Bayer Interpolation with Skip Mode

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Abstract

The Bayer patterned colour filter array is commonly used with single chip cameras, with bilinear interpolation commonly used to demosaic the raw image to form a full colour image. When skip mode is used for sensor readout, the pixels are read out in 2×2 blocks. This requires modifying the interpolation weights. Several linear and bilinear interpolation schemes are compared. It is shown that with the output pixels located in the corners of the 2×2 Bayer blocks (for a half resolution output image) produces the best reconstruction in terms of PSNR, and output pixels located in the centre of the Bayer blocks gives the best visual reconstruction.

Keywords: CMOS camera, Bayer interpolation, Skipping mode, Demosaicing, Artefacts

1 Introduction

Most low cost colour cameras use a single chip where each pixel captures only a single colour channel of the colour image. This is achieved by integrating an array of colour filters, one for each pixel, when the sensor is fabricated. The most commonly used colour filter array is the Bayer pattern [Bayer, 1976] although other filter patterns are possible [Parulski, 1985]. The Bayer pattern, shown in Figure 1, has half green pixels, quarter blue pixels and quarter red pixels. To form a full colour image, it is necessary to interpolate the missing components from those that are available. This interpolation process is also known as demosaicing.

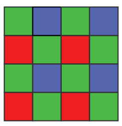


Figure 1: Colour filter array for the Bayer pattern

There is a trade-off between computational complexity and the quality of accuracy of the results. Three types of artefacts are commonly encountered from demosaicing:

- Blurring. The reduced sampling of channels results in a loss of fine details. Recovering the missing details by interpolating across edges will blur those edges.
- Colour bleeding. The samples for the different channels are in different locations. Interpolating them independently can result in the different colour channels being interpolated differently, resulting in unnatural colours, particularly visible around edges.
- Zipper effect. The alternating rows and columns within the colour filter array pattern can result in an alternating colour pattern most visible around edges and lines. This alternating pattern looks a little like a zipper.

The simplest interpolation approach is nearest neighbour interpolation. This uses a 2×2 window to copy the value from the nearest previously available pixel for a given colour channel. Since each colour channel is shifted slightly differently, this results can result in colour bleeding around edges.

The next simplest approach is bilinear interpolation, which averages the pixels on each side of the unknown channels using a 3×3 window. This gives significantly better results than nearest neighbour interpolation, while still being relatively simple to implement. However the quincunx sampling of the green channel is quite different from that of the red and blue, giving zipper artefacts around edges.

A simple improvement over basic bilinear interpolation is to detect the predominant orientation of any edges within the green channel (by taking the difference at red and blue pixels between the horizontally adjacent and vertically adjacent green pixels), and interpolating along the edges rather than across the edge. This removes much of the zipper artefact, and can reduce the blurring. For this reason, edge directed bilinear interpolation has probably become one of the most commonly used demosaicing algorithms.

There is a wide range of more advanced methods (see [Lu and Tan, 2003, Gunturk et al., 2002, Hsia, 2004, Li et al., 2008, Li and Randhawa, 2009]), which aim to improve the quality by reducing the artefacts. These generally require a larger window size, and result in increased computational complexity.

1.1 Camera Readout Modes

Low cost cameras are usually made using CMOS fabrication technology, and can result in quite large resolution sensors being available at relatively low cost. Since the pixels within a CMOS sensor are potentially individually addressable, sensor manufacturers have introduced a number of readout modes which enable a subset of the pixels to be read. This has the potential of reducing the resolution of the output image with the advantage of increasing the frame rate of the camera.

Windowing reads out only a rectangular subset of the pixels within the camera, directly reducing the image resolution. Only the pixels with a small portion of the complete field of view are read out. To read out the same field of view as before, a significantly shorter focal length lens must be used. Such short focal length lenses are prone to lens distortion.

Another readout mode available is skip mode [Fossum, 1997] where every second (or third, etc) pixel and row is read out. Such subsampling reduces the resolution without affecting the field of view, enabling the existing lens to be used. For single chip colour sensors, however, the skipping pattern has to take into account the pattern associated with the colour filter array. Taking every second pixel on every second row will only output a single colour channel. Therefore, for colour sensors the skip mode operates at a granularity of a 2×2 block rather than individual pixels [Micron, 2006]. The corresponding readout pattern is shown in Figure 2.

