Real-time Super Resolution Equipment for 8K Video

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Abstract: Resolution is one of the most important things when assessing image quality, and image quality improves in proportion to resolution. Super Resolution (SR) is a resolution improving technology that is different from conventional image enhancement methods. SR methods, of which there are many, typically have complex algorithms that involve iterations, and it is not easy to apply them to video running in real time at 50 or 60 frames a second; i.e., each frame would have to be processed in 20 ms (50 Hz) or 16.7 ms (60 Hz). In this paper, a simple form of SR that uses non-linear signal processing is proposed to cope with the difficulties in real-time processing. Real-time hardware equipped with an FPGA (Field Programmable Gate Array) for 4K and 8K video is shown and its SR capability is discussed.

1 INTRODUCTION

HDTV digital broadcasting started at the beginning of this century and since has spread all over the world. The resolution of HDTV is 1920×1080, five times higher than analogue TV systems such as PAL, SECAM, and NTSC. Although CRT displays were in the mainstream at the beginning of HDTV broadcasting, LCDs have become the common these days. LCDs are cost effective, lightweight, and high in resolution. Currently, almost all TV and computer displays are LCDs. If we view digital HDTV broadcasting as a paradigm shift, the spread of LCDs is surely another one. Moreover, the resolution of LCDs has been growing dramatically. In fact, 4K displays that have four times higher resolution than HDTV are now on the market. The problem is that there is no 4K broadcasting. To fill in for the dearth of 4K content, attempts are being made to up-convert HDTV content to 4K resolution and show it on 4K displays. Here, the resolution of 4K is 3840×2160, so the HDTV content has to be enlarged by double horizontally and vertically.

Such enlargements always cause blur. Figure 1 is an enlargement made by cropping the white rectangle area in Figure 2 and blowing it up 1.3 times. As one can see, it is very blurry compared with the white rectangular area in Figure 2. This simple example illustrates that images are easily degraded by enlargement and suggests that up-converted 4K content from HDTV would look even worse, as the enlargement factor would be 2, not 1.3. Moreover, it is doubtful that Enhancer (Schreiber, 1970; Lee, 1980; Pratt, 2001) would be a sufficient means of enhancing such up-converted content. New technologies are needed to deal with this problem.

Super Resolution (SR) is a technology that creates a high-resolution image from low-resolution ones (Park et al., 2003; Farsiu et al., 2004; Eekeren et al., 2010; Houa et al., 2011; Protter et al., 2009; Panda et al., 2011; Matsumoto and Ida, 2010). The keyword phrase "Super resolution" gets about 190 million hits on Google. Indeed, there are many SR proposals, but most of them are complex algorithms involving many iterations. Such algorithms are almost impossible to into real-time hardware.

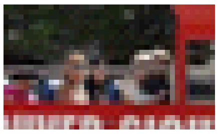

Figure 1: Enlarged image.

Figure 2: Original image.

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SR for TV should have low delay. In live news broadcasts especially, conversations between announcers in the TV studio and persons at the reporting point tend to be affected by delays. For viewers, the superimposed time is not accurate on a TV screen if the delay is longer than 60 seconds. For these reasons, complex SR algorithms with iterations cannot be used in TV systems.

Non-linear signal processing (NLSP) has been proposed as an alternative to the conventional image enhancement methods (Gohshi and Echizen, 2013), and it has several advantages compared with them. Since it does not use iterations or frame memories, it is sufficiently lightweight to be installed in an FPGA (Field Programmable Gate Array) for real-time video processing. Furthermore, it can create frequency elements that are higher than those of the original image, as has been proven by performing two-dimensional fast Fourier transform (2D-FFT) results(FFTs (Gohshi and Echizen, 2013). Although there is real-time hardware that can process enlarged images (Gohshi et al., 2013), its FPGA has a maximum speed of 30 Hz, far less than 60 Hz or 50 Hz of video. In addition, certain frequency elements are emphasized too much. In this paper, we present new real-time NLSP hardware that is free of these problems.

