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DECONVOLUTION PROCESS WITH GPU IN A WAVEFRONT CODING MICROSCOPY SYSTEM

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ABSTRACT

A Wavefront Coding microscopy system is implemented in order to extend the depth of field of an optical system. An $LC - SLM$ is used to display the profile of a phase mask. A set of optically coded images is recorded in an axial range $[-1, 1.5]$ mm. To accelerate the deconvolution process, a routine developed directly on a GPU is implemented. Using this GPU based approach, the deconvolution time is reduced by providing an additional speed up to the visualization. Digital images are acquired using an experimental setup and results are presented.

Keywords: Wavefront Coding, GPU, Microscopy system, Spatial Light Modulator.

1. INTRODUCTION

Increasing the depth of field (DoF) and maintaining a high resolution have been the classical aim in an optical system. It is well known, that the microscopy systems have a limited DoF. When the biological sample is analyzed under a microscope, commonly the sample is thicker than the DoF. A typical microscopy system produces blurry images in the portion of the object that lies outside of the DoF. To attain images with an extended DoF with high resolutions implies the use of high numerical aperture (NA). However, this leads to a reduction of the DoF.

Wavefront Coding (WFC) technique [1] is an effective way to extend DoF of a microscopy system compared to classical microscopy systems. WFC modulated the wavefront by inserting a properly designed phase mask (PM) in the exit pupil of an imaging system. Point spread function (PSF) can be highly invariant to defocus in an axial range. The images thus obtained are blurred. In addition, a deconvolution process is applied in order to get a final clear image and recover the frequency content of the coded image. Using liquid crystal spatial light modulator ($LC - SLM$) is possible to display any profile to PM. The implemented WFC microscopy system with the use of $LC - SLM$ has led to the desirability of a flexible system. Several PMs have recently proposed, a novel phase mask based on the Jacobi-Fourier polynomials was used [2].

In general, the computational time to perform the deconvolution process is according to the size of the image to be reconstructed. Applied in microscopy, it is required to obtain a quick result for the corresponding analysis. Recent methodologies such as Field-Programmable Gate Array ($FPGA$) [3] or Graphic Processing Unit (GPU) [4] work as hardware accelerators have been used for alternative accessories with better performance in digital processing. The $FPGA$ has been used to perform a reprogrammable implementation.

To accelerate the processing time, an algorithm that uses GPU technology is implemented. GPUs were developed as coprocessors dedicated to graphic functions on a computer [5]. It is auxiliary hardware that allows parallel process to accelerate algorithms that contain operations that can be carried out automatically, while another part of the code is executed in the CPU as shown in Fig. 1. $NVIDIA®\ GPUs$ are graphical card used in image processing. They have different levels of internal memory that they use to store the data, each one has different speed and bandwidth. It offers the advantage of being able to program GPU in high-level language.

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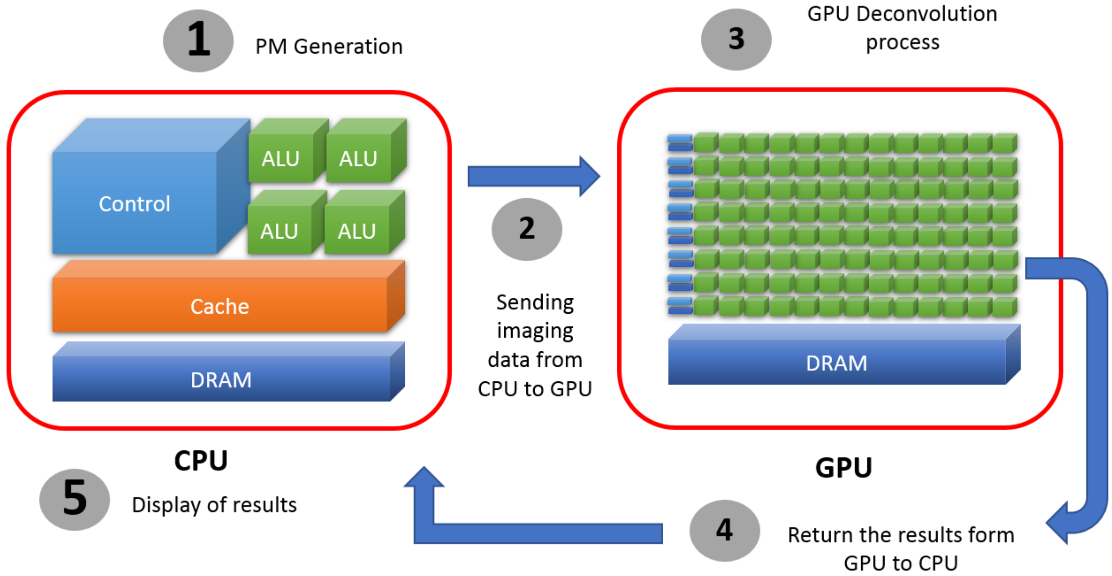