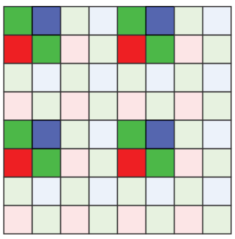


Figure 2: Pixel access pattern when accessing every second pixel in skip mode, with pale pixels not read out

When interpolating an image with skipping, the bilinear interpolation weights have to be adjusted to give evenly spaced output pixels. The best approach for accomplishing this has not been discussed before in the research literature. Different approaches for demosaicing with skipping every second pixel will be investigated and compared within this paper. Section 2 outlines the different interpolation strategies that will be considered. The methodology for comparing the different schemes is described in Section 3. The results are analysed in Section 4 before drawing conclusions in Section 5.

2 Bayer Interpolation Strategies

Using standard bilinear interpolation without skipping is clearly inappropriate because even rows and even columns are offset by 1 input pixel (or half an output pixel). The weights of the input pixels will clearly need to be adjusted. The fist question is where, relative to the input samples, should the output pixels be located. The most obvious choice is pixel centred, with the output aligned with one of the pixels (see the left pattern in Figure 2). Alternatively, the pixels could be aligned with the corners of the input pixels. Here there are two possible configurations or strategies (see Figure 2). The pixels can either be centred on the centre of a 2×2 block, or on the corners of the block. Other configurations are possible, but lack symmetry so will not be considered.

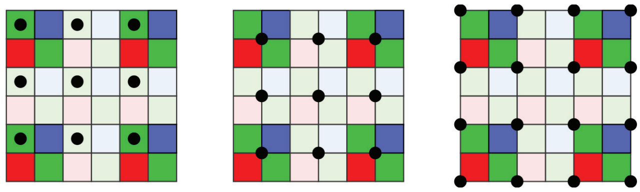


Figure 3: Positioning of the output samples. Black dots show the centres of the output pixels. From the left: pixel-centred, block-centred, and block-cornered configurations

The performance of each of these configurations will be considered. The grouping of pixels in blocks means that to access all of the neighbouring pixels required for bilinear interpolation, a 4×4 window in the input image is needed (or 5×5 for the block-cornered method). For the red and blue channels, the pixels are available on a regular grid, making bilinear interpolation straight-forward to estimate the value at arbitrary locations. For the green channel, there are two such grids. The grid with a pixel closer to the output position will generally give the better interpolation results. In some cases this is not clear (in particular with the block-cornered scheme), so the interpolation results from the two grids are averaged.

2.1 Pixel-centred

The weights for the pixel-centred configuration for the three colour channels for each of the output pixel samples are shown in Figure 4. Of the four pixels within the 2×2 block to align the output image to, we have chosen the green pixel on the first row of the block. This was chosen because there are twice as many green pixels as red and blue. Selecting the other green pixel would give similar results because of symmetry. Selecting either the red or blue, while possible, lacks symmetry in that the red and blue channels would require different sets of weights. In the results, this scheme is labelled *PC*.

Note that for the green channel, in the second and third column, there are simpler horizontal and vertical averages available as shown in Figure 5 (labelled *PCL*), interpolating using the nearest pixel gives a lower error. An alternative to consider using the nearest green is interpolating linearly along the diagonals, as shown Figure 5. This method is labelled *PCD*.

2.2 Block-centred

The weights for the block-centred configuration are shown in Figure 6. For the green channel, averages are taken between the nearest two green pixels. For the red and blue channels, the weights of the four adjacent input pixels are determined using bilinear interpolation. In the results, this scheme is labelled *BC*.

For the red and blue pixels in the centre of the block, it is also possible to interpolate simply along the diagonal as shown in Figure 7. The effect of this simplification will also be considered, and is labelled *BCD*.

2.3 Block-cornered

The final configuration considered is the block-cornered configuration, with the weights shown in Figure 8. In the results, this scheme is labelled *BN*.

