Real-time Nonlinear Signal Processing Super Resolution of 8K Endoscope Cameras

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Abstract: Presently, 8K is the highest resolution of video systems. Originally, 8K research started only for broadcasting services. However, aside from broadcasting, 8K resolution video systems have also an important application in medical field, and endoscopic surgery is in its practical stage. In endoscopic surgery, a 0.02 mm thread is used. This 0.02 mm thread is not visible when using a 4K endoscope. However, when an 8K endoscope is employed, the thread is visible; however, fine focus is still necessary. Moreover, adjusting the focus of 8K by using the common tools only, such as view finders or small monitors, is very difficult. Hence, commercial HD/4K cameras are equipped with auto-focus functions; however, the central areas are not always the focus points. The focus is very deep and the focus points change during endoscopic surgeries. Owing to these reasons, a surgeon should manually control the endoscope focus. It is always very difficult to adjust the focus accurately. Super resolution (SR) has been proposed to sharpen out-of-focus images. However, a real-time SR technology is necessary for the 8K endoscope. In this study, a nonlinear signal processing super resolution (NLSP) is introduced to improve the resolution of 8K endoscope cameras. NLSP can enhance the 8K endoscope images and improve the camera's focus depth.

1 INTRODUCTION

The progress in video technologies has been remarkable. High-definition televisions (HDTVs) are the standard TV since a long time ago. HDTVs (2K), which are already unavailable in the market, have been replaced with 4K televisions. Broadcasting in 8K, which has four times the resolution of 4K, began in 2018 and 8K commercial TVs were also released. Aside from broadcasting services, 4K/8K is also applied in the medical field. Endoscope cameras are one of the important applications of 4K/8K. An endoscopic surgical operation targeted for the 8K endoscope system is the laparoscopic surgery. During a laparoscopic surgery, small holes are made in the abdominal or chest wall of a patient. The surgeon inserts the endoscope into the body cavity of the patient and all the operations are performed using a monitor. The medical doctor cannot directly view the target areas. Laparoscopic surgery is a popular operation because patients' physical load is minimal, with shorter recovery time than that of laparotomy. Given that the 1992 laparoscopic surgery became the subject of health insurances in Japan, the number of operations is increasing annually. The proposal of the Ministry of Health, Labor and Welfare aims to shift 70% of the total number of operations into laparoscopic surgery. However, the actual percentage of laparoscopic surgeries remains at 30%–40%. Although current laparoscopic surgery requires a high degree of skill and experience owing to the insufficient resolution of an endoscope, the lack of trained surgeons is the reason that the needs of patients are not fully catered for. An 8K endoscope provides a sufficient video resolution for laparoscopic surgery; in other words, it has a good visibility and the difficulty level of endoscopic surgery is low. Aside from improving the safety of patients, the number of capable surgeons is expected to increase. By using 8K endoscopes, surgeons can already view the thread used in laparoscopic surgery with a diameter of 0.02–0.029 mm, wherein this thread is not visible when 4K endoscopes are utilized. In other words, the 4K endoscope cannot meet the resolution required for the laparoscopic surgery. However, accurately adjusting the focus of the 8K endoscope is necessary to locate

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the 0.02–0.029 mm thread on a monitor.

