Image Analysis Project

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Abstract

In many digital cameras, the image sensor is covered with a pattern of color filters to capture different colors of light. Color Filters Array (CFA) of RGB filters are overlaid over the sensors and arranged in periodic patterns. The incident light is filtered by each filter, before reaching the sensor. Depending on the CFA pattern, the camera sensor captures only one color component (red, green, or blue) at each pixel location. Thus, the image acquisition process involves assigning a color to each sensor pixel according to this pattern.

I. Statement

The project aims to perform a demosaicing to recover all the missing colors for each pixel and then the full RGB image.

As follows, the data used to perform the reconstruction algorithm:

- 4 mosaiced image of size (1024,1024,3) ;
- the forward operator modeling the effect of a CFA camera with 2 different patterns available: *bayer* and *quad bayer*.

II. Theory of the solution chosen

The most common color filter array is the Bayer filter, which uses red, green, and blue filters arranged in a checkerboard pattern. The Quad-Bayer filter, or 4x4 Bayer, is an evolution of the standard Bayer filter and is designed to improve the overall image quality, especially in low-light conditions.

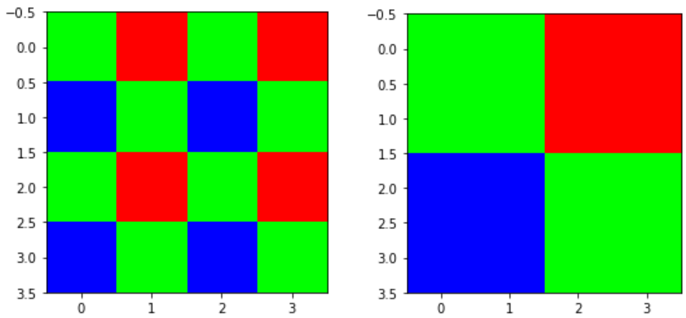


Fig.1. Bayer pattern (left side) and Quad Bayer pattern (right side)

The main difference between Bayer and Quad-Bayer patterns lies in the arrangement of color filters and the introduction of pixel binning in the Quad-Bayer pattern. This process combines the values of adjacent pixels of the same color within the 2x2 grid, creating a larger pixel with more accumulated light information.

A. Reconstruction method for Bayer pattern

The method I chose to perform reconstruction is the spectral difference (SD) technique [1]: a specific approach to reconstructing a full-color image from a sensor that captures only a single color channel at each pixel location. This technique is a subset of demosaicing methods based on injecting complementary spectral information from all interpolated sparse channels.

Spectral information refers to the distribution of light across different wavelengths. By analyzing these spectral differences, one can better estimate the missing color information.
This method can refine the results by minimizing color artifacts, preserving image details, and achieving a visually pleasing and accurate representation of the original scene.

Analysis of Bayer pattern

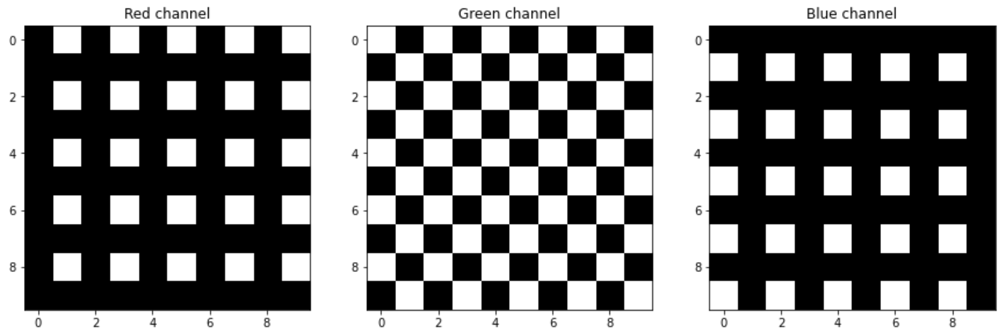


Fig.2. Pixel arrangement in the Bayer pattern for each channel

One can easily observe that the green pixels are twice as numerous as the red and blue ones.
This arrangement comes from the human eye's property of being more green-sensitive.