Fig. 1. Deconvolution processing with GPU.

In this paper we present the implementation of a WFC microscopy system along with a deconvolution process with GPU. A Jacobi PM for extended DoF is implemented in $LC-SLM$. Section 2 describes the technique of WFC Microscopy System. In section 3, the images obtained by the optical system are presented. Additionally, the deconvolution process with GPU was performed to reduce computational time. The results obtained are summarized in Section 4. Finally, Section 5 presents the conclusions of this work.

2. WAVEFRONT CODING THEORETICAL BACKGROUND

WFC is an optical digital hybrid technique that consists of two stages. In the first, optical coding is done to produce an image that is modified depending on the mask used. In the second stage digital processing should be used to obtain final high quality images as shown in Fig. 2.

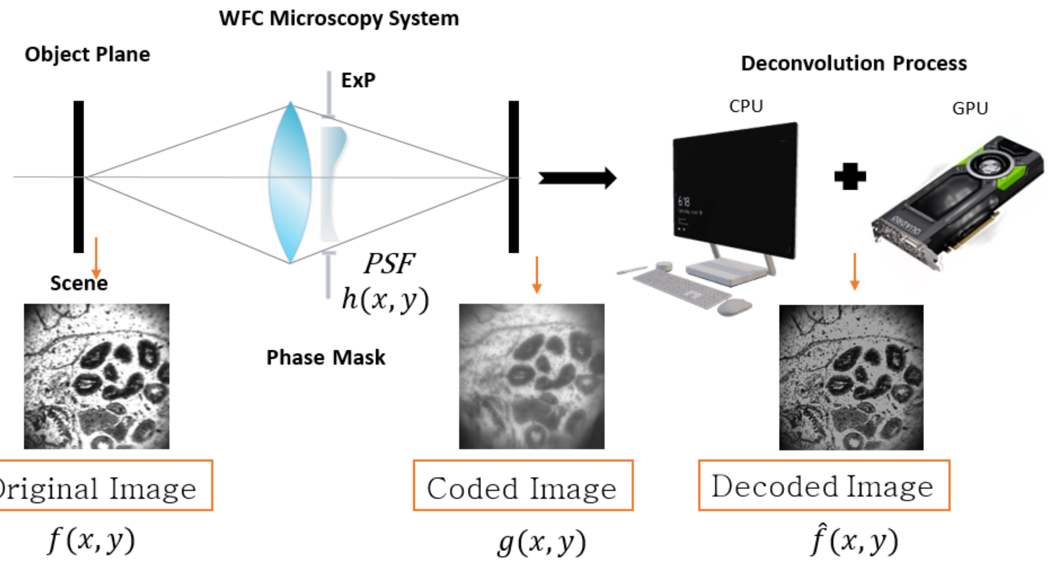


Fig. 2. WFC Microscopy system schema.