According to clinical experiments, the surgeon cannot precisely adjust the focus of the 8K endoscope because the focus point on the screen constantly shifted during operation. Thus, the high-resolution (HR) advantage of the 8K endoscope cannot be fully utilized. During surgical operation, the region of interest (ROI) always changes. Although the ROI might be at the center of the screen at the beginning of the operation, the image must often be refocused at the top-left or bottom-right regions. Generally, autofocus functions automatically adjust the focus at the center of the screen. Moving the endoscope to set the ROI at the center position of the screen is possible. However, freely moving the endoscope during operation is not advisable because organs might be affected, causing the patient to feel pain. Hence, the endoscope should be placed in a fix position during operation and the focus is manually controlled. Aside from the operating surgeon, another surgeon is required to supervise the 8K endoscope focus. Because freely adjusting the focus with a small monitor is impractical, an LCD monitor with the size of more than 50 in. must be used for the surgery. However, accurately controlling the focus is still very challenging even if a 50 in. monitor is used. The 8K cameras' focus control is also an issue in broadcasting and content-making industries. Commercial HD/4K/8K cameras are not equipped with auto-focus function because focus control is one of the special areas of content production. The focus point in a frame is one of the techniques of content direction, and the focus position is not always at the center of a frame. Hence, focus adjustment depends on the camera man's technique, and the camera man manually controls the focus depending on the directors' request. Until the HDTV development, the camera man can manually adjust the focus by using the view finder, which was usually built in the camera. However, adjusting the focus of 4K cameras with the view finder becomes challenging even for a professional camera man because this view finder is too small to accurately control the focus. Even if the focus seems fine on the view finder, the result is often out of focus when the footage will be viewed on a larger screen. Thus, focus control becomes more difficult for 8K cameras. In 8K content production, a 55 in. 8K monitor and a focus person are necessary.

Professional 4K cameras are equipped with focus assist function (Funatsu et al., 2013)(Ikegami, 2015)(Hitachi, 2015). The principle of the focus assist function is very simple; in other words, the edges are detected from the image and are superimposed. The focus is controlled by maximizing the superimposed edges in the ROI. This method is similar to the enhancer technique (unsharp mask). The edges are detected using a high pass filter (HPF), the absolute value is calculated, and the absolute value edges are superimposed on the image. Then, the camera man adjusts the focus by maximizing the edges. Given that the edges are detected using an HPF, the edges caused by noise appear on the entire frame when noise is mixed into the image. When the lighting condition is good, the noise is suppressed. However, a good lighting condition is very rare and generally noise is mixed into the images. Owing to the noise issue, the focus assist is not applicable to general videos. The noise results in the difficulty of adjusting the appropriate focus position. Although the focus is not fine, clear images can be captured if the depth of the focus is high. However, the depth of an organ captured by the endoscope has a wide range. Thus, a signal processing method is required to widen the focus depth.

2 SUPER RESOLUTION (SR)

SR is a technology used in enhancing the resolution of an image/video. Although many SR proposals exist (Ledig et al., 2017)(Houa and Liu, 2011)(van Eekeren et al., 2010)(Shahar et al., 2011)(Bannore, 2010), they are only applicable to still images and cannot work real-time because they need iterations. A real-time signal processing is necessary for laparoscopic surgery. One issue of existing SR technologies is first capturing an HR image and then developing low-resolution (LR) images from the HR ones. However, no HR is available and we only have one LR. Thus, we must create an HR from only one LR. If we apply SR for the endoscope video, then we should create HR from every frame, and their several parts are out of focus. In previous SR papers, reconstructed HR is compared with the original HR based on the peak signal-to-noise ratio (PSNR). However, determining the PSNR in practical applications is impossible because we do not have the original HR and we only have one LR. Because we cannot measure the PSNR, we must define SR. In this study, we define SR first as a technology that can produce high-frequency elements that do not possess the original LR, and, then, it can also enhance image quality. The former definition can be easily proven by using two-dimensional fast Fourier transform (2D-FFT). However, most of the SR studies did not report the FFT results of the LR and HR images. The latter definition indicates that invisible things can become visible by the SR processing in this study. In the laparoscopic surgery, a 0.02 mm diameter thread is used and is only visible when an 8K endoscope with fine focus is used. However, even in fine focus condition, viewing the 0.02 mm thread by using the 4K endoscope is still impossible. Meanwhile, even if the focus is not fine, the 0.02 mm thread is still visible when an 8K endoscope is utilized. If the 0.02 mm thread on out-of-focus areas can be seen with the SR signal processing, then, SR is proven to improve the image quality.