1. <u>Bilinear interpolation</u>

Before applying the spectral difference technique, each channel is interpolated with a specific filter. In this case, the filter is a commonly used 3x3 kernel.
Each missing sample obtained is a weighted sum of the closest available neighbors.
The reconstructed channel results from a convolution between a filter and the corresponding channel of the adjoint image.

$$\mathbf{U}^{[b]}_{::1} = \frac{1}{4}\begin{bmatrix}1 & 2 & 1\\ 2 & 4 & 2\\ 1 & 2 & 1\end{bmatrix}, \quad \mathbf{U}^{[b]}_{::2} = \frac{1}{2}\begin{bmatrix}0 & 1 & 0\\ 1 & 2 & 1\\ 0 & 1 & 0\end{bmatrix}, \quad \mathbf{U}^{[b]}_{::3} = \frac{1}{4}\begin{bmatrix}1 & 2 & 1\\ 2 & 4 & 2\\ 1 & 2 & 1\end{bmatrix}$$

Fig.3. Kernels applied on the adjoint image to perform interpolation.

The kernels related to the blue and red channels are the same as they are equally distributed (cf. Fig.2).

2. <u>Enhancement with spectral difference technique</u>

In practice, the spectral difference method lies in two steps: calculating differences and image estimation.

a) Calculating differences

First, we compute the difference between the *k-th* sparse channel and the spectral component of the *l-th* channel of the pixels assigned to the *k-th* channel.

That means that, for a fixed channel *k*, we subtract the element-wise product of the *l-th* channel of the interpolated acquisition (cf. previous stage) — and the *k-th* channel of the Bayer pattern, from the *k-th* channel of the adjoint image of the raw acquisition.

$$\mathbf{d}^{[l]}_{:k} = \mathbf{y}^{\boxdot}_{:k} - \widetilde{\mathbf{y}}^{\boxdot}_{:l} \odot \mathbf{h}_{:k}$$

Then, we obtain 6 detail-enhanced images for each combination of channels:

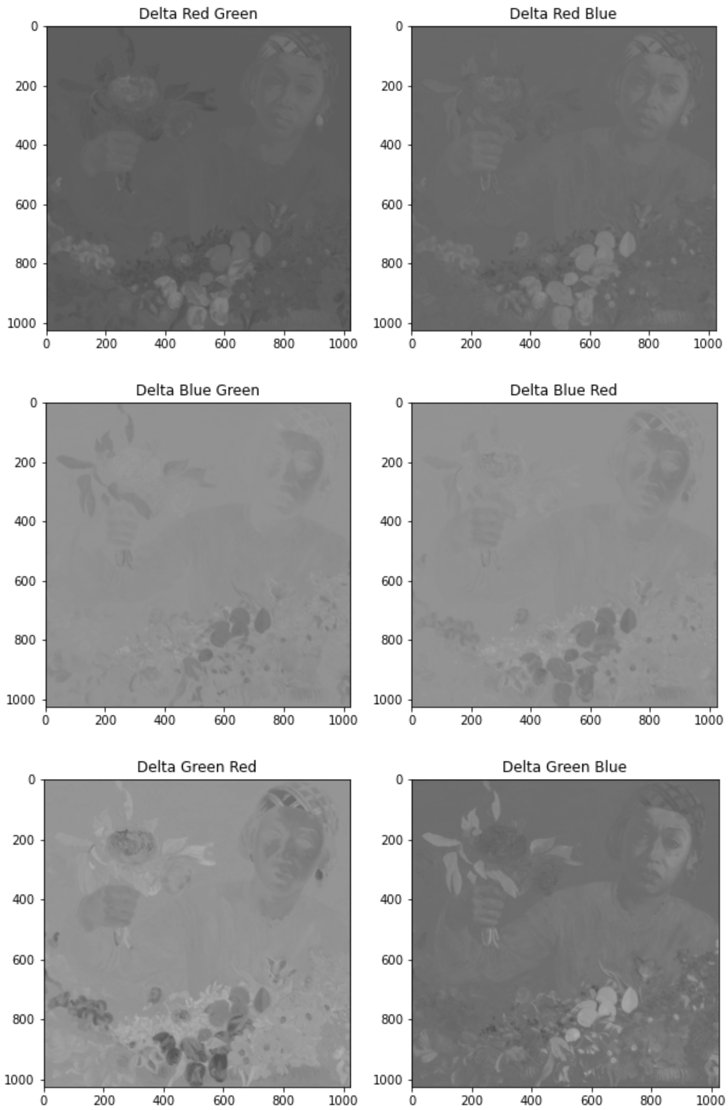


Fig.4. Detail-enhanced images for each combination of channels

b) Estimation of the image

The estimation relies on the injection of the details, calculated previously, in the interpolated acquisition. Practically, it is a linear combination of the spectral information from the other channels as depicted by the following equation:

$$\widehat{\mathbf{x}}_{:k} = \sum_{l=1}^{N_b} \left(\mathbf{y}^{\boxdot}_{:l} + \widetilde{\mathbf{d}}^{[l]}_{:k} \odot \mathbf{h}_{:l} \right)$$

Each channel *k* of the output image is the sum, over all the other channels *l*, of the *l-th* channel of the interpolated acquisition and the result of the convolution between the detail-enhanced acquisition between the *k-th* and *l-th* channel and the *l-th* channel of the mask.

Then, the estimation is normalized and the pixel values are restricted to the interval [0,1].