The geometrical image is given by [6],

$$g(x,y) = h(x,y) * f(x,y), \tag{1}$$

where $g(x,y)$ represents the digital image acquired by the sensor, $f(x,y)$ is the intensity distribution of the object, $(*)$ is the convolution operator, and $h(x,y)$ is the PSF of the system. Applying the convolution theorem, it can be expressed by,

$$G(u,v) = H(u,v)F(u,v). \tag{2}$$

We can estimate the original image $\hat{f}(x,y)$ as,

$$\hat{f}(x,y) = \mathfrak{F}^{-1}\left[\frac{G(u,v)}{H(u,v)}\right], \tag{3}$$

where $\mathfrak{F}$ denotes the Fourier transform. Furthermore, to consider the presence of noise, the restoration can be done through the Wiener filter defined by [6],

$$W(u,v) = \frac{H^*}{|H|^2+K}, \tag{4}$$

where H is the Fourier transform of the PSF, H^* denotes a conjugate complex, and K is the relationship between the noise spectrum and the degraded image spectrum.

3. WAVEFRONT CODING MICROSCOPY SYSTEM

A hybrid approach that combines optical coding and digital postprocessing is implemented. Since the cubic PM was first proposed [1], researchers designed several PMs up to now to extend DoF [7]. The design of PM has received a great attention due to the fact that is one of the key tasks in WFC system. The shape of the PM has different characteristics on achieving DoF extension. We used a novel proposal based on Jacobi-Fourier polynomial to extend DoF [2].

3.1 Coded Image

The experimental implementation of the WFC technique was performed using a spatial light modulator (SLM) to display gray-level distribution which represent the Jacobi PM [8]. The digital image obtained with the WFC microscopy system is shown in Fig. 3b.

a) b)

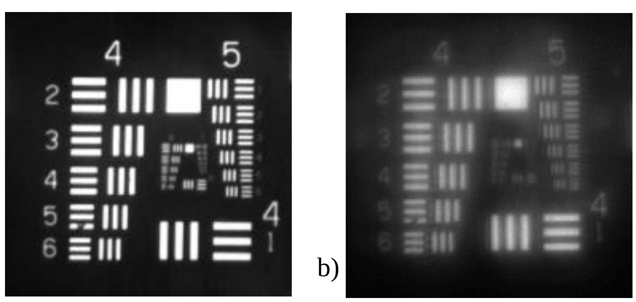


Fig 3. Digital images obtained with a a) classical microscopy system, and b) WFC microscopy system using a Jacobi PM with α=5λ.

3.2 Deconvolution process with GPU

A pixel-by-pixel restored method based on Wiener filter is implemented in GPU. A characteristic of the deconvolution algorithm used is that it is computationally simple and inherently parallel.

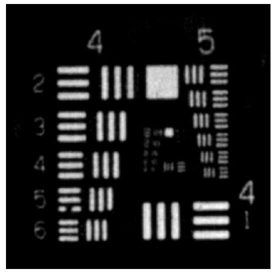


Fig 4. Restored image of WFC Microscopy system obtained from the deconvolution process in GPU.

In literature, the basic mathematical formulation to analyze the resolution power of the optical system is given by,