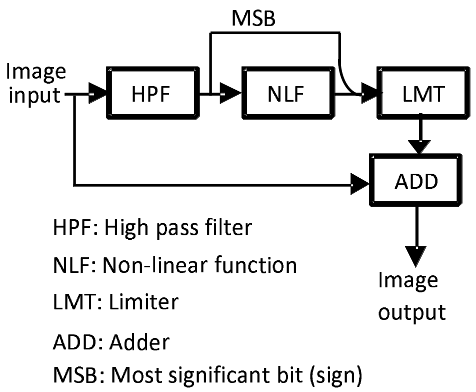


Figure 3: NLSP algorithm.

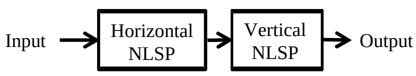


Figure 4: Sequential NLSP.

2 PREVIOUS RESEARCH ON NLSP

The basic idea of NLSP is like that of the one-dimensional signal processing shown in Figure 3 (Gohshi and Echizen, 2013). The input is distributed to two blocks. The upper path creates high-frequency elements that the original image does not have as follows. The original image is processed with a high pass filter (HPF) to detect edges. The output of the HPF is edge information that has a sign, i.e., plus or minus, for each pixel. After the HPF, the edges are processed with a non-linear function (NLF). If an even function such as x^2 is used as the NLF, the sign information is lost. To stop this from happening, the most significant bit (MSB) is taken from the edge information before the NLF and restored after the NLF. Non-linear functions generate harmonics that can create frequency elements that are higher than those of the original image. NLSP using a number of non-linear functions should be able to create high-frequency elements. Here, we propose $y = x^2$ for plus edges and $y = -x^2$ for minus edges.

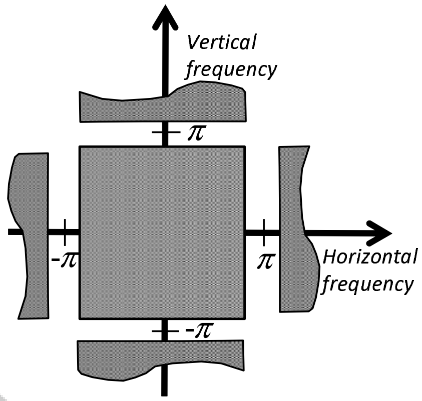


Figure 5: 2D image spectra.

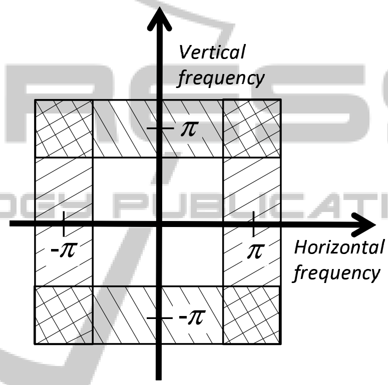


Figure 6: Enhanced areas in 2D.

It is well known that images are expanded in a Fourier series (Mertz and Gray, 1934).Here, we take a one-dimensional image $f(x)$ to make the explanation simple. $f(x)$ is expanded as follows.

$$f(x) = \sum_{n=-N}^{+N} a_n \cos(n\omega_0) + b_n \sin(n\omega_0) \qquad (1)$$

Here, ω_0 is the fundamental frequency and N means a positive integer. The HPF attenuates low-frequency elements including the zero frequency element (DC). We denote the output of the HPF by $g(x)$ and it becomes as follows.

$$g(x) = \sum_{n=-N}^{-M} a_n\cos(n\omega_0) + b_n\sin(n\omega_0) + \sum_{n=M}^{N} a_n\cos(n\omega_0) + b_n\sin(n\omega_0) \quad (2)$$

M is also a positive integer and $N > M$. The frequency elements from $-M$ to M are eliminated with the HPF. DC has the largest energy in the images, and it sometimes causes saturation whereby the images become either all white or all black. The square function does not cause saturation by eliminating DC, and it has the following effect. Edges are represented with $\sin(n\omega_0)$ and $\cos(n\omega_0)$ functions. The square function generates $\sin^2(n\omega_0)$ and $\cos^2(n\omega_0)$ from $\sin(n\omega_0)$ and $\cos(n\omega_0)$. $\sin^2(n\omega_0)$ and $\cos^2(n\omega_0)$ generate $\sin2(n\omega_0)$ and $\cos2(n\omega_0)$.