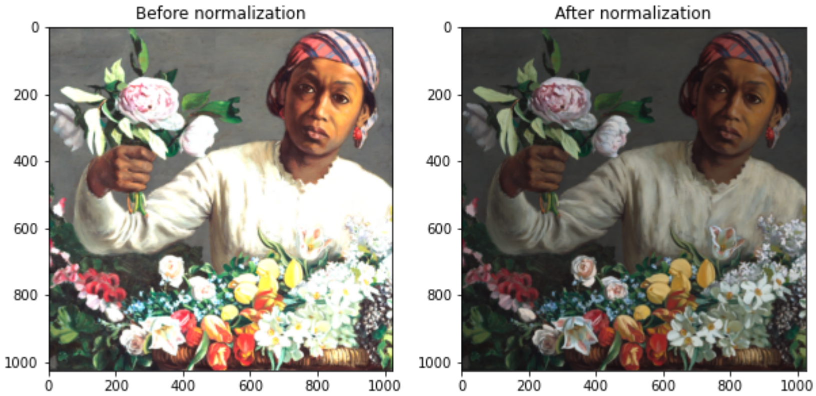


Fig.5. Reconstructed image before and after normalization

3. Results

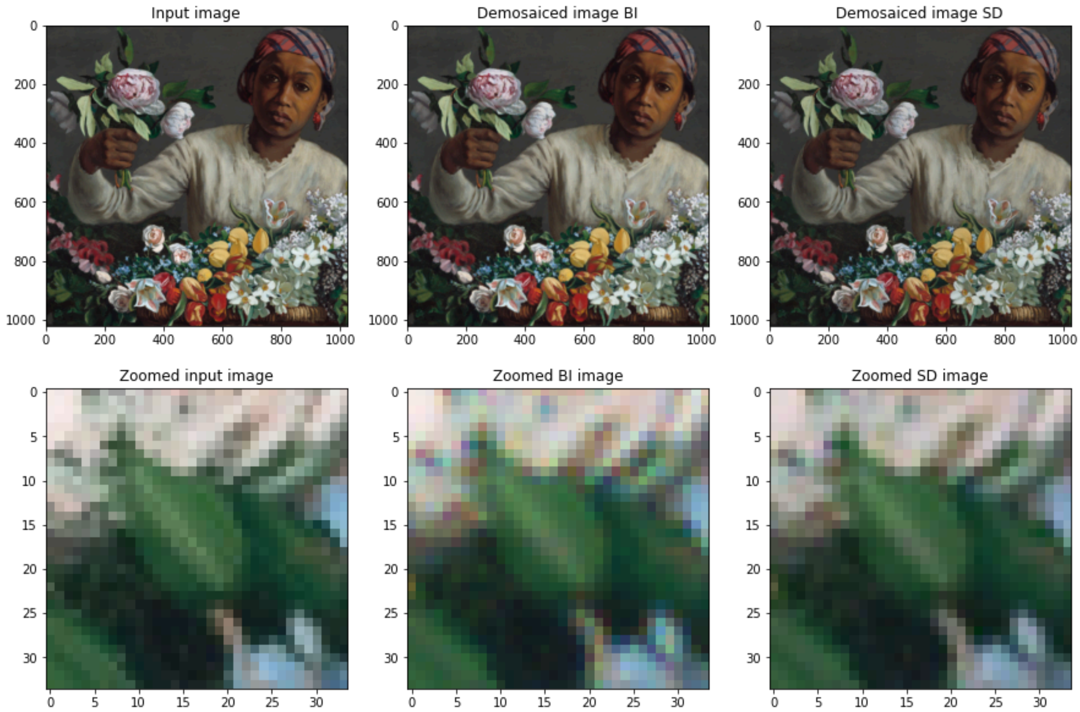


Fig.6. Result of each step of the demosaicing procedure

One can easily notice that, on the zoomed images, the SD step has 'harmonized' the tone of the image obtained at the end of the interpolation step. The color difference between neighboring pixels is less pronounced and comes closer to the reference image. The reconstructed image is also smoother than the input image, due to the interpolation.

4. Validation indexes

Quality indexes used are:

- **PSNR** (Peak Signal-to-Noise Ratio): a metric used to quantify the quality of an image by measuring the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation.
  The higher value the better quality.

- **SSIM** (Structure Similarity Index): a metric used to assess the perceived quality of an image. It quantifies the similarity between two images, considering structural information and luminance variations. It ranges from -1 to 1, 1 being the best value.

	PSNR	SSIM
Only bi-linear interpolation	34.63	0.9502
Bi-linear interpolation + SD *without normalization*	8.19	0.6799
Bi-linear interpolation + SD *with normalization*	**30.98**	**0.9725**

Table 1. Quality indexes over the different steps of the procedure

Even though the SD technique has led to a decrease in the PSNR of the reconstructed image, one may observe that it has well improved the SSIM.

SSIM is based on the property of the human visual system to be highly sensitive to structural information and luminance changes in images. It measures three components of similarity: luminance (mean intensity), contrast (standard deviation), and structure (covariance).

In the case of reconstruction problems, SSIM may be more appropriate to evaluate than PSNR (or MSE). As observed previously on the zoomed image, the SD technique led to an image that better respects the global aspect of the reference image.

B. Reconstruction method for Quad-Bayer pattern

1. Quad Bayer to Bayer conversion by swapping method

The Quad-Bayer pattern is an extension of the traditional Bayer pattern, seen previously, as each 2x2 Bayer unit cell is divided into four subpixels - in our case, with two green filters, one red filter, and one blue filter (GGRRBBGG).

