UNIVERSAL SPATIAL UP-SCALER WITH NONLINEAR EDGE ENHANCEMENT

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ABSTRACT

Spatial image resizing is an important issue for pixel oriented displays with variable input formats. A known example is a scaling factor of two for up-scaling from Standard Definition (SD) to High Definition (HD) format. Nonlinear image processing introduce higher harmonics to enhance the image sharpness. However it may create annoying alias artefacts, too.

We investigated an up-scaler for rational factors with nonlinear detail enhancement. The method for scaling is based on economic diamond shaped filters. The additional available frequency space is filled with higher harmonic frequencies created from the detail signal by an improved approach for nonlinear signal processing. The bandwidth of higher harmonics is limited to the output Nyquist frequency in order to prevent aliasing.

Index Terms - image scaling, nonlinear processing, detail enhancement, edge enhancement, diamond scaler

1. INTRODUCTION

Pixel oriented-displays with various resolutions replace traditional CRTs. In this context it can be observed an increase of graphics and video formats over the past years. This holds for displays as well as for source materials. The adjustment of different source formats for representation on any pixel-oriented display is a main focus of current research. High-quality, low-cost image scaling are investigated to perform the interpolation/decimation between the input and the output format.

Particularly high resolution displays (HD 1280x720, 1920x1080) become ever more popular and will be used for different formats, e.g. HD, SD or others. The benefits of the higher resolution of HD displays are not well used by up-scaling with linear signal processing and linear peaking methods. Linear methods use the frequency range in the lower resolution source baseband only. Nonlinear signal processing creates higher harmonics above the source baseband which may fill the additionally frequency space up to Nyquist limit of the display format. These harmonics enhance the image sharpness significantly. However harmonic frequencies above the Nyquist limit of the display resolution may cause aliasing. Therefore the bandwidth limitation of higher harmonics is very important.

Figure 1 - Frequency response up to the Nyquist limit f_c of the source image after up-scaling with the diamond scaler; left: by factor 3; right: by factor 10

The proposed scaling method is based on Sample and Hold (S&H) for interpolation followed by diamond shaped post-filters. This scaling approach is described in [1]. It achieves high quality scaling with easy filter design using at maximum seven multiplications for any output pixel at any rational up-scaling factor. The original pixel structure is widely eliminated after up-scaling which is a major advantage over bi-cubic interpolation. Diamond scalers have an almost circular frequency response without the complexity of circular polyphase filters. Fig. 1 compares the frequency responses for the interpolation factors 3 and 10 up to the Nyquist frequency of the source image. Clearly the uniform circular frequency response can be recognized. At the baseband Nyquist limit an attenuation of 9-12 dB is reached, but all baseband signal frequencies remain. Linear peaking filters may enhance the frequency components up to the source Nyquist limit, but they do not create higher harmonic frequencies.

A number of techniques have been proposed for nonlinear image enhancement. Common nonlinear techniques generally fall into one of two categories [3]: In the first category, spatial domain methods modify the interpolation process depending on the image content [6][7]. In the second category techniques are used which work in the frequency domain by creating new frequencies [2][4]. The proposed approach in [2] is the only one which works very simple even for any rational up-scaling factors.

Our novel approach with nonlinear signal processing creates higher harmonics above the source Nyquist frequency and adds them to fill the additionally available frequency space of the output format. The basic approach for nonlinear edge enhancement is already described in [2]. In the follow-
ing an improved method for the generation of higher harmonics is presented. Thereby the available frequency space is importantly better used. The results of this improved approach are compared with the diamond scaler including peaking and the basic approach in [2].

2. NONLINEAR SCALING APPROACH

In dependence of the up-scaling factor an increased frequency output baseband is available. The design of nonlinear scalers should take this additional frequency space into account. For the deployment in a wide range of applications it is necessary to keep the algorithm simple, independent of the scaling factor. Further it is a goal to keep as many parameters as possible fixed. Our implemented approach is shown in Fig.2.

The block diagram in Fig.2 includes three paths. The lower path shows the basic diamond scaler by rational factor $L/M$ to the output format. The enhancement of this scaled signal shares the basic structure of other high-frequency enhancement methods, except that the linear high-pass filtering is expanded with additionally non-linear components. The middle path represents the high-pass signal and the upper path an additionally gradient signal. In these paths likewise an up-scaling by factor $2 \cdot L/M$ takes place which doubles the Nyquist limit of the desired output format. This doubling is necessarily, in order to avoid aliasing in the range of the newly created higher harmonics. Harmonic frequencies above the output Nyquist frequency are eliminated by the low pass filter with fixed coefficients prior to the decimation by 2.