These NLFs create frequency elements that are two times higher than the input (Gohshi and Echizen, 2013), and they can be used to double the size of the images horizontally and vertically, such as in the conversion from HDTV to 4K TV. It is necessary to apply NLSP horizontally and vertically (Figure 4), since images and videos are two-dimensional signals. Computer simulations based on Figure 4 have been presented (Gohshi and Echizen, 2013) and real-time (30 Hz) hardware based on Figure 4 has been developed (Gohshi et al., 2013). However, these developments pointed out two issues. Using the sequential NLSP shown in Figure 4, specific frequency elements are processed twice in a two-dimensional frequency domain ; this causes artifacts and increases noise. Figure 5 shows an example in the two-dimensional frequency domain. The horizontal axis is the horizontal frequency, and the vertical axis is the vertical frequency. The origin of the axes is called direct current (DC) since the frequency of DC is zero. In Figure 5, the spectra around DC is fully presented. The same spectra is repeated every 2π and parts of the spectra from $(2\pi,0),(-2\pi,0),(0,2\pi),(0,-2\pi)$ are shown. π on the horizontal axis and the vertical axis in Figure 5 are the horizontal and vertical Nyquist frequencies.

The first issue is degradation of images whose frequency components are processed twice. Figure 6 shows the areas in the spectra that are processed by the sequential NLSP shown in Figure 4. The areas hatched with lines having positive slopes are subjected to the horizontal signal processing, whereas those areas hatched with lines having negative slopes are subjected to the vertical signal processing. The four corner areas are subjected to both horizontal and vertical signal processing. These corner areas have both horizontal and vertical high-frequency elements. Yet by processing these areas twice, the corner areas are emphasized in excess, and this degrades the video quality. When dots in an image that have both horizontal and vertical high-frequency elements move, they cause flicker. The NSLP emphasizes the flickers on the dots and degrades video quality. Noise that also has both horizontal and vertical high-frequency elements exists in these corner areas. If these dots that have both horizontal and vertical high-frequency elements are processed with NLSP two times, the noise will be emphasized. Noise always degrades video quality.

The second issue is the speed of the FPGA. The FPGA embodying the sequential NLSP shown in Figure 4 can only work at 30 Hz (Gohshi et al., 2013). Although this is fast enough to work on 24 Hz movie content, it is not fast enough for 50 Hz or 60 Hz video content.

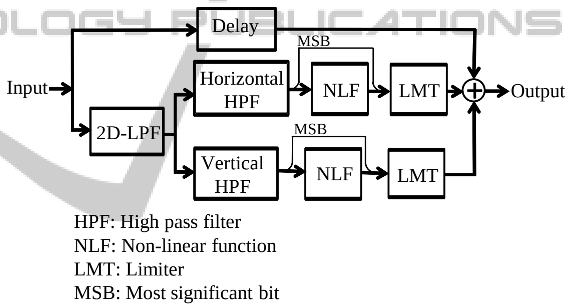


Figure 7: Block diagram of real-time hardware.

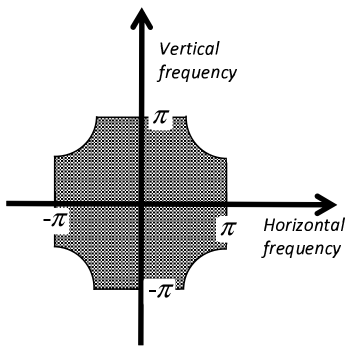


Figure 8: Characteristics of 2D-LPF.

3 ADVANCED HARDWARE ALGORITHM

Figure 7 is a block diagram of the real-time video processing that is free of the issues discussed in section 2. The input is distributed to two paths. The bottom line

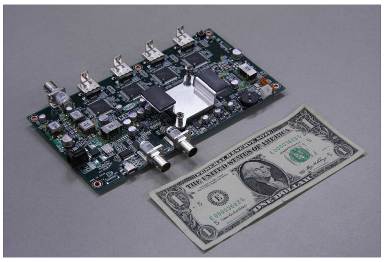


Figure 9: Appearance of real-time hardware.

includes a two-dimensional low pass filter (2D-LPF) and a parallel NLSP part. The 2D-LPF decreases the diagonal artifacts, and the parallel signal processing enables the hardware to operate on 60 Hz moving images.

