Single exposure lensless phase imaging

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I. Introduction

This paper is devoted to development of a phase retrieval imaging technique based on phase modulation of the object wavefront and angular spectrum free propagation from object to the modulation phase mask and from this mask to the camera. The free propagation is modelled by the angular spectrum operator [1]. In contrast with the traditional microscopy, our system is lensless, which can provide high-resolution reconstruction with large field of view while the set-up became portable and cost-effective. A random phase mask between the object and camera creates a coded diffraction pattern without twin image effects. The complex-domain block-matching 3D (BM3D) filtering is applied in order to reach pixel resolution with a one single wavelength experiment. A spatial light modulator (SLM) is used for the phase-mask generation and the image is captured by a CMOS sensor of the camera. Previously developed optical setup and image reconstruction algorithm [2] based on multiple observations are modified here to use only one observation. A sparse modelling of the complex-valued object to be reconstructed leads to its BM3D filtering [2,3].

II. System setup

A. Propagation with Angular Spectrum

The main goal of phase retrieval is to achieve detailed 3D reconstructions of the object while only the intensity of the light radiation is captured. This intensity measurement of $y \in \mathbb{R}_+^{NxN}$ without noise can be written as

$$y = |P_1\{u_m\}|^2 \qquad (1)$$

where $u_m \epsilon \mathbb{C}^{NxN}$ is the coded 2D complex image of the object in the mask plane and $P_1: \mathbb{C}^{NxN} \longmapsto \mathbb{C}^{NxN}$ is the forward propagation of the laser beam from the mask to the sensor plane with the distance d_1. The wavefront u_m in the mask plane contains the propagated light from the object which is modulated by SLM as

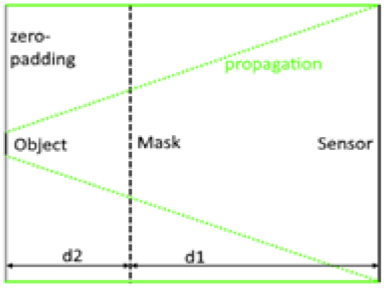
$$u_m = M \circ P_2\{u_o\}. \qquad (2)$$

Here $'\circ'$ is a symbol of the element-wise Hadamard product of the 2D object image $u_o \epsilon \mathbb{C}^{NxN}$ with the mask matrix $M \epsilon \mathbb{C}^{NxN}$, which can be written as $M(k,l) = A_m \exp\left[j\phi_{k,l}\right]$ and it results in a coded diffraction pattern on the sensor plane [1]. The mask makes possible to observe higher range of frequencies by changing the distribution of the diffraction pattern and enlarging. The propagation distance of the operator P_2 is d_2.
As mentioned earlier an angular spectrum (AS) method is used to calculate the propagation between the planes which defines the transfer function of the Rayleigh-Sommerfeld model as

$$u(x,y,d) = \mathcal{F}^{-1}\left\{H\left(f_x,f_y,z\right) \cdot \mathcal{F}\{u(x,y,0)\}\right\} \qquad (3)$$

$$H\left(f_x,f_y,z\right) = \begin{cases} e^{i\frac{2\pi}{\lambda}d\sqrt{1-\lambda^2\left(f_x^2+f_y^2\right)}}, & f_x^2+f_y^2 \leq \frac{1}{\lambda^2} \\ 0 & otherwise \end{cases} \qquad (4)$$

$u(x,y,d)$ is a wave front propagated on a distance d, while $u(x,y,0)$ is the starting plane. $\mathcal{F}$ and $\mathcal{F}^{-1}$ stay for the Fourier transform and the inverse Fourier transform respectively, and $H\left(f_x,f_y,z\right)$ is the transfer function specified by the AS method [2].
Due diffraction on the edges of the object, the number of pixels N needed for capture one propagated pixel is depending on the distance between the object and the camera $d = d_1 + d_2$, the λ wavelength of the laser beam and the Δx size of the camera pixel, and can be expressed as [4]



1. Figure: Optical setup

$$N \geq \frac{d \cdot \lambda}{\Delta x^2} \qquad (5)$$

The required pixel number can exceed the pixel number of object, phase mask and sensor, therefore we should use zero padding for the object, mask and sensor images in order to obtain the better resolution and avoid aliasing effects.
From equation (1) and (2) we can see the connection between the captured intensity y and the object u_o:

$$y = \left|P_1\left\{M \circ P_2\{u_o\}\right\}\right|^2 \qquad (6)$$

In every iteration of the algorithm, the light is propagated forward from the object to the sensor plane and backward using the squared root of the captured intensity y from equation (6) for substitution as the amplitude of u_m, while the phase of u_m is kept unchanged.

B. BM3D filtering

Due the loss of phase information in observations, we need to reduce the appeared disturbances and noise in u_0, so after the backpropagation of every iteration, a BM3D filter is applied, which is based on an enhanced sparse representation of images in transform domain. It is also known as *nonlocal self-similarity sparsity*, because the algorithm is searching for similar patches in overlapping areas of the image, to create a 3D group arrays.