A common way to deal with the Quad-Bayer pattern is to turn it into a standard Bayer one.
This procedure implies downsampling the pattern by a swapping method [2] that involves 3 steps (cf. Fig.8.):

- swap two columns every two columns
- swap two lines every two lines
- swap back some green pixels of the diagonal

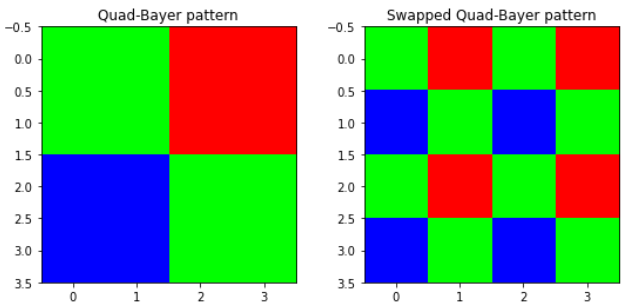


Fig.7. Original Quad-Bayer pattern (GGRRBBGG) (left side)
and Quad-Bayer pattern swapped into standard Bayer (GRBG) (right side)

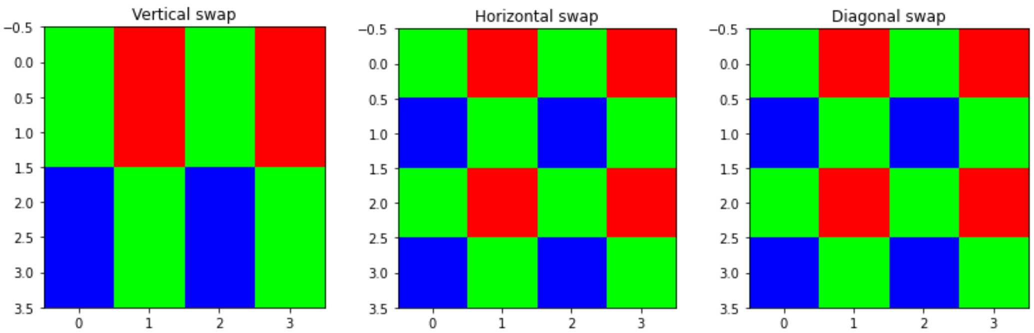
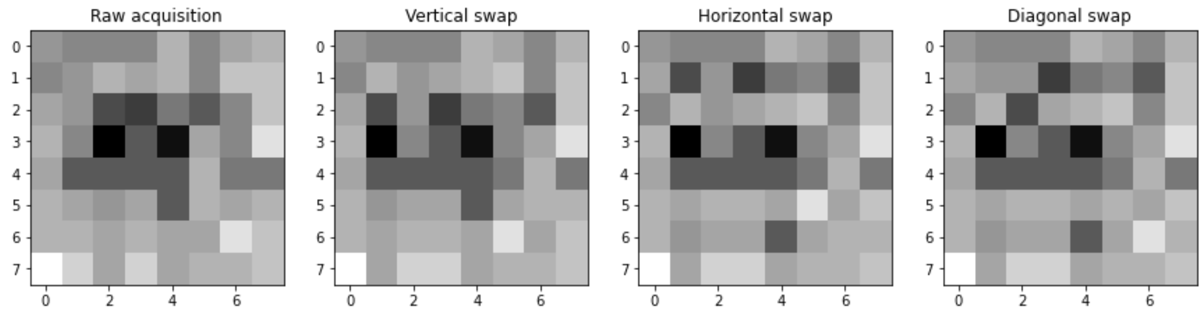


