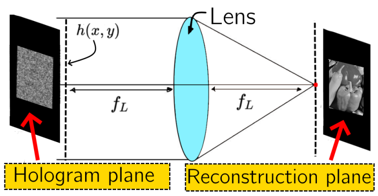

FIG. 1: Lens performing an optical Fourier transform of the hologram. f_L is the focal length of the lens.

II. HOLOGRAM CALCULATION

■ Modified GS algorithm

The original Gerchberg-Saxton (GS) algorithm is based on simulated forth and back propagation of the image wavefront and hologram wavefront, and applying ampli-

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tude constraints to obtain a concentration of the image information in the hologram phase [2]. There are several modifications of the original GS algorithm, which may include additional amplitude or phase constrains [3]. The modification used in this work takes into account that there is only interest on a particular image region of the reconstruction area. So the target amplitude can be fixed only there, letting a degree of freedom in the amplitude of the remaining area (the noise region). That results in a faster convergence of the reconstructed intensity to the target value, as will be verified in the results section.
The amplitude constraint in the image region $\tilde{A}_{mod}$ is expressed as:

$$\tilde{A}_{mod} = \begin{cases} \sqrt{I_{target}} & x, y \in \text{image region} \\ A & x, y \notin \text{image region} \end{cases},$$

where A is the amplitude kept from the iterative process. Figure 2 shows the flow diagram for this iterative hologram generation, where the amplitude constraint is implemented from D to A.
This method is of particular interest if a black frame wants to be added to the target image. As the image region is smaller than the complete reconstruction area, it can be shifted, which allows for example to avoid the central zero order (no-modulated light) appearing in the center of the reconstructed image, which was its application in this work. Also the black frame permits to separate the reconstructed image from the replicas.

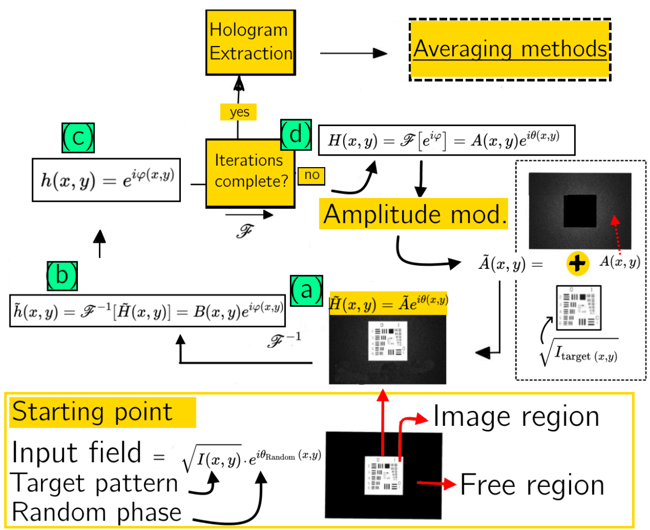

FIG. 2: Hologram computation flow diagram. A random phase is added to the initial target amplitude. Amplitude constraints from B to C (phase only constraint) and from D to A (target amplitude constraint). The hologram phase is extracted from φ.

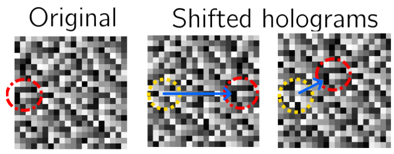

FIG. 3: Original hologram shifted different distances.

III. SPECKLE REDUCTION BY AVERAGING

Speckle reduction by averaging is based on displaying multiple holograms which reconstruct images with different speckle patterns that average out when integrated to form a single final reconstruction.

■ Conventional averaging

The easiest way of averaging is setting a different initial random phase on the GS algorithm to generate the holograms that are to be averaged [6]. Each displayed hologram will have a reconstruction with random speckle distribution. Averaging those random distributions $I_{avg} = \frac{1}{N}(I_1 + I_2 + ... + I_N)$ leads to a reduction of the speckle contrast(SC) according to $\longrightarrow \frac{1}{\sqrt{N}}$, where N is the number of averaged images. On the other hand, the reconstruction speed reduces proportional to the number of averaged patterns, because the different holograms are displayed sequentially and the SLM frame rate is limited. Also, it is necessary to calculate N holograms, which requires computational effort.

■ Shift averaging

Another approach is to simply circularly shift a single hologram on the SLM [4]. That doesn't require to calculate other holograms. Figure 3 shows two examples of shifted holograms in different directions. This shift adds a linear phase to the reconstruction plane, which varies the speckle pattern. Averaging then different shifted patterns will reduce the SC.
There are two ways of reducing speckle depending on how we choose the shifting vector $\vec{r_s} = (x', y')$ for each of the averaged holograms.
▷ **Random shifts:** If x', y' are chosen randomly, the stochastic speckle distribution, as with conventional averaging, will make speckle reduce as $\longrightarrow \frac{1}{\sqrt{N}}$.
▷ **Specific shifts:** There is also the option to select (x', y') specifically to increase the speckle reduction strength with the same number of holograms compared to the random shifting. That is derived from the identity for the sum of complex roots. Golan et al. [4] showed that speckle is even completely eliminated if all the combinations of x_i and y_i are considered. Where $x'_i = i\frac{M}{c}, y'_j = j\frac{M}{c}$, where i and j range from 1 to M, c is the number of shifting steps in each direction and the array size of the hologram is MxM.

■ Pixel sepatation (PS)

The pixel separation method (PS) [5] reconstructs less

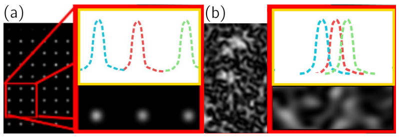

FIG. 4: Field overlapping area is illustrated qualitatively. Reconstructions for (a) PS and (b) GS reconstruction.

pixels per image, increasing the distance between neighbouring points, so the overlapping of their PSF distributions is reduced. Figure 4 (a) shows the qualitative field distribution of each PSF and its resulting intensity pattern. Image (b) shows a simulation of the speckle where field overlapping is not reduced. The procedure for separating image points is dividing the original target intensity distribution into a set of $N = n^2$ sub-images, where each image has a spacing n between reconstructed pixels. If the target sub-images are added up the original image is recovered. Figure 5 shows an example of generated target sub-images.

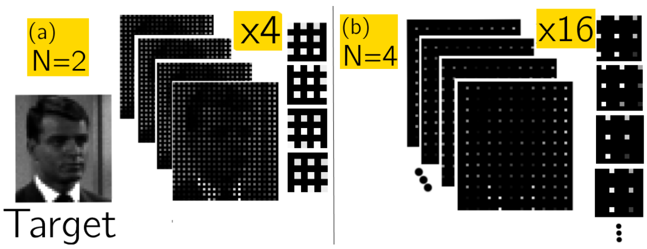

FIG. 5: Target images for: (a) $n = 2, N = 4$, (b) $n = 4, N = 16$.

IV. EVALUATION OF THE METHODS

Methods were evaluated by the peak signal-to-noise ratio (PSNR), speckle contrast (SC) and the quality index (Q).

Q is defined as $Q = \frac{4\sigma' \langle I \rangle \langle I_t \rangle}{(\sigma^2+\sigma_t^2)\left(\langle I \rangle^2 + \langle I_t \rangle^2\right)}$. Where σ' is $\sigma' = \frac{1}{MN-1} \cdot \sum_{a=1}^{M} \sum_{b=1}^{N} \{I(a,b) - \langle I \rangle\} \{I_t(a,b) - \langle I_t \rangle\}$

$\langle I_t \rangle$ is the average intensity of the target image, $\langle I \rangle$ is the average intensity of the evaluated image, M and N are the number of pixels on each side of the image, and the sum is over all the image pixels.

The value of Q is between -1 and 1 and has its maximum at 1 if the reconstruction is perfect. C_s is defined as $C_s = \frac{\sigma}{\langle I \rangle}$, and it is evaluated on a constant target intensity region.

Finally, the PSNR is defined as: $\mathrm{PSNR} = 10 \log_{10} \frac{I_{max}}{MSE}$. Where I_{max} is the maximum pixel intensity of the image and the Mean Squared Error (MSE) is computed as $\mathrm{MSE} = \frac{1}{MN} \sum_{a=1}^{M} \sum_{b=1}^{N} \{I(a,b) - I_t(a,b)\}^2$.