The high pass and gradient filters process the input signal and extract detail information on which the creation of higher harmonics is based. These filter operations are accomplished in the source baseband independent of the succeeding scaling factor. From the nonlinear processing results a new detail signal which contains upper frequencies of the source baseband as well as newly created higher harmonic frequencies. There is no need to carefully limit higher harmonics in the frequency space, since this is done by the succeeding low-pass filter. Both together, creation of higher harmonics plus bandwidth limitation to the output Nyquist frequency is an efficient way for picture enhancement without creating annoying aliasing.

3. GENERATION OF HIGHER HARMONICS

The nonlinear creation of higher harmonics is accomplished in the extended frequency range. For that the up-scaled gradient signal and the up-scaled detail signal are combined in an appropriate way. The principle is explained in Fig.3.

The top representation in Fig. 3 depicts an ideal bandwidth-limited step response between 16 and 235 in comparison to the result of the basic diamond scaler by factor 3. The difference between these signals is shown in the bottom diagram. This difference signal added to the diamond scaled image would reconstruct the ideal step response. The aim of our nonlinear detail enhancement is an adjustment of the high-pass filtered output of the diamond scaler to the depicted theoretically optimal difference signal. However the necessary harmonic frequencies can’t be produced by a linear operation. In the bottom graph of Fig.3 the optimal difference signal is shown in addition to the high-pass filtered signal and the gradient signal.

The generation of higher harmonics is realized as follows. The gradient signal ($F'(x,y)$) describes the absolute value of the first derivation of an image with a derivative operator. The high-pass signal ($F''(x,y)$) is the second derivation. In this approach a 2D non-separable high-pass-filter was used. Both signals mark edges in images in a different way.
Gradient signals indicate the center of edge transitions by a maximum value however signals of the second derivation by a zero crossing. We use these characteristics of both to the improvement of the high-pass signal, i.e.

\[ F_d(x, y) = (F'(x, y)^2 + F''(x, y)^2) \cdot \text{sgn}(F''(x, y)) \]  

where the operator \( \text{sgn}() \) is the Signum-function and is defined as follows:

**Definition: Signum-function**

\[
\begin{align*}
   y &= \text{sgn}(x) = \\
   &\begin{cases} 
   -1 & \text{for } x < 0 \\
   0 & \text{for } x = 0 \\
   +1 & \text{for } x > 0 
   \end{cases}
\end{align*}
\]

\( F_d(x, y) \) contains all created harmonic frequencies. This method works in dependence of the signal amplitude whereby lower amplitudes have less influence on the creation of harmonics than large amplitudes. That means that edges are preferentially treated, even if the input signal includes additional noise. The succeeding processing adjusts the level (gain) and a low-pass filter eliminates harmonics above the output Nyquist frequency.

**4. COMPUTATIONAL COST**

Specific attention was given for simplicity of computations. In the following the cost of computations only for complex operations will be considered. Fig. 2 presents the used functions. In our experiments a [3x3] high-pass filter was applied for the extraction of the high signal frequencies in the second derivation. For the generation of the gradient signal were likewise used two [3x3] filter, for each spatial direction ones. These filters work in the low resolution of the input signal. For all three paths the diamond scaler was used. The costs of the use of diamond scaling were examined in [5]. The result is that a maximum number of six pixels in the neighbourhood are necessary to calculate an output pixel at any rational scaling factor. In the worst case this sums up to a maximum of 35 multiplications per output pixel for the diamond up-scalers in Fig. 2 only. Investigations showed that for an up-scaling by factor two for all three paths approximately 18 multiplications per output pixel are needed. Finally a separable [3x3] low-pass filter was applied to limit the harmonic frequencies above the Nyquist frequency in the output baseband.

**5. EXPERIMENTS AND RESULTS**

In this section we show experimental results which indicate that our enhancement algorithm extends the frequency content of an input picture achieving a visually improved output signal. First a synthetic example is depicted. Fig. 4 compares in the top plot the difference signal from the bottom plot of Fig. 3 with the corresponding enhanced detail signal including all harmonics. Very clearly a good approximation to the optimal difference signal can be recognized. The bottom plot of Fig. 4 shows the output of the ideal step response compared to diamond scaled edge and the nonlinear enhanced edge. A gain of 1.8 was applied to the enhanced detail signal for the nonlinear enhanced signal. The nonlinear enhanced output signal shows nearly the same slope as the input edge step.

Fig. 5+6 depict the spectra of an up-scaled car image by the rational factor 2.4. Fig. 5 represents the output spectra of the simple diamond scaler and the diamond scaