Time efficient Gabor fused Master Slave optical coherence tomography

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In this paper the benefits in terms of operation time that Master/Slave (MS) implementation of optical coherence tomography can bring in comparison to Gabor fused (GF) employing conventional fast Fourier transform based OCT are presented. The Gabor Fusion/Master Slave Optical Coherence Tomography architecture proposed here does not need any data stitching. Instead, a subset of *en-face* images is produced for each focus position inside the sample to be imaged, using a reduced number of theoretically inferred Master masks. These *en-face* images are then assembled into a final volume. When the channelled spectra are digitized into 1024 sampling points, and more than 4 focus positions are required to produce the final volume, the Master Slave implementation of the instrument is faster than the conventional fast Fourier transform based procedure.

INTRODUCTION

In any Optical Coherence Tomography (OCT) [1] imaging instrument, the transversal resolution is determined by the beam spot size incident on the sample to be imaged, i.e. it depends on the optical design of the interferometer's object arm. A quite high numerical aperture (NA) is required to improve the transversal resolution, but this also decreases the depth of focus, therefore a compromise between lateral resolution and depth scanning range must be found. The modern Optical Coherence Tomography technology is based on spectral (or Fourier) domain principles with the disadvantage that the backscattered intensities of all scattering centers along the axial range of the imaged sample are collected under a fixed focus. Therefore, a low numerical aperture interface optics is commonly used, that leads to a lower transversal resolution. If a higher lateral resolution is required, then the increase in the numerical aperture leads to a reduction of the depth of focus. Solutions such as the ones based on Bessel beam formation using axicon lenses can provide some trade-off between the transversal resolution and the depth of focus but cannot achieve high transversal resolution that can only be attained with high numerical aperture values.

The number of needed repetitions of acquisitions, N, was defined in [2] as the ratio between the axial range (AR) over the depth of focus (DOF). The value of N determines the minimum number of focus positions, to obtain a similar transversal resolution along the whole axial interval targeted in the sample, made from several N depths of focus intervals. The data acquisition and calculations need to be performed for each set value of the focus position. The procedure of assembling a final volume of the tissue with selected parts under different focus is known as Gabor filtering [3]. The immediate problem of Gabor filtering applied to current fast Fourier transform (FFT) based spectral (Fourier) domain optical coherence tomography consists in at least a proportional increase of the overall time of acquisition until a final volume is assembled, with the number N of repetitions.

In this paper we show that by applying the principle of Master Slave (MS) [4], large R number of acqusitions can be performed for a large number of focus positions, for an increase in the time needed that does not grow proportionally with R. This improvement in the total time required comes from the different principle of operation of the FFT based OCT and the MS-OCT.

In comparison with conventional FFT based OCT technology, where 3D volumetric data sets are assembled from many A-scans, when using the MS technique, volumes are assembled from *en-face* (C-scan) OCT images. This difference is paramount for the implementation of the Gabor filtering. Because the FFT based technology delivers an entire A-scan for each focus adjustment, the parts of the A-scans outside the depth of focus are discarded and only the brightest part is retained. The selected parts of A-scans are finally stitched together to form a final volume.

When the OCT instrument is based on MS implementation, there is no need to cut (render), discard and/or stitch parts of the axial reflectivity profiles. Simply, because there is a processor for each axial depth, there is no need to compute all the *en-face* OCT images for the Q depths within the confocal gate interval. Due to this calculus simplification, no results are discarded and an important advantage in the processing time is achieved. The larger the number R of focus positions, the Master Slave becomes more and more efficient in comparison with the conventional FFT based procedure, as demonstrated in the following sections of the manuscript.

PRINCIPLE OF OPERATION

The principle of operation of a Master Slave powered Gabor Filtering OCT instrument is illustrated in the block diagram in Fig. 1 operating according to the flow diagram in Fig. 2.

The OCT imaging instrument is equipped in Fig. 1 with a modality of focus adjustment (here a translation stage TS to move a lens L, or equally a liquid lens can be used instead). The OCT system can be equipped with either a spectrometer and be driven by a broadband source such as a super-luminescent diode or a supercontinuum optical source or equipped with a fast photodetector and driven by a swept source laser. Instead of performing FFT for each spectrum acquisition (either by reading the camera in the spectrometer or by sweeping the swept source), the OCT is equipped with a MS protocol [4,5]. The MS protocol involves a comparison operation of the electrical signal proportional to the spectrum at the interferometer output with replicas of the same signal (masks), performed by the Master Slave processing block.