The input is distributed to the delay block and the 2D-LPF block. The delay path is the same as the input, and the signal is delayed until the signal processing on the other paths ends. The second path goes to the 2D-LPF. The 2D-LPF reduces the diagonal issue that is mentioned in section 2. Figure 8 shows the two-dimensional frequency characteristics of the 2D-LPF. 2D-LPF passes the checker marked area and eliminates the diagonal frequency elements, i.e., the four corners shown in Figure 6. It also cuts the noise. However, the human visual system is not so sensitive to the horizontal and vertical high-frequency elements, i.e. the four corners shown in Figure 6 (Sakata, 1980). This means these frequency elements in the NLSP video do not affect the perceived resolution. Thus, to maintain the original diagonal resolution, the original diagonal frequency elements are sent through the delay line and added to the output.

The 2D-LPF eliminates diagonal frequency elements and splits the signal into two paths. The upper path is the horizontal NLSP, and the lower path is the vertical NLSP explained in section 2. The three video paths are added together at the end to create the NLSP video.

This parallel signal processing is fast. It reduces the delay from input to output, as discussed in section 1, and it can work at 60 Hz, unlike the sequential NLSP shown in Figure 4. Figure 9 shows the NLSP hardware. It up-converts full HDTV (1920×1080) to 4K (3840×2160), and it processes the up-converted 4K video with NLSP to increase the resolution at 60 Hz. The NLSP algorithm is installed in the FPGA, which is located under the heat sink. Although there are many parts on the circuit board, most of them are input and output interface devices and electric power devices.

Figure 10 shows an image processed with the NLSP hardware shown in Figure 9. Figure 10(a) is just an enlargement from HDTV to 4K, and it looks blurry. Figure 10(b) shows the image processed with NLSP after the enlargement. Its resolution is clearly better than that of Figure 10(a). Figure 10(c) and 10(d) are the 2D-FFT results of Figure 10(a) and Figure 10(b). Figure 10(d) has horizontal and vertical high-frequency elements that Figure 10(c) does not have. This shows that real-time hardware works and its function is the same as the simulation result.

4 EFFECT OF 2D-LPF

This section describes the effect of the 2D-LPF. Figure 11(a) shows the NLSP result when the 2D-LPF is turned off, and Fig. 11(b) shows the result when the 2D-LPF is on. Comparing these two figures, we can see there are artifacts around slanted lines that are the diagonal frequency elements (Figure 11(a)). On the other hand, artifacts are less evident in Figure 11(b). This means that the 2D-LPF reduces the diagonal frequency elements in Figure 6. Figures 11(c) and 11(d) show the effect of the 2D-LPF on noise. Figures 11(e) and 11(f) are enlargements corresponding to the black rectangular areas in Figure 11(c) and 11(d). A quick comparison indicates that Figure 11(f) has less noise.

Slanted lines in an image have both horizontal and vertical high-frequency elements. In the frequency domain, slanted lines correspond to two of the four cross-hatched corners in Figure 6. The lines in the image that go upwards to the right correspond to the cross-hatched areas in the first and third quadrants in Figure 6. The lines in the image that go downwards toward the right correspond to the cross-hatched areas in the second and fourth quadrants in Figure 6.

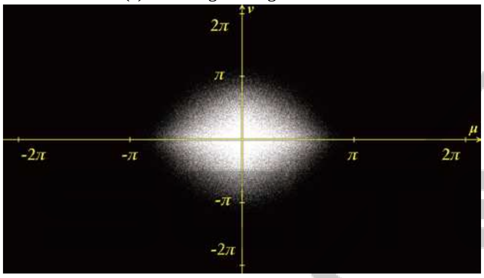
Dot-shaped noise in an image has frequency elements in the cross-hatched areas of all four quadrants of Figure 6. The artifacts are reduced because the 2D-LPF cuts off the frequency elements in these four corners.