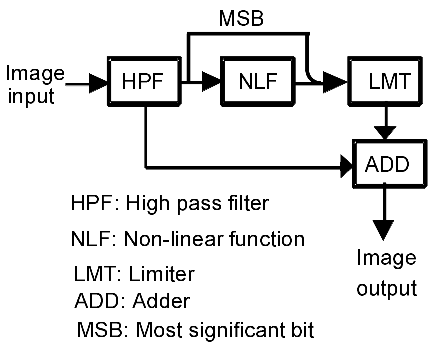


Figure 1: This caption has one line so it is centered.

3 NLSP

NLSP was originally proposed for up-converted image from HDTV to 4KTV (Gohshi et al., 2017) and works in real-time. Currently, most commercial 4KTV sets are equipped with SR functions. However, the SR functions that are presently used are inferior to NLSP (Mori et al., 2015). The basic idea of NLSP is similar to that of one-dimensional signal processing shown in Figure 1. The input is distributed into two blocks. The upper path establishes high-frequency elements that the original image does not have as follows: the original image is processed using i.e.,or minus) for each pixel. After the HPF, the edges are processed with a nonlinear function (NLF). If an even function (e.g., $y = x^3$) is used as the NLF, then, the sign is lost. To prevent information loss, the most significant bit is obtained from the edge information prior to the NLF and restored after the NLF. NLFs generate harmonics that can develop frequency elements that are higher than that of the original image. NLSP by using a number of NLFs should be able to produce high-frequency elements. Here we propose a cubic function, $y = x^3$, as the NLF.

Generally, images are expanded in a Fourier series (Mertz and Gray, 1934). Herein, we utilize the one-dimensional image $f(x)$:

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

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.

$$\begin{aligned} g(x) = &\sum_{n=-N}^{-M} a_n \cos(n\omega_0) + b_n \sin(n\omega_0) \\ &+ \sum_{n=M}^{N} a_n \cos(n\omega_0) + b_n \sin(n\omega_0) \end{aligned} \tag{2}$$

where 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 output of NLF 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 cubic function $y = x^3$ generates $\sin^3(n\omega_0)$ and $\cos^3(n\omega_0)$ from $\sin(n\omega_0)$ and $\cos(n\omega_0)$. $\sin^3(n\omega_0)$ and $\cos^3(n\omega_0)$ generate $\sin 3(n\omega_0)$ and $\cos 3(n\omega_0)$. Theoretically it can be explained as follows.

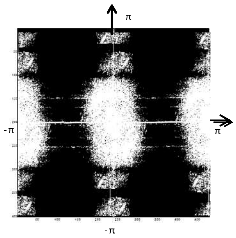
$$\begin{aligned} (g(x))^3 = &\sum_{n=-3N}^{-M} c_n \cos(n\omega_0) + d_n \sin(n\omega_0) \\ &+ \sum_{n=M}^{3N} c_n \cos(n\omega_0) + d_n \sin(n\omega_0) \end{aligned} \tag{3}$$

where c_n and d_n are the expansion coefficients of Equation 3. Although Equation 3 has the high-frequency elements from $(N+1)n\omega_0$ to $3N$, these elements do not exist in the input image, that is, Equation 1. Given that these high-frequency elements are produced with the NLF, some of them are too large and should be processed with LMT. After the LMT processing, the developed high-frequency elements are added into the input by using the ADD function in Figure 1. The high frequency elements, produced by NLF, that are three times higher than the input, and they can be used to double the size of the images horizontally and vertically, such as during the up-conversion from 4K to 8K. Moreover, given that images and videos are two-dimensional signals, applying NLSP horizontally and vertically is necessary. NLSP is not a simple edge enhancement, such as the enhancer. Aside from the enhancer, other technologies, such as blind deconvolution (Richardson, 1972) (Lucy, 1974) and SR, are also available. However, because these technologies require iterations, they cannot work in real-time for the 8K endoscope.

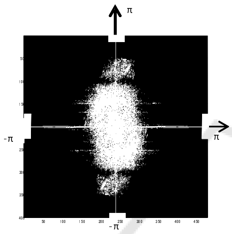
(a) Original image (256 × 256 pixels)

(b) Enlarged image of (a) with Lanczos2 filter (512 × 512 pixels)

Figure 2: Example of image enlargement.



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



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

Figure 3: 2D-FFT result.

Figure 4: NLSP processed result of Figure2 (a).

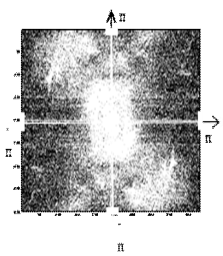


Figure 5: 2D-FFT result of Figure4.

4 CAPABILITY OF THE NLSP

In this section, a simulation result is discussed to prove the capability of the NLSP. Herein, we use an image enlarged with the Lanczos-2 filter (Duchon, 1979) because the enlargement always causes blur. Figure 2(a) shows a 256×256 pixel image, and Figure 2(b) illustrates the a 512×512 pixel image enlarged of Figure 2(a). Compared with Figures 2(a) and 2(b), Figure 2(b) has an enlargement blur. Figure 3 illustrates the two dimensional fast Fourier transform (2D-FFT) results of Figure 2. In Figure 3(a) the same spectrum is repeated every 2π, which is the sampling frequency, horizontally and vertically. In Figure 3(b), the spectrum appears only in the center position because the horizontal and vertical sampling frequencies become double and the other spectrum appears outside of the image. Figure 4 illustrates the NLSP-processed image of Figure 2(b). By comparing Figures 2(b) and 4, Figure 4 is evidently better. Figure 5 shows the 2D-FFT of Figure 4. Figure 5 has the high-frequency elements that Figure 2(b) does not possess indicating that NLSP can produce high-frequency elements that the input image cannot possess. In section 2, we define SR first as a technology that can produce high-frequency elements that are not present in the original LR, and then it also improves the image quality. By comparing Figures 2(b) and 4, the former condition of SR defined in Section 2, is satisfied. In the case of Figures 3(b) and 5, the latter condition of SR is also met. We also develop a real-time 4KTV NLSP hardware shown in Figure 6. Although many devices are present on the circuit board, most of them are interface devices for the input and output. The

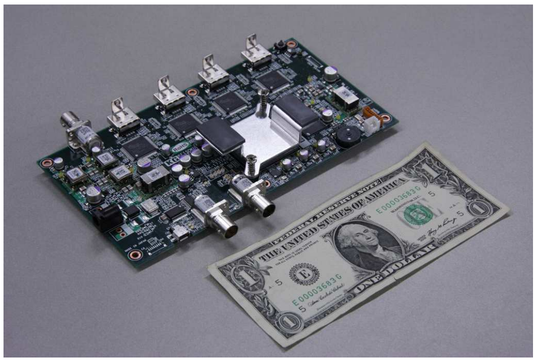


Figure 6: Real time NLSP hardware.

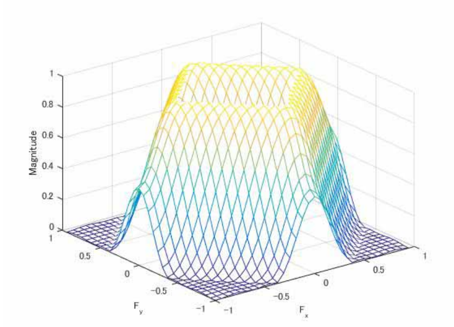
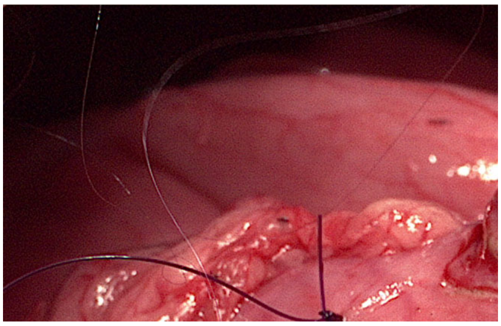
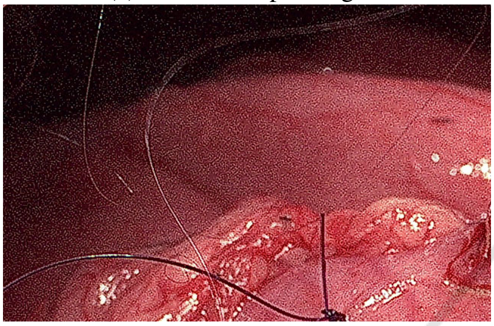