The advantage of the method is using a so-called collaborative filtering, where after transform these arrays we can hard-threshold them and achieve a filtered image by inverse transformation. The process is repeated for each pixel thus the final image is obtained by meaning the overlapping patches. The detailed concept of the algorithm can be seen in [3], and can be expressed as

$$\varphi' = BM3D_{phase}(\varphi, th_\varphi) \quad (7)$$

$$A' = BM3D_{amplitude}(A, th_A) \quad (8)$$

where A and φ are the amplitude and phase of the complex domain image $u = A\exp[i\varphi]$, while A' and φ' are their sparse approximations. The thresholding parameters th_φ and th_A are initialized in the beginning of the program, but can be changed in every iteration.

III. SIMUALTIONS AND LIMITATIONS

We successfully applied the developed algorithm in simulations using the setup and parameters close to the real system which is currently in implementation. These parameters are strictly limiting the obtained accuracy, but even with these constraints, we managed good quality reconstruction and pixel resolution.

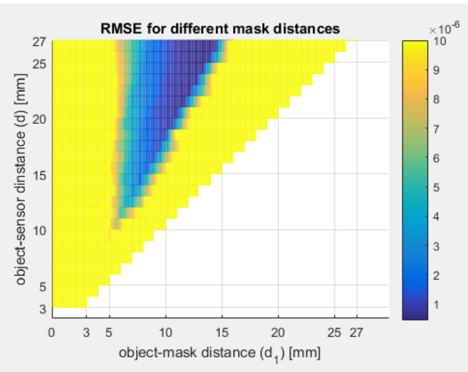
A. Parameters

a) light source: A coherent laser beam is used to illuminate the object, with the wavelength of $405\,nm$. We assume parallel beam and plane wave propagation.

b) object: A binary amplitude and phase United States Air Force (USAF) test target is created to examine the accuracy of the system. The smallest line is 1 pixel wide corresponding to the sensor's pixel size of $1.55\,\mu m$.

c) sensor: The Flea3 (FL3-U3-120S3C-C) camera contains a 12MP Sony IMX172 CMOS sensor with 12 bit ADC. The resolution is $3000\ x\ 4000$ with the pixel size of $1.55\,\mu m$.

d) mask: The binary amplitude and phase mask is generated by SLM, therefore the parameters of the mask are limited by this SLM. Each $36\,\mu m$ pixel is characterized with a 55% filling factor, so taking the mentioned sensor size each pixel will contain $23\ x\ 23$ subpixel which from only the middle $17\ x\ 17$ subpixel square is avaiable for modulation.

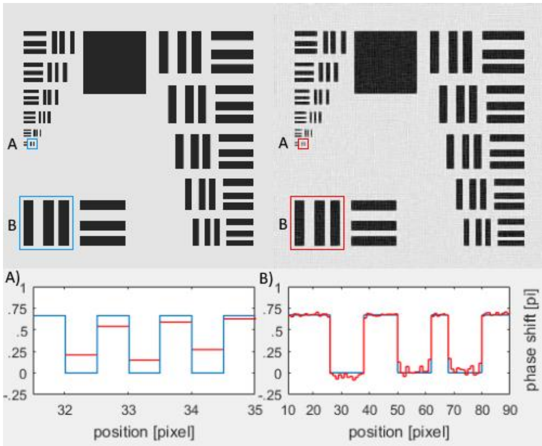


2. Figure: experiments to select reliable distances without real-life restrictions

e) distances: The spaces between the object-mask-sensor setup are calculated via numerical experiments without the real-life restrictions, where the accuracy is given by the relative root mean square error (RRMSE) of the object phase. As it can be seen in Fig.2 inserting the mask too close to the object or the sensor results in the worse accuracy than placing the mask between them. In other hand bigger distances increase the required number of pixels and complex image size according to the equation (5). Therefore the Fourier transform of these large matrices requires more calculation time and memory. Another limitation is that the camera has a $19\,mm$ C-mount, so $d_1 > 19\,mm$.

B. Results

Considering these constraints the numerical experiments we could achieve pixel resolution from total distance of $35\,mm$, with iteration number of 60. The BM3D thresholding parameters are set to high values during the first half of the iterations to achieve stronger filtering, and then lowered in every round to get smoother reconstruction. With calculation time of 17 minutes, we can achieve the required accuracy as it can be seen in Fig.3.



3. Figure: Original (top left) and reconstructed (top right) phase of the image, and the cross-section of their smallest (A) and largest (B) details. The blue color represents the original, the red the reconstructed image

CONCLUSION

We have developed the method for reconstruction of 3D phase object from only one 2D intensity image, using the parameters of an existing setup. BM3D filter is successfully implemented in the algorithm to achieve pixel resolution. Based on the demonstrated reliable results in simulations we are planning to realize this algorithm in real-life experiments.

REFERENCES

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