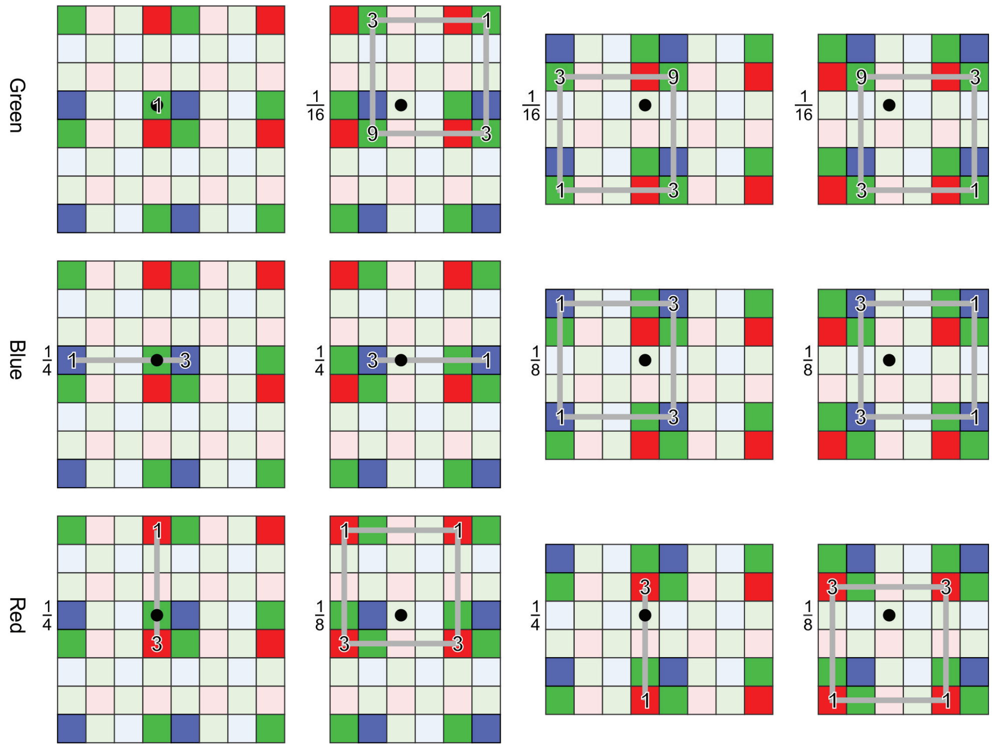


Figure 4: Weights for the pixel-centred scheme (*PC*)

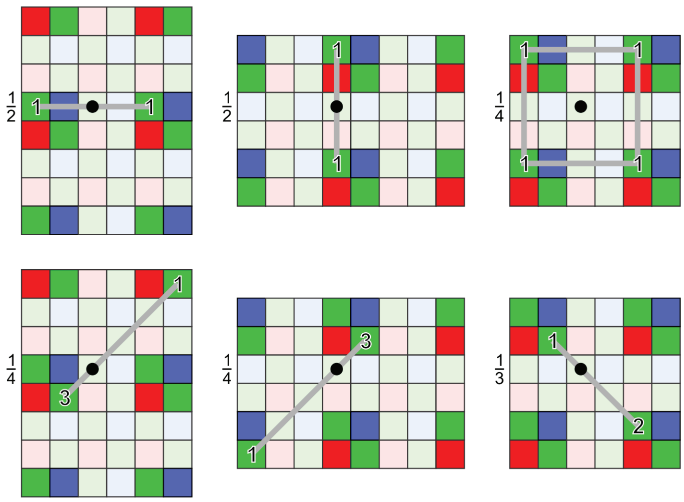


Figure 5: Alternative weights for the pixel-centred green channel (upper row: *PCL*, lower row: *PCD*)

For some of the outputs, a diagonal linear interpolation is also possible. The corresponding weights for these are shown on the left of Figure 9. Applying this to the green channel is labelled *BND1G* in the results, while extending it to the red and blue channels as well is labelled *BND1*. For the other green output pixels, it is also possible to make use of symmetry to perform a diagonal interpolation, as shown in the right of Figure 9. This is labelled *BND2G*.