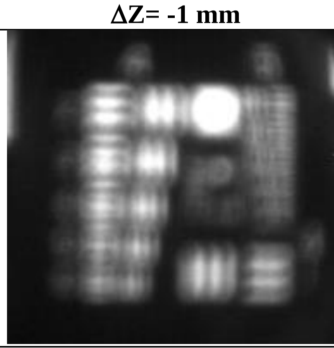
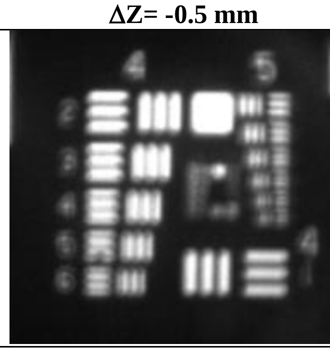
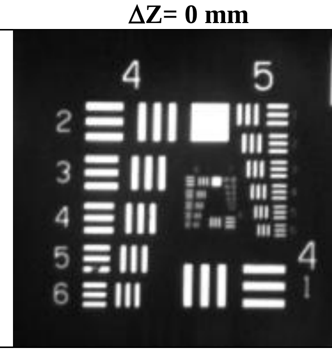
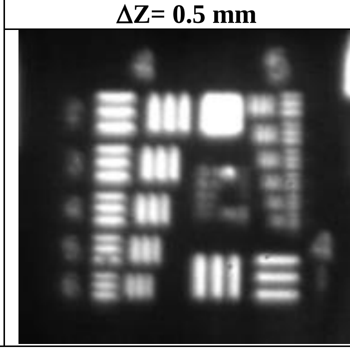
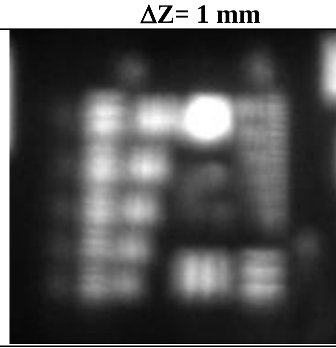
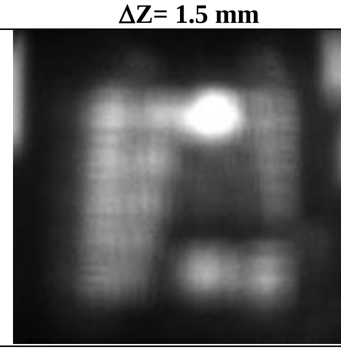
$$R = 0.61\frac{\lambda}{NA}, \tag{5}$$

where λ is the wavelength and NA the numerical aperture of the microscope objective. According to the data of the optical system, $\lambda = 610$ nm and $NA = 0.055$. Therefore, we can calculate the resolution limit as 6.76 µm.

4. WAVEFRONT CODING RESULTS

In this study, images have been obtained in steps of $\Delta Z = 0.5mm$ in an axial range of [-1 mm, 1.5 mm]. With this process, digital images of a WFC microscopy system could be obtained. The microscope objective used in the experimental setup was a Mitutoyo® $2x$ with $A = 0.055$. The size of the images obtained is $2048\ x\ 2048$ pixels. Table 1 shows the images obtained by the system without PM.

Table 1. Digital images recorded at different values of ΔZ from a classical microscopy system.

Strength	ΔZ= -1 mm	ΔZ= -0.5 mm	ΔZ= 0 mm
Jacobi PM α=0			
	ΔZ= 0.5 mm	ΔZ= 1 mm	ΔZ= 1.5 mm
Jacobi PM α=0			

In Table 2 is shown optically coded images from a WFC microscopy system using the Jacobi PM with a strength of 5 λ. It is possible to observe that these images present a blur nearly uniform. And Table 3 shows deconvolved images using the Wiener filter implemented in GPU.

Table 2. Digital coded images from a WFC microscopy system using Jacobi PM with α=5λ.

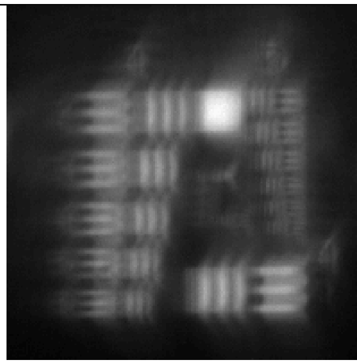
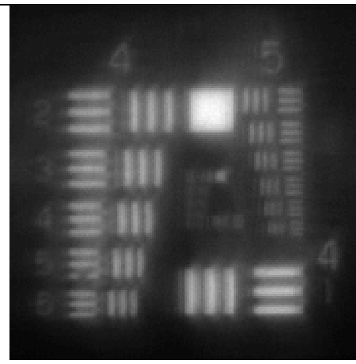
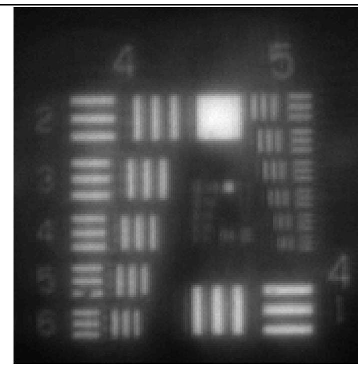
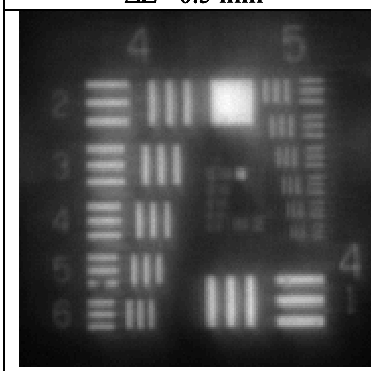
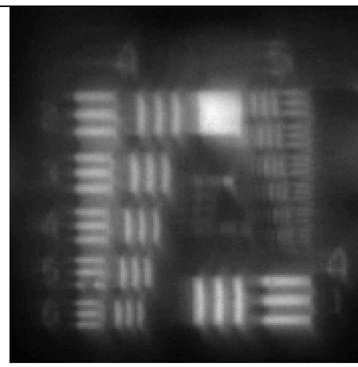
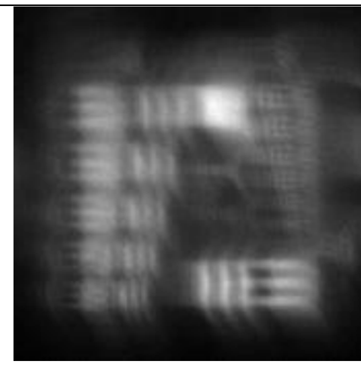
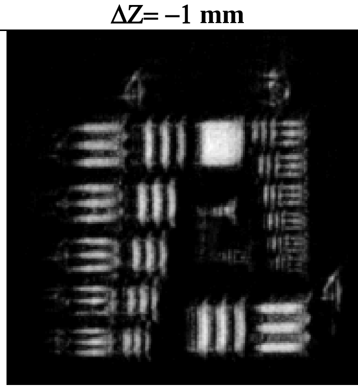
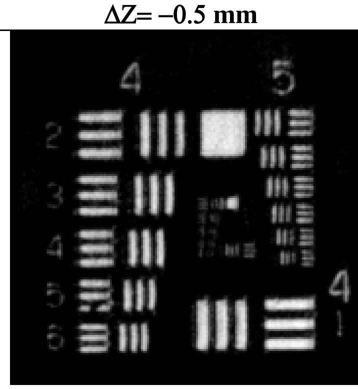
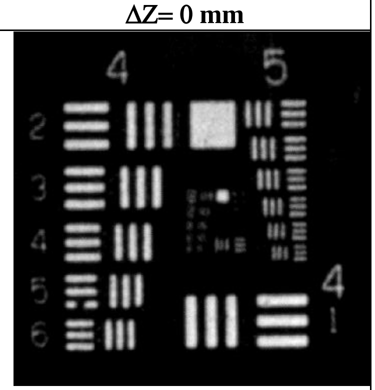
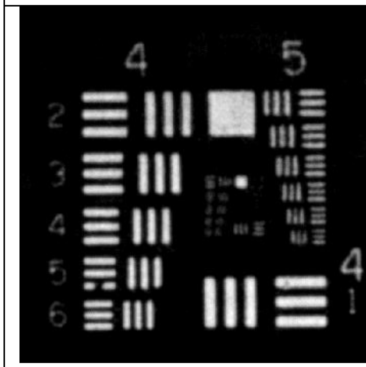
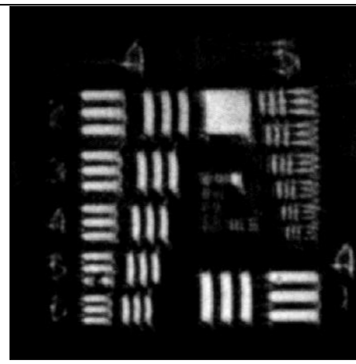
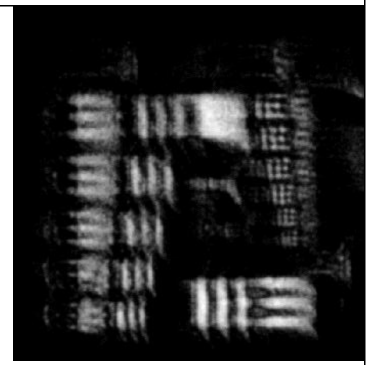
Strength	ΔZ= −1 mm	ΔZ= −0.5 mm	ΔZ= 0 mm
Jacobi PM α=5			
	ΔZ= 0.5 mm	**ΔZ= 1 mm**	**ΔZ= 1.5 mm**
Jacobi PM α=5			