5 FOCUSING EFFECT

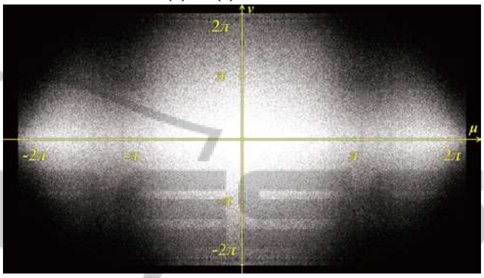
Although film cameras have been used in the movie industry for a long time, most movies are made today with more cost-effective HDTV cameras. These professional HDTV cameras do not have auto focus systems that commercial camcorders have. Production zoom lenses are used to make TV content since several scenes are shot in a single take. In these takes, the camera focus is often changed from one object to another. It is not easy, even for professional camera persons, to adjust the focus with a small viewfinder.

(a) 4K image enlarged from HD

(b) 10(a) with NLSP



(c) 2D-FFT result of Figure 10(a)



(d) 2D-FFT result of Figure 10(b)

Figure 10: Image processed with real-time NLSP.

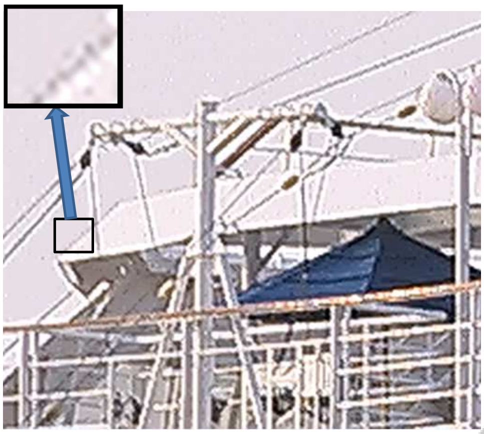
Although TV content is often out of focus, we cannot recognize this on a TV screen because of its relatively small size. However, if that content were shown on a large screen of a movie theater, it would appear as blurry as content shot with a commercial camcorder's auto-focus. On the other hand, movies have high resolution and appear sharp on large screens in theaters. That means although TV content and movie content are shot with HDTV cameras, the difference between them has to do with the lens focus. Single focus lenses are used in the movie industry, whereas zoom lenses are used to make TV content. Thus TV content is affected by blurring caused by zoom lenses, while movie productions face the difficulty of performing multi-focus shots in a single take. These two aspects of the gout-of-focus problemh are part of the topic of image restoration, and many ideas have been put forward to deal with them (Figueiredo and Nowak, 2003)(Pan and Blue, 2011)(Karungaru et al., 2009). However, the methods presented so far need iterations or parameter adjustments made under certain hypotheses. It is not easy to use them in practical applications.

It would be useful if there were a technology that could focus a shot after it has been made. Here, we would like to point out that NLSP has a focusing effect. Figure 12(a) is a blurry image. The original image is crisp (it is part of a test pattern), and it was processed with an LPF to make it blurry. Figure 12(b) is the result of processing Figure 12(a) with the NLSP hardware. Comparing these figures, we can see that the resolution of Figure 12(b) is better and the focus looks adjusted. This effect is due to the characteristics of NLSP. NLSP can generatee high-frequency elements that the original image does not have, and these high-frequency elements have a focusing effect.

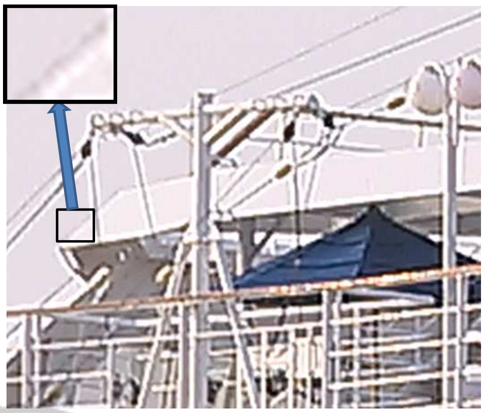
6 4K TO 8K UP-CONVERTER WITH NLSP

8K TV is currently under development. At the moment the baseband speed of 8K is four times higher than 4K. At the same time 8K content is very rare. 4K content up-converted to 8K does not have satisfactory resolution. However, if 4K content could be up-converted with sufficient resolution, it would be very useful for 8K development.