Let us say that for the whole axial range, a Q number of axial points, in depth, are targeted. For Q number of axial points, Q masks are prepared at the calibration step (the Master stage). In this paper, a number of Q = 600 is used. For each axial depth, a single mask is sufficient to produce an *en-face* OCT image from a particular axial position. In comparison with conventional FFT based OCT technology, where sub-volumes are assembled from several A-scans, here sub-volumes are assembled from *en-face* OCT images. This difference is reflected into the implementation of the Gabor filtering.

Benchmarking for GF/MS-OCT is evaluated here for different number of repetitions, R, of focus positions, where R should exceed N = AR/DOF. This means that for each depth position, if R is equal or larger than N, then only Q/R masks are used for Q/R depths.

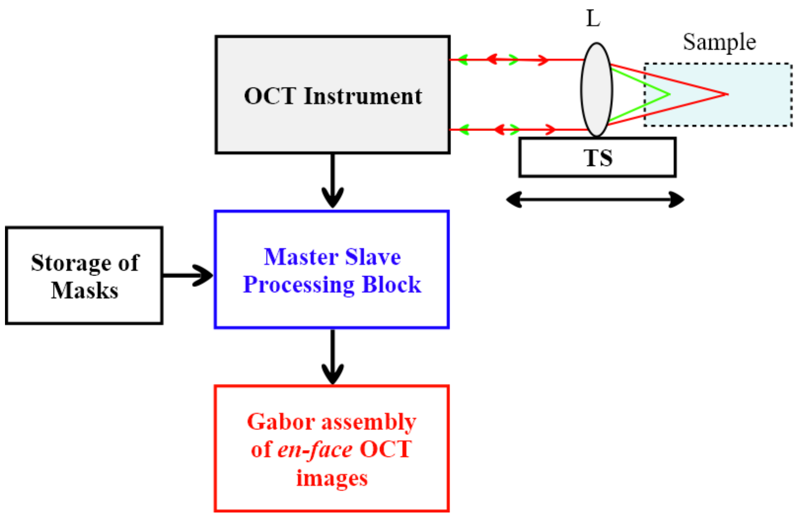

Figure 1. Schematic diagram of the Master Slave enhanced Gabor filtering optical coherence tomography imaging instrument. TS: translation stage, L achromatic lens

In our MS based implementation, there is no need to cut and stitch A-scans. Simply, because there is a processor for each depth, there is only required to compute results for the axial depths within the confocal gate interval (DOF). Such procedure automatically leads to the highest brightness *en-face* images for each focus position. Then these *en-face* images are assembled into the final volume (Gabor fused image).

The translation stage TS shown in Fig. 1 is utilized for positioning the focus inside the sample to be imaged at different axial depths ($\zeta_1 \ldots \zeta_R$). For each such axial position, Q/R *en-face* OCT images are calculated according to the flow diagram presented in Fig. 2.

At the Master stage, P channeled spectra using a mirror are recorded, followed by their storage on the memory of the computer (RAM). P can be any integer number larger or equal to 2. In this experiment, only a number of P = 3 channeled spectra are experimentally collected. Using these 3 channeled spectra, a special program [5] evaluates all Q (600 in this paper) masks for all necessary axial depths in the final volume.

At the slave stage, for each focus position, a subset Q/R of theoretically inferred masks are utilized to compute Q/R *en-face* OCT images for R focus positions (R frame acquisitions). Focus is initially placed at ζ inside the sample as determined by the initial position of the translation stage TS. z_r is the focusing position in the sample corresponding to r, the repetition index, r = 1,2…R.