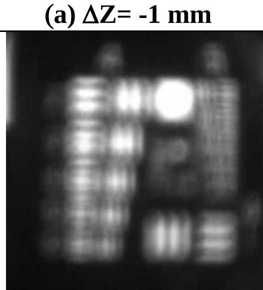
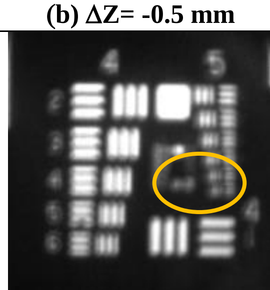
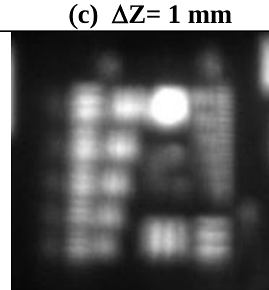
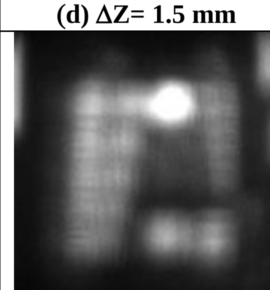
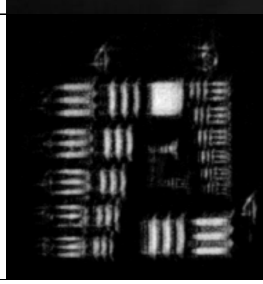
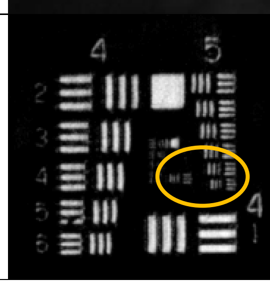
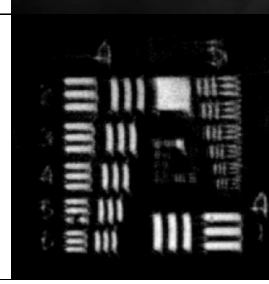
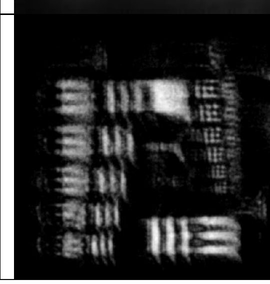
Table 3. Restored images for different values of ΔZ for a WFC microscopy system using Jacobi PM with α=5λ.

Strength	ΔZ= −1 mm	ΔZ= −0.5 mm	ΔZ= 0 mm
Jacobi PM α=5 Wiener Filter K=0.001			

		ΔZ= 0.5 mm	ΔZ= 1 mm	ΔZ= 1.5 mm
Jacobi PM **α=5**	Wiener Filter K=0.001			

According to the Table 4, the DoF range has been extended from $[-0.5\,mm\ to\ 1\,mm]$. The value of K used for restoration is 0.001. The system can resolve up to element 1 of group 6, which is equivalent to a resolution of 7.81 μm. The images obtained have not been preprocessed. However, images restored outside this range are visibly better than those obtained by the classical system.