The hardware up-converter with NLSP can process HDTV and generate 4K in real time. Since the pixel of 4K is 3820×2080, it can be divided into four HDTV video sections. Four 4K video sections can be generated using the same hardware on each HDTV section. These four up-converted 4K videos can then be combined to create 8K video in real time. Figure 13 shows an example of 8K video up-converted from 4K. There are four pairs of images. The column (a) images are the original 4K frames and the column (b) ones are double enlargements 8K frames made with

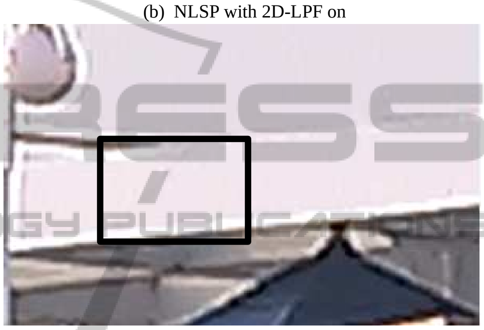


(a) NLSP with 2D-LPF off



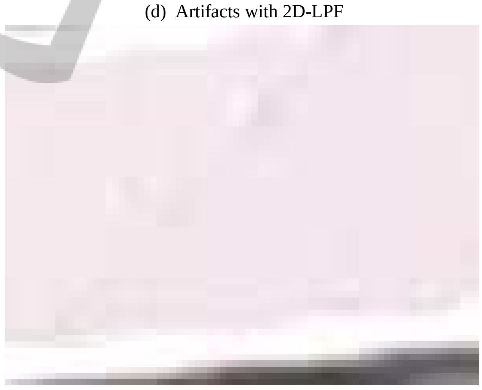
(b) NLSP with 2D-LPF on

(c) Artifacts without 2D-LPF



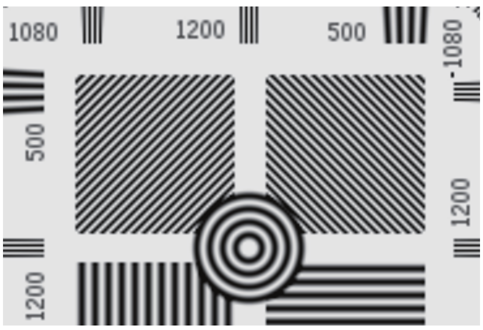
(d) Artifacts with 2D-LPF

(e) Noise without 2D-LPF

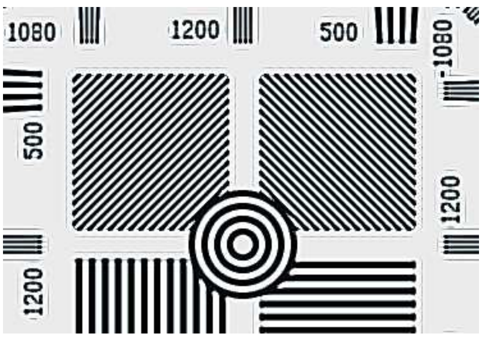


(f) Noise with 2D-LPF

Figure 11: Effect of 2D-LPF.



(a) Blurry image



(b) Focused image

Figure 12: Focusing effect.

(a) 4K ship (b) 8K ship

(c) 4K wall (d) 8K wall

(e) 4K bus (f) 8K bus

(g) 4K roof (h) 8K roof

Figure 13: 4K and up-converted 8K images.

NLSP in real time. The images enlarged with NLSP do not show any blur. This means NLSP improves resolution. The up-converter also works in real time (60 Hz).

7 CONCLUSIONS

NLSP real-time hardware for 8K was presented. Since the NLSP algorithm can create high-frequency elements that the original image does not have, it can create a high-resolution image in spite of the enlargement. Using parallel signal processing and a 2D-LPF, it works in real time even on enlarged 8K video shown at 60 Hz. The use of NLSP in up-conversion from 4K to 8K removes the blur caused by the enlargement and works in real time. It also has a focusing effect and can be applied to defocused video in real time. The papers on Super Resolution Image Reconstruction reported the PSNR between the original image and SR processed images since those studies used the original images. However, there are no original 8K images used in the examples of this paper. The subjective assessment is the only assessment method, and it will remain as future work to examine the possibility of developing a more objective measure.

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