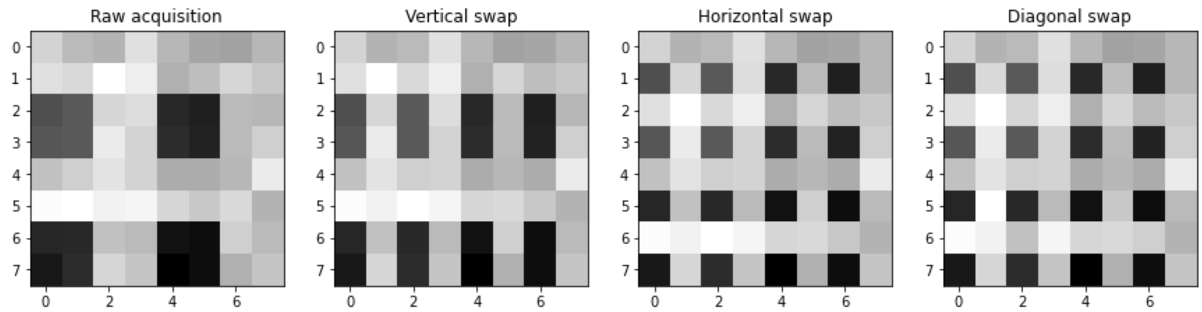
Fig.8. Steps of the swapping method

2. Quad to Bayer conversion of raw acquisition

Then, we apply the same swapping process to the mosaiced image (the input image) before applying the demosaicing algorithm seen in section A.



(a)



(b)

Fig.9. Quad to Bayer conversion by swapping method on raw acquisition on a 8x8 portion of the image.
Examples for 2 different images (a) and (b)

Once this done, we apply the same steps as the previous part dedicated to Bayer pattern, meaning applying the full demosaicing process which combines interpolation and spectral difference to the adjoint image of the raw acquisition.

3. Demosaicing processing

Finally, the results of the different steps are as follows:

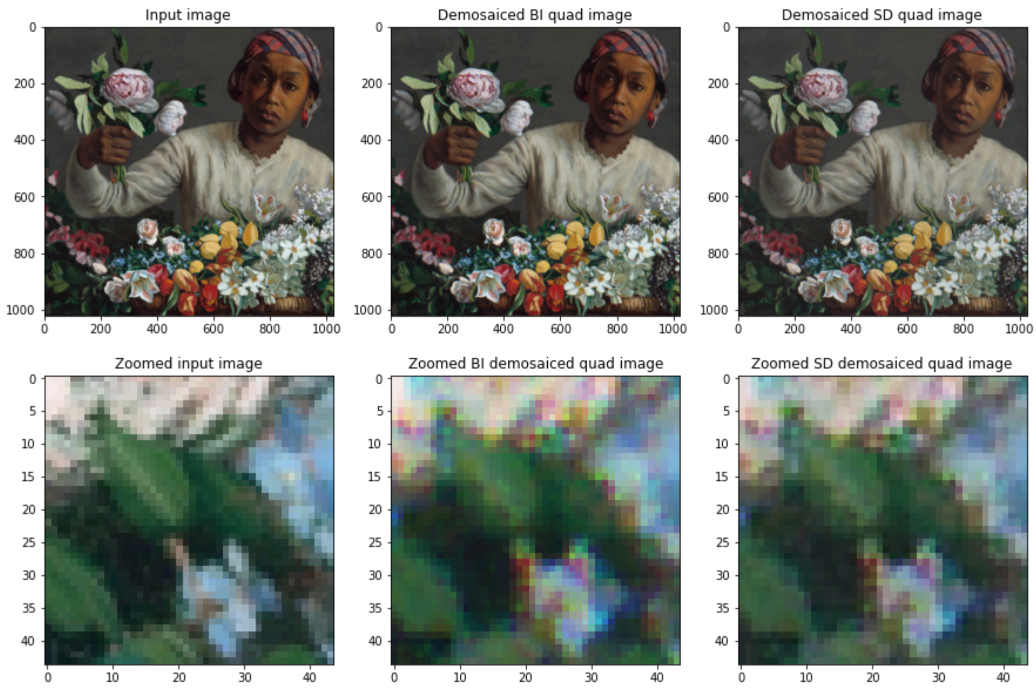
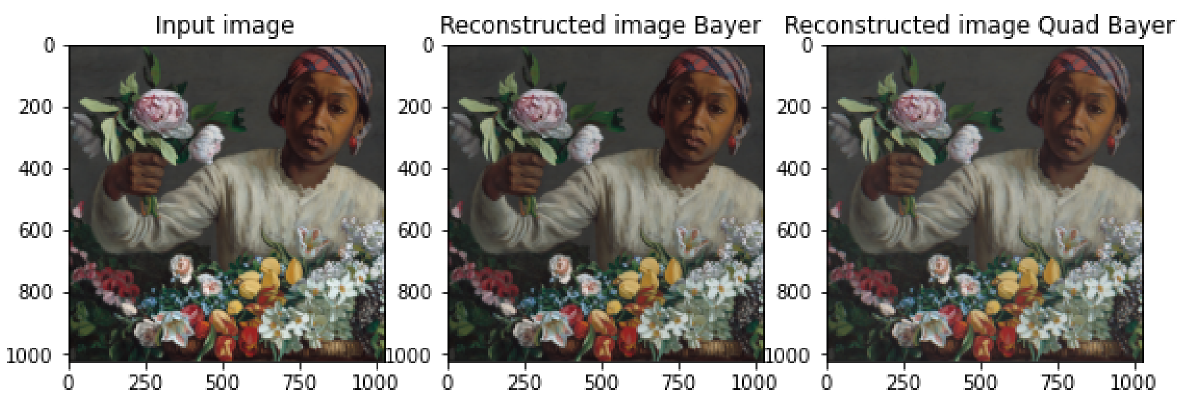