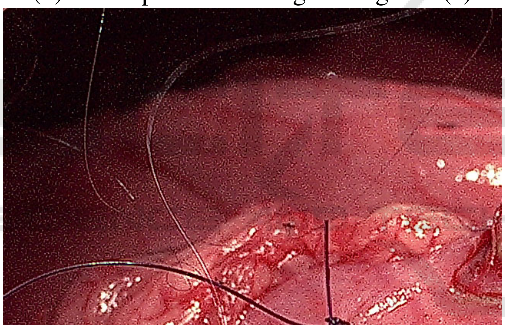
Figure 7: 2D-LPF characteristic.



(a) 8K endoscope image 1

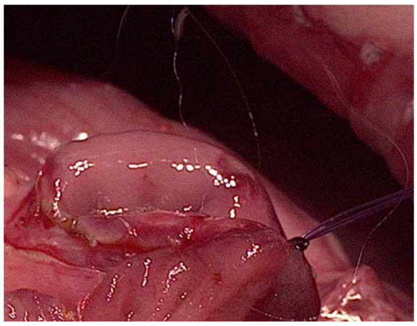


(b) NLSP processed image of Figure 8(a)

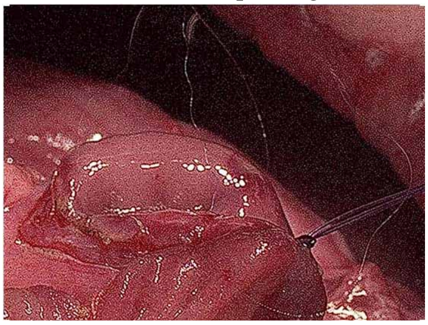


(c) NLSP and 2D-LPF processed image of Figure 8(a)

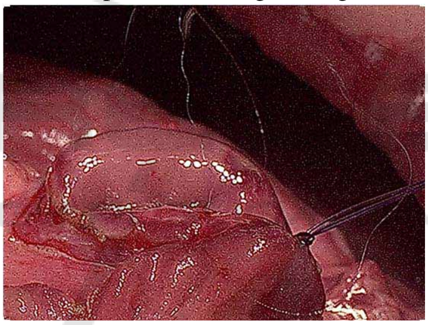
Figure 8: 8K endoscope image and processed images 1.



(a) 8K endoscope image 2



(b) NLSP processed image of Figure 9(a)



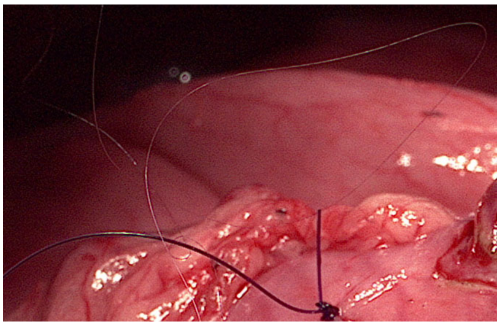
(c) NLSP and 2D-LPF processed image of Figure 9(a)

Figure 9: 8K endoscope image and processed images 2.