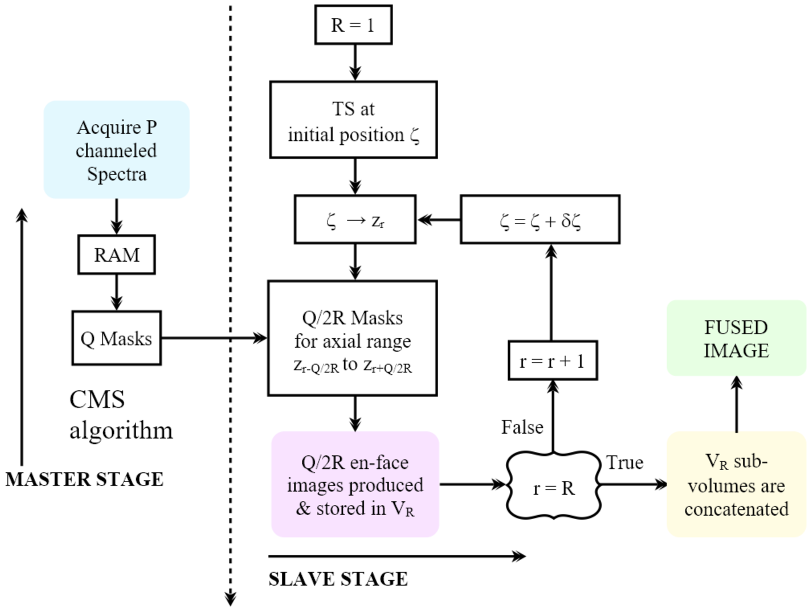

Figure. 2 Diagram presenting the complete process of producing a Gabor fusing image in a Master Slave enhanced Gabor fused OCT imaging system

The MS operation consists in comparing each theoretically inferred mask with the channelled spectrum obtained from the interferometer when scanning over the sample. Several mathematical operations were evaluated, such as direct correlation calculation, FFT based correlation or matrix multiplications [6].

RESULTS

The Gabor fusing method is extremely time consuming due to the repetition of acquisition for R times. If the conventional FFT based OCT method was used, for each z_r axial position of the focus, a large volume in terms of its axial range compared to the significant values volume would be generated. The larger the numerical aperture of the interface optics in the sample arm of the interferometer, the shorter the depth of focus and the larger the volume part that is discarded before stitching.

Time is taken by the digital processing, as each A-scan is the result of a succession of sequential mathematical operations (apodization followed by zero padding and dispersion compensation algorithms for example) and finally of the fast Fourier transform.

For each channeled spectrum which is digitized into N_k sampling points, a number of $N_z = N_k/2$ axial points are used to cover the entire final axial range. Let us suppose that a final fused volume has a size of $N_x \times N_y \times N_z$. In Table 1 the theoretical comparison of number of FFT operations and number of Master Slave calculations for different sub-volumes size is presented. Whilst the number of FFT operations continuously increase with R, demanding proportionally more time, the number of Master Slave operations stays constant.

	1 sub-volume of size $N_x \times N_y \times N_z$	2 sub-volumes of size $2 \times N_x \times N_y \times N_z/2$	4 sub-volumes of size $4 \times N_x \times N_y \times N_z/4$	8 sub-volumes of size $8 \times N_x \times N_y \times N_z/8$	16 sub-volumes of size $16 \times N_x \times N_y \times N_z/16$
FFT operations	$1 \times N_x \times N_y$	$2 \times N_x \times N_y$	$4 \times N_x \times N_y$	$8 \times N_x \times N_y$	$16 \times N_x \times N_y$
MS multiplications	$N_x \times N_y \times N_z$	$2 \text{ x } N_x \times N_y \times N_z/2$ $= \mathbf{N_x \times N_y \times N_z}$	$4 \text{ x } N_x \times N_y \times N_z/4$ $= \mathbf{N_x \times N_y \times N_z}$	$8 \text{ x } N_x\ N_y \times N_z/8$ $= \mathbf{N_x \times N_y \times N_z}$	$16 \text{ x } N_x \times N_y \times N_z/16$ $= \mathbf{N_x \times N_y \times N_z}$

Table 1. Comparison between the number of FFT operations and MS multiplications for a fused volume of size $N_x \times N_y \times N_z$.

In order to perform the comparison of the conventional FFT operation with that of MS operation, let us consider a number of 7 situations (R = 1, 2, 4, 8, 16, 32 and 64 smaller sub-volumes, for $N_x = N_y = 200$, $N_z = 512$ (we have $N_z = 512$ as each channelled spectrum is digitized into 1024 sampling points) in Fig. 3.