Fig.10. Result of each step of the demosaicing procedure from a Quad-Bayer pattern

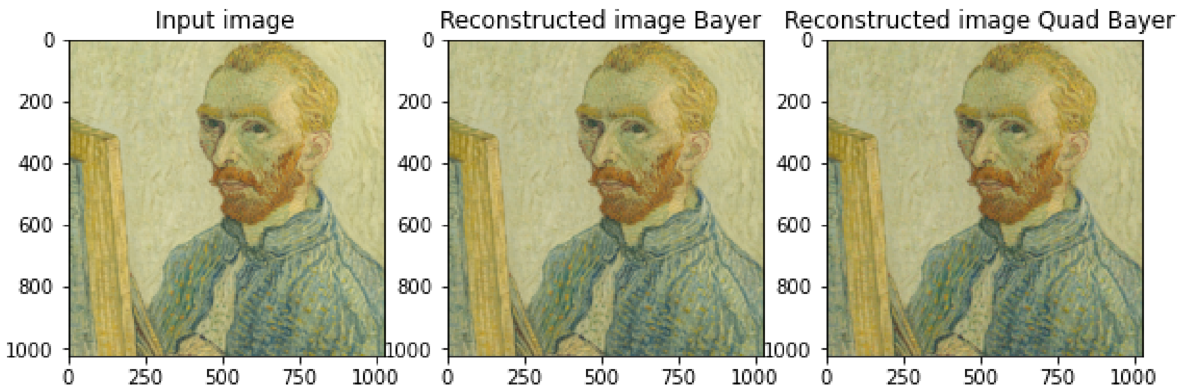
The process has introduced some changes in the pixel values as one may observe on the zoomed images. However, those distortions are not noticeable when looking at the whole image.