Table 4. Comparative performance of a classical microscopy system vs WFC microscopy system. Digital images recorded at (a) -1 mm, (b) -0.5 mm, (c) 1 mm and (d) 1.5 mm.

	(a) ΔZ= -1 mm	(b) ΔZ= -0.5 mm	(c) ΔZ= 1 mm	(d) ΔZ= 1.5 mm
Classical microscopy system				
WFC microscopy system				

The following computation times were obtained for the deconvolution process. Fig. 5 shows the computational cost of the Wiener method of digital images of $256x256$, $512x512$, $1024x1024$ and $2048\ x\ 2048$ pixels when they run on Matlab® R2018a with an Intel® Xeon® processor CPU ES-2609 v3 @ 1.90 GHz 1.90 GHz CPU. The GPU used is NVIDIA® QUADRO® M5000 with 8GB memory, 2048 cores and a memory bandwidth of 211 GB / sec. In Fig. 4. a restored image is displayed with the algorithm implemented in GPU. When the image processing is done with the use of the GPU, the time decreases considerably. This offers the possibility of being able to visualize the results in a faster way.

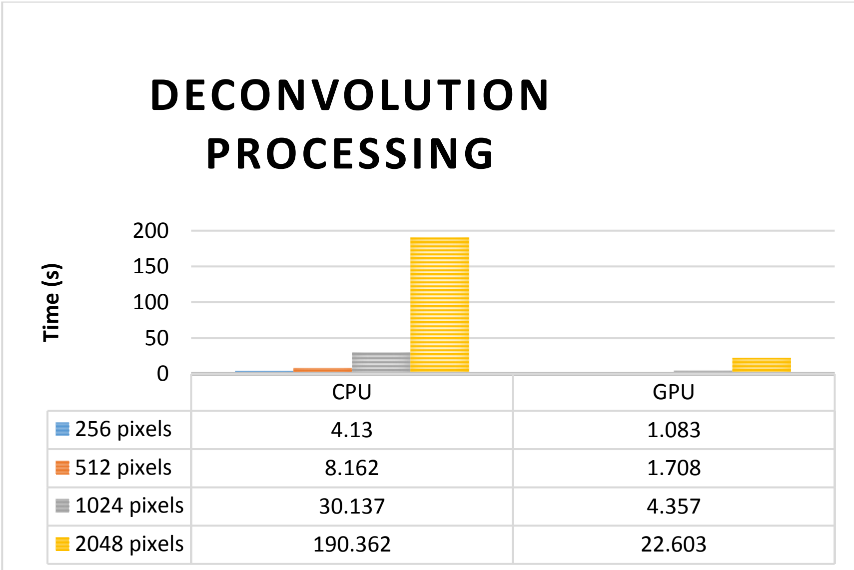


Fig. 5. Computational time in GPU during the deconvolution process.

5. CONCLUSIONS

In light microscopy, it is of great importance to implement new methods for automating labor intensive tasks that require a faster image acquisition during analysis. A WFC microscopy system has been implemented in order to extend the DoF of the system. The PM used is based on Jacobi –Fourier polynomials and displayed in an $LC - SLM$. A set of coded images has been recorded by the given hybrid optical system. The digital coded images are show in Table 2. A deconvolved algorithm is implemented in GPU to processing time optimization. The Wiener restoration method is intrinsically parallel. The digital decoded images are show in Table 3. For the restoration of the images, the computing time required is show in Figure 5. The results of Table 4 show that Jacobi PM indeed can be used to extend the DoF. The DoF range has been extended from $[-0.5\ mm, 1\ mm]$.

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