V. SIMULATION RESULTS

■ Modified GS evaluation

Figure 6 shows the evaluation of SC and PSNR over the number of iterations on the GS algorithm. Both the modified an the original GS were evaluated for (5, 10, 20, 40, 80, 160, 300) iterations. In the simulation no speckle is added, so both SC and PSNR are a measure for the convergence of the algorithm towards the target intensity values. It is visible that the modified algorithm converges, in few iterations, to a low SC under 2% and an acceptable image quality. In contrast, it is not possible for the normal GS to achieve a better convergence from the one shown at 300 iterations, with a SC around 15%.

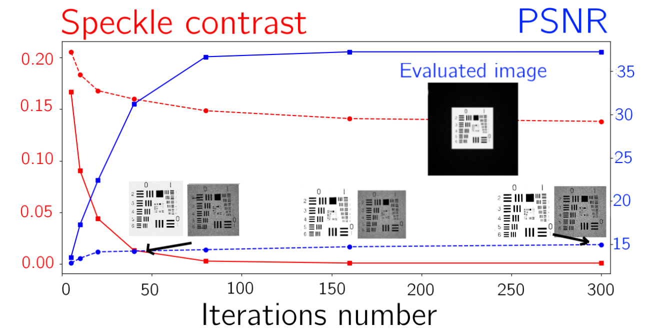

FIG. 6: PSNR is shown as blue curve, and SC as red curve. Image quality is shown for 40, 160 and 300 iterations. The modified GS values are plotted with a solid line while the original GS is plotted with a dashed line.

■ Averaging methods evaluation

Figure 7 shows the evaluation of Q, PSNR an SC for the stochastic "$1/\sqrt{N}$ methods", for shifting and PS. The number of pixel spacing or shifting steps are $n = c = 2, 4, 6, 8$ and the number of holograms $N = n^2 = 4, 16, 36, 81$.

From the comparison of the different graphs we see that the shifting method outperforms the stochastic methods. For the pixel separation method, some frames converge better than others to their target value. This seems to lead to an image degradation independent of speckle, and worse results are obtained with pixel spacings above n=6 (N=36).

VI. EXPERIMENTAL RESULTS

■ Optical setup

To evaluate the methods, the optical system shown in figure 8 was used. It is formed by: a 1064nm Nd:YAG laser, followed by 1064nm filter, which was used to block the pumping wavelength of the laser at around 808nm. Next the beam is expanded by a telescope with focal lengths $f_1 = 15mm$ and $f_2 = 300mm$, and the angle of incidence is as close as possible to normal incidence. The SLM is a Hamamatsu LCOS model X10468, with a resolution of

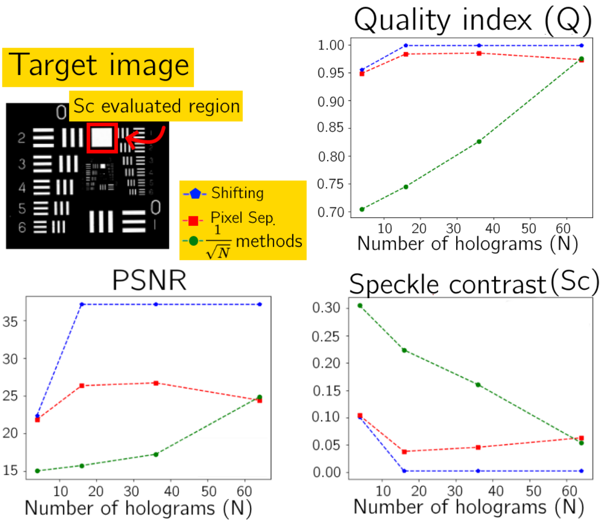

FIG. 7: Evaluation of Q, PSNR and SC. SC is evaluated on the target region.

600x792 pixels and a pixel pitch of $20\mu m$. Then a lens of focal length $f_L = 100mm$ performs an optical Fourier transform of the modulated laser beam. The camera used to capture the image is a model QICAM Fast 1394, (1392 x 1040) pixels and a pixel pitch of $4.65\mu m$.