3 Comparison Framework

To be able to objectively assess the accuracy of the demosaicing, it is necessary to have ground truth data. An image dataset commonly used for testing demosaicing algorithms is the Kodak photo CD image set. This is a set of full colour images [Kodak, 1991] of a range of scenes with varying amounts of fine detail and

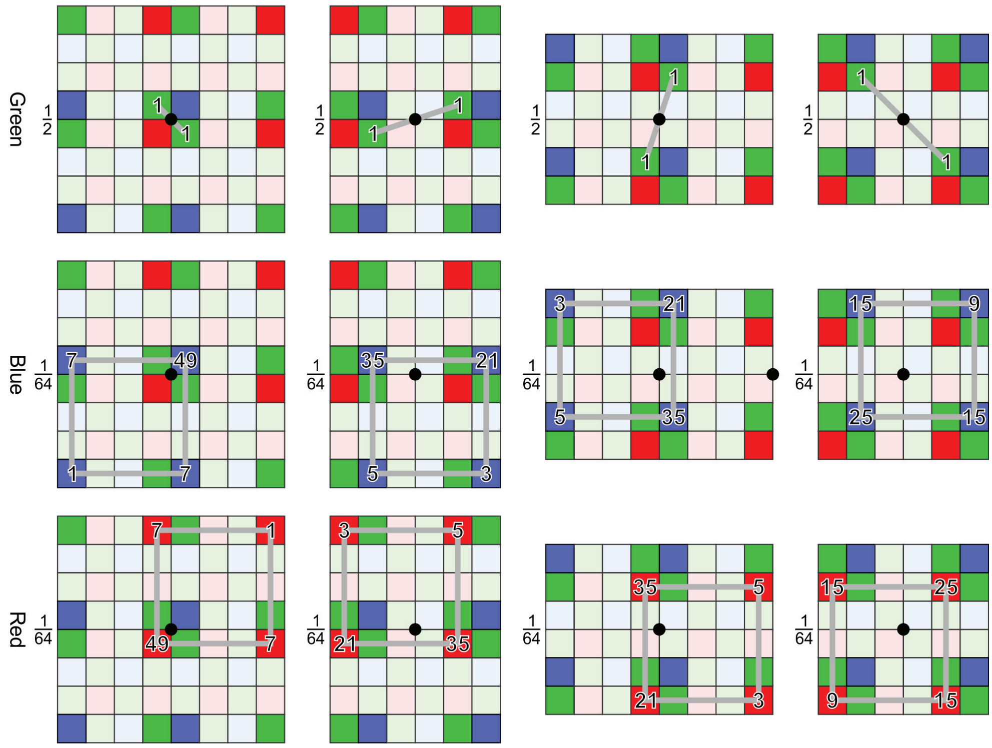


Figure 6: Weights for the block-centred scheme (*BC*)

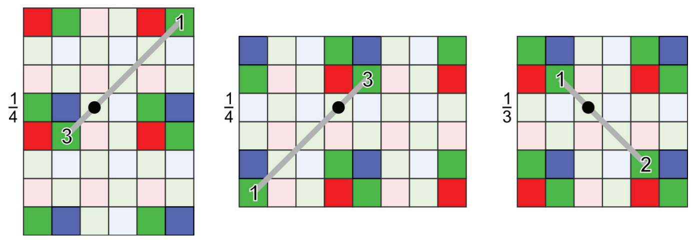


Figure 7: Alternative weights for the block-centred red and blue channels for diagonal interpolation (*BCD*)

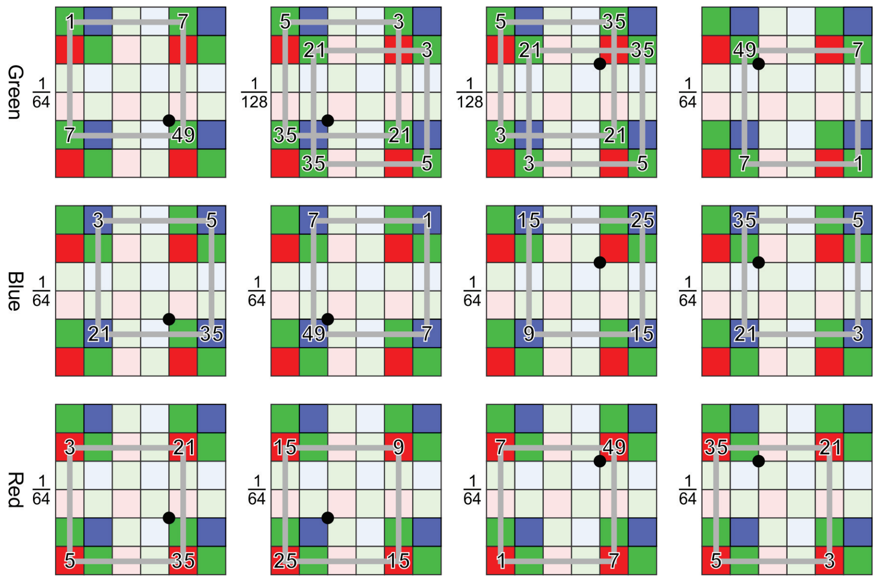


Figure 8: Weights for the block-cornered scheme (*BN*)