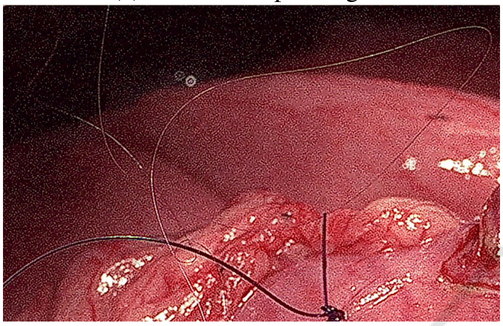
NLSP algorithm is written in a field-programmable gate array (FPGA) under the heat sink at the center of the circuit board.

5 EXPERIMENTAL RESULT OF THE 8K ENDOSCOPE IMAGE USING A REAL-TIME NLSP HARDWARE

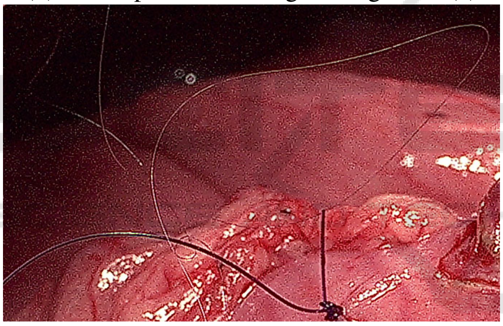
Because the input and output of the real-time hardware is 4K, we need four parallel circuit boards when we use the hardware to an 8K video in real-time. The full 8K image cannot be illustrated in the paper owing to space limitations. Figures 8–10 show the experimental results. These areas are cropped from the full 8K endoscope images and contain the 0.02 mm threads. Figures 8(a), 9(a) and 10(a) show the areas of the original 8K endoscope images. Figures 8(b), 9(b) and 10(b) illustrate the NLSP-processed images by using the real-time hardware shown in Figure 6. When comparing the original images (Figures 8(a), 9(a) and 10(a)) with the NLSP-processed images (Figures 8(b), 9(b) and 10(b)), the threads become more visible in the out-of-focus areas. However, the NLSP processing creates an undesirable effect which is noise. A two-dimensional low-pass filter (2D-LPF) is introduced to reduce the noise. Figure 7 presents the characteristic of 2D-LPF. The 2D-LPF decreases only the number of diagonal high-frequency elements to reduce the noise. Given that the 2D-LPF is pro-



(a) 8K endoscope image 3



(b) NLSP processed image of Figure 10(a)



(c) NLSP and 2D-LPF processed image of Figure 10(a)

Figure 10: 8K endoscope image and processed images 3.

gramed in the FPGA illustrated in Figure 6, the 2D-LPF can also work in real-time.

Figures 8(c), 9(c) and 10(c) show the NLSP- and 2D-LPF-processed results of the original images shown in Figures 8(a), 9(a) and 10(a), respectively. When comparing Figures 8(c), 9(c) and 10(c) with Figures 8(a), 9(a) and 10(a), the noise is reduced and the 0.02 mm threads remain visible. However, the noise level is not sufficiently low in the 2D-LPF-processed images shown in Figures 8(c), 9(c) and 10(c). Although an infinitive impulse response filter-type noise reducer is a practical signal processing for videos, it does not work well (Lee, 1980). Three requirements necessary to completely reduce the noise are : (1) sufficient lighting conditions, (2) high-sensitivity photoelectric device, and (3) noise-reducing signal processing. The improvement of the lighting conditions seem to be easy. However, heat increases in proportion to brightness. Bright lights emit more heat that might hurt organs because the light is used inside the body. Although high-sensitivity photoelectric device is useful, it is time consuming. Currently, the new noise-reducing signal processing is believed to be practical.

6 CONCLUSION

In this study, a real-time SR system that consists of NLSP and 2D-LPF is proposed. The SR system is applied to the 8K endoscope video. It enhances the image quality and the unfocused 0.02 mm thread becomes visible, indicating that the proposed real-time SR system improves the focus depth. The future work will be focused on the development of a novel noise-reducing signal processing method for 8K endoscope.

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