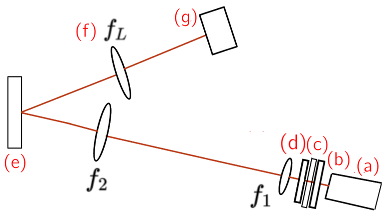

FIG. 8: a,b,c,d,e,f,g show in order: laser, filter, $\lambda/2$, polarizer, SLM, Fourier lens and the camera.

■ Averaging

Methods explained above generate N holograms. Hologram displaying and image acquisition are synchronized to take one frame of each partial reconstruction, then these reconstructions are added up computationally, to form the final image. The updating frequency of the holograms is limited by the SLM refreshing time. Our model allows a maximum frequency of 60Hz, which means a minimum refresh time of $\sim 17ms$ per hologram.

■ Speckle contrast evaluation

Figure 9 shows the speckle contrast evaluation at the selected region for the pixel separation (A) and hologram shifting (B) methods. The number of averaged holograms N was N = 4,16,36,64, which means a minimum reconstruction time ($\tau \approx 17\,N$) of $\tau = 68, 272, 612$ and 1088 ms. A visual comparison between reconstructions of one and 100 shifted holograms is also shown.

From this evaluation, it's visible from the frames a,b,e,f that averaging only 12 holograms more presents a significant SC reduction for both methods, which is reduced by half. In the case of n=2 pixel spacing, the neighboring PSF's still greatly overlap, so there is little speckle reduction. Similarly, averaging only 4 reconstruction with the shift method is not enough to eliminate the speckle completely. The rest of the frames c,d,g,h show a better SC reduction with more averaged patterns. From 16 to 36 holograms, the SC is reduced by $\sim 30\%$ and from 36 to 64 by another $\sim 20\%$, resulting in a very small SC of around 0.08-0.09. In contrast to the simulations (where the same holograms were used), the pixel separation methods shows a lower speckle contrast in the experiment. This might come from differences between the simulated PSF and the experimental PSF, which includes different types of aberrations.

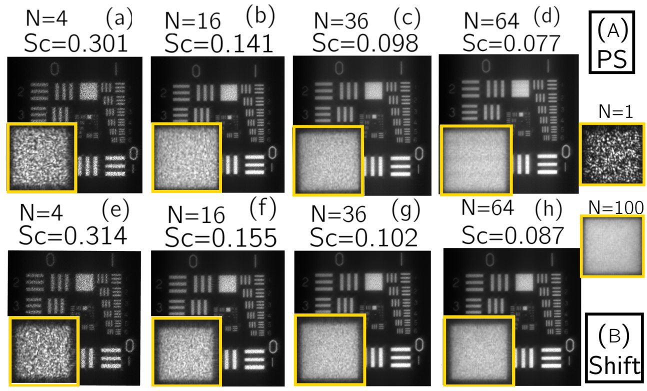

FIG. 9: Row A, pixel separation, and B shifting . N is the number of holograms and SC the speckle contrast.

■ Image quality evaluation

Figure 10 shows the "Cameraman" image, which was reconstructed averaging 100 holograms with the mentioned techniques. Pixel separation (c) and shifting (d) show a better image quality than the stochastic $1/\sqrt{N}$ methods (a) and (b). This visual impression is also supported by the lower SC in the evaluated area of the image. With the pixel separation method the best perceived image quality and lowest SC was obtained. More images showing high-quality image reconstruction with the pixel separation method are shown in figure 11.

VII. CONCLUSIONS

• The modified GS algorithm performs better to calculate holograms of intensity pattern with a black frame for separating the zero order and replicas. The original GS algorithm does not converge sufficiently close to the target intensities in this case.