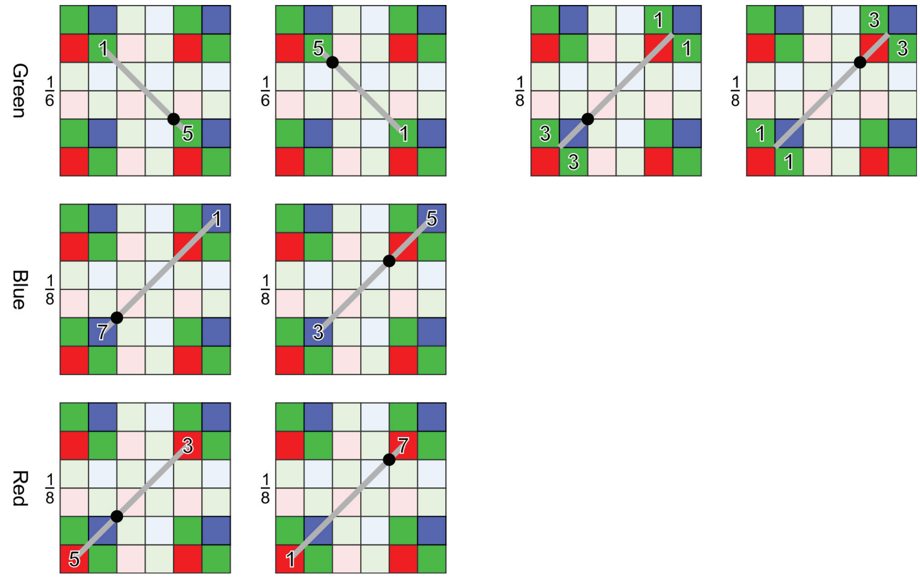


Figure 9: Alternative weights for the block-cornered scheme using diagonal interpolation (left *BND1G* and *BND1*, right *BND2G*)

structure. From these, image capture by a single chip sensor can be simulated. Since the unsensed colour channels are available in the original image, the demosaiced image can be compared with the original, and the error objectively determined. Let I be the original input image, downsampled by the skip factor, and R be the reconstructed image after demosaicing, then

$$E_{RMS} = \sqrt{\frac{1}{N}\sum^{N}(R-I)^2} \tag{1}$$

where N is the number of pixels in the image. From this, the $PSNR$ in dB can be derived

$$PSNR = 20\log_{10}\left(\frac{255}{E_{RMS}}\right) \tag{2}$$

One limitation of the PSNR is that it does not always agree with subjective visual assessment. For this reason, the results of the different interpolation schemes will also be assessed visually.

For the block centred and block cornered schemes, the output pixel grid is offset from the input by half a pixel horizontally and vertically. For this, the ground truth image was estimated by averaging 2×2 blocks of the input image before downsampling.

4 Results and Discussion

The different interpolation schemes are applied to each of the 24 images in the test set, with the average PSNR over the set calculated. The results are listed in Table 1. For all of the schemes, using the diagonal interpolation gives a small drop in the average PSNR (although for some images there may be a slight improvement). However, with the small dataset used, this drop is not statistically significant.

The block-centred scheme gave a significant improvement in PSNR over the pixel-centred scheme. The block-cornered scheme gave a small but statistically significant improvement over the block-centred scheme in terms of PSNR. As with the other methods, using diagonal interpolation did not improve the results on average (although *BND1G* gave the best PSNR for about one quarter of the images tested). However the difference in average PSNR between *BN* and *BND1G* is not statistically significant.