The time required to produce a single volume with 512 axial points is 0.1 s for 40,000 A-scans using the FFT based OCT technique. The time required by the FFT based procedure increases faster than proportionally with the number R, as shown by the blue curve in the figure bellow. From 0.1 s to 9 s, this is 90 times, larger than R = 64 times. The time for a single volume with 512 axial points using the MS method is 0.55 s.

Using the MS method, the larger R, the smaller the number of *en-face* images in each set, leading to a constant number of Master Slave (comparison) operations. The time required is described by the red curve in the figure bellow. This time doubles for 64 volumes with 8 axial points each. As irrespective the case, calculations for a constant number of 512 axial points are performed, i.e. for the same number of theoretically inferred masks, we expected constant time, but benchmarking has resulted in the doubling of time, perhaps due to the need to recharge the loop 64 times, according to Fig. 2. For R > 4 , the process of producing R Gabor fused volumes using the GF/MS-OCT is quicker than using the GF/FFT-OCT method (Fig.3).

Let us consider that for 1/512, the numerical aperture NA of the interface optics in the sample arm is adjusted for the depth of focus DOF to match the axial range needed, AR. The case 64/8 signifies a situation where the focus is repeated for N = R = 64 times, i.e. the DOF = AR/64. This corresponds to an increase in the numerical aperture by a factor of $\sqrt{R} = \sqrt{64} = 8$ 8, as the DOF ~ NA^2. This brings an improvement in the transversal resolution that is proportional to 1/NA, i.e. of 8 times. For R = 64 focus positions, the Master Slave technique can produce volumes of almost 8 times quicker than the FFT based OCT. For the 64/8 case, the FFT based OCT returns A-scans of 512 axial positions that are significant (bright) within 512/64 = 8 axial points only, i.e. 494 points per each A-scans need to be discarded.

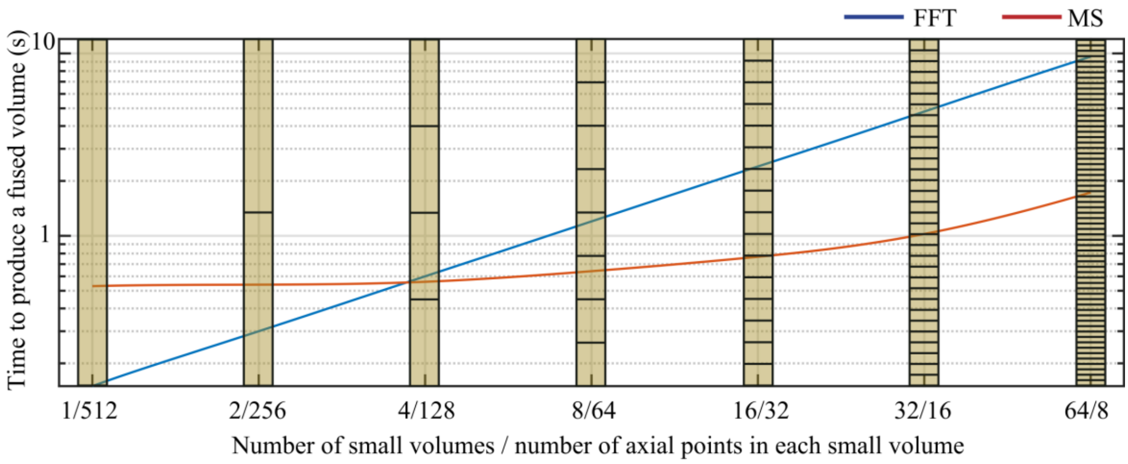

Fig. 3. Time to produce a fused 3D image using the conventional FFT based (blue curve) and using the Master Slave approach (red curve), for 7 values of R.

In conclusion, the MS procedure opens the avenue of time efficient high NA microscopy combined with Gabor filtering, for large number of focus repetitions. We will show more quantitative data in the conference, such as achievable improvements in the transversal resolution for the same time demanded by both GF/FFT-OCT and GF/MS-OCT, as well experimental results on displaying simultaneously multiple *en-face* OCT images and cross sections in the volume assembled of “all in focus” *en-face* images.

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