• Speckle reduction techniques based on averaging methods are an effective option if a precise, artifact-free pattern needs to be reconstructed. Corresponding applications could be beam shaping or static image reconstruction. However, in very dynamic applications such as real

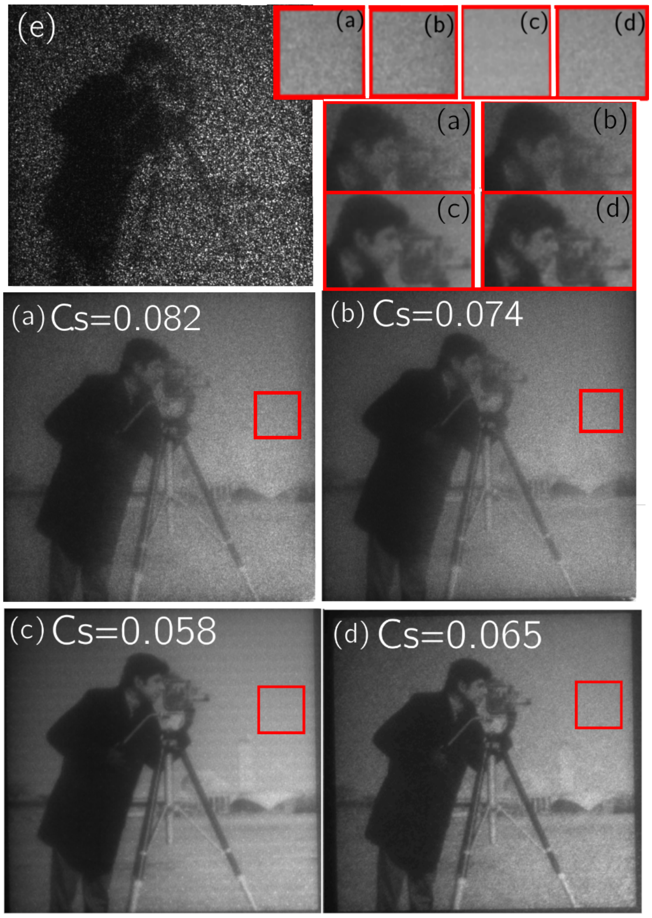

FIG. 10: SC is evaluated on the target background region for: (a) Conventional averaging (b) Random shifting method (c) Pixel separation method (d) Shifting method. (e) One hologram GS reconstruction.

time video projection, a better approach would be to use phase-smoothing methods without sequential averaging. That results in a trade-off in image quality, but the image displaying-rate would be the same as the SLM updating frequency.

• There is also a compromise between computation time and image quality. On the one hand, the pixel separation method has shown better experimental results with a higher image quality and lower speckle contrast. On the other hand, the shifting method is computationally more efficient since it requires only to calculate one hologram. In contrast to that, the pixel separation method requires a large number of FFT operations ($N = n^2$), so it is really time expensive when a large number of holograms are used.

• Finally, as recent research results have shown [7], demanding hologram computation times are not a barrier anymore if they are addressed with machine learning. So if future SLM devices present higher updating frequencies, averaging methods could enhance it's full potential with 3D projection in real time systems.

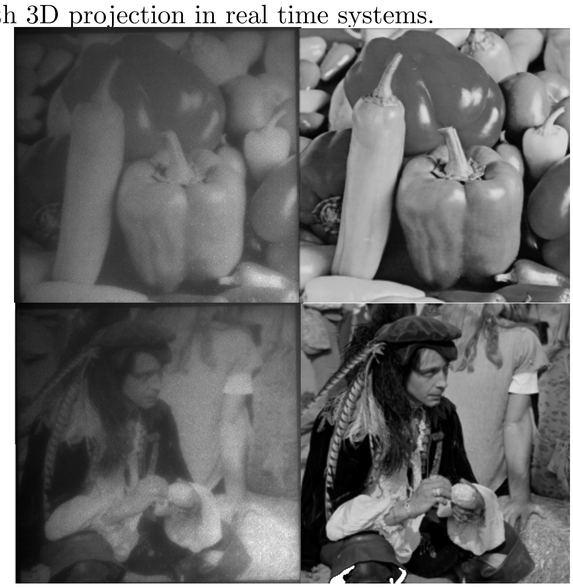

FIG. 11: Pixel separation reconstructions for N = 100 holograms. Right image is the target.

Acknowledgments

I would like to thank my advisor, for his excellent tutelage during this TFG. And also thank to E. Martin, M. Montes and R. Bola for their lessons and the opportunity to undertake this work.

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