One new artefact resulting from using skip mode is a level of blockiness or jumping along diagonal lines and edges. This can be clearly seen in Figure 10, especially along the mast regions. This is most noticeable

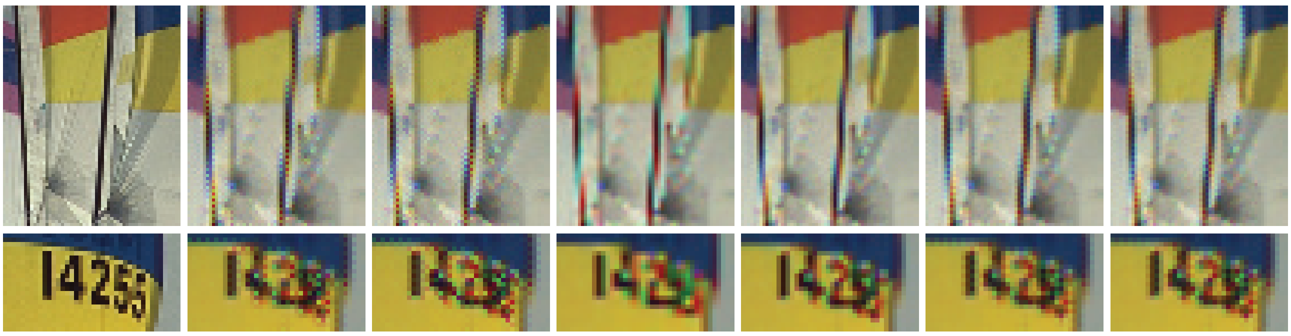
Scheme	Average PSNR	Number best	PSNR for Figure 10 image
PC	24.714 dB	0	26.405 dB
PCL	24.411 dB	0	26.107 dB
PCD	24.604 dB	0	26.350 dB
BC	26.269 dB	1	27.733 dB
BCD	26.226 dB	0	27.700 dB
BN	26.605 dB	17	28.061 dB
BND1G	26.601 dB	6	28.087 dB
BND1	26.331 dB	0	27.889 dB
BND2G	26.455 dB	0	27.905 dB

Table 1: PSNR averaged over 24 images of the Kodak image set, and for the image in Figure 10.

ground truth | pixel-centred (*PC*) | block-centred (*BC*) | block-cornered (*BN*)

Figure 10: Example image showing the different demosaicing schemes

within the pixel-centred interpolation, but is also apparent with the other schemes. This is an inevitable result of the 2×2 block based sampling. Also apparent from Figure 10 is a significant blurring and loss of fine detail. This is primarily a consequence of using bilinear interpolation, and could perhaps be improved by using more advanced interpolation methods.



ground truth | *PC* | *PCD* | *PCL* | *BC* | *BN* | *BND1G*

Figure 11: Detail from the mast region and number regions

To facilitate visual assessment, part of the mast region if Figure 10 is expanded in Figure 11. The pixel-centred scheme (*PC*) has quite significant zipper artefacts. These can be almost completely eliminated by using the simpler horizontal and vertical averaging (*PCL*), although this is at the expense of increased blurring and colour bleed. Visually, using diagonal interpolation (*PCD*) is indistinguishable from the (*PC*) method.

Block-centred interpolation (*BC*) gives significant visual improvement of both colour bleed and geometric distortion over the *PC* method, and appears to be free of zipper artefacts.

The block-cornered method appears to have slightly less colour bleeding than the other methods. The slight blurring makes the geometric distortion visually less noticeable. It does, however, have moderate zipper artefacts. In terms of visual quality, there is no noticeable difference between *BN* and *BND1G*.

Overall, in terms of visual evaluation, if the zipper artefact is deemed objectionable, then the block-centred method is preferable (*BC*), otherwise the visual assessment confirms the objective results given from the PSNR.

5 Conclusion

With CMOS sensors, skip mode readout allows the resolution of the image to be reduced without affecting the field of view of the camera. When skip mode is used with Bayer pattern sensors, pixels are read out in 2×2 blocks because of the colour filter array pattern. When demosaicing the raw image to produce a full colour image, aligning the output pixels based on the block structure gives better results than aligning them based on the input pixel locations. For downsampling by a factor of 2, aligning the pixels to the corners of the 2×2 Bayer blocks gives slightly better results than aligning them to the block centres. This reduces the geometric distortion resulting from the block structure of the sampling. Corner alignment does suffer from moderate zipper artefacts, so if these are likely to be an issue either visually or for subsequent processing, then block-centred alignment is preferable.

Future work involves investigating whether edge directed interpolation can reduce the artefacts (blur in particular) and give an improvement in PSNR. This, and other more advanced interpolation techniques, are complicated by the uneven sampling associated with skip mode readout.

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