III. Final results

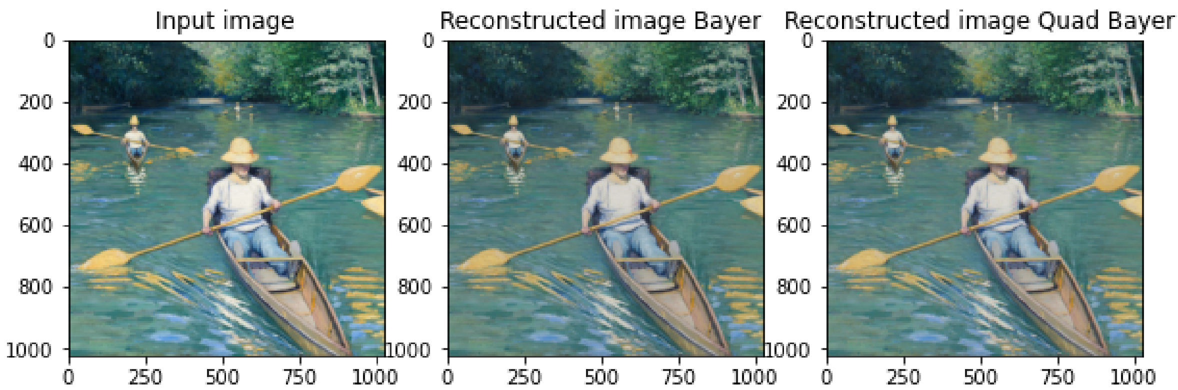
Table 2 below lists the reconstructed images obtained for the 4 images raw acquisitions and the validation indexes associated with:



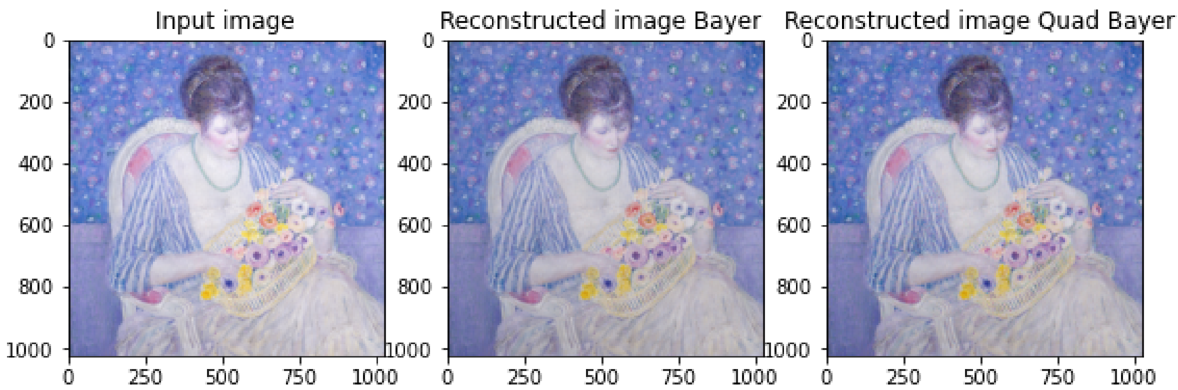
#1



#2



#3



#4

Acquisition	Index	CFA = Bayer	CFA = Quad Bayer
#1	PSNR	30.98	28.18
	SSIM	0.9725	0.9003
#2	PSNR	29.63	25.03
	SSIM	0.9235	0.7709
#3	PSNR	27.57	26.38
	SSIM	0.9275	0.8189

#4	PSNR	22.60	22.30
	SSIM	0.8917	0.7449

Table 2. Values of quality indexes for the set of acquisitions

One may observe that turning the Quad-Bayer pattern into a Bayer pattern leads some decrease in reconstruction performance when we apply the same demosaicing process. However, the reconstructed image is visually satisfying - the SSIM remains high - and we need to zoom in to observe the distortions introduced by the process.

Conclusion

To improve the process, we could use other interpolation filters in the first step of the algorithm proposed. Besides, demosaicing an image obtained through a Quad-Bayer filter seems more tricky than with a Bayer one and involve more complex steps.
Methods based on machine learning exist and could be well adapted to learn the characteristics of the raw acquisition to perform efficient demosaicing.

Reference

[1] Daniele Picone. Model Based Signal Processing Techniques for Nonconventional Optical Imaging Systems. Signal and Image processing. Université Grenoble Alpes [2020-..], 2021. English. ffNNT : 2021GRALT080ff. fftel-03596486f URL: https://theses.hal.science/tel-03596486

[2] Pyxalis URL:
https://pyxalis.com/wp-content/uploads/2021/12/PYX-ImageViewer-User_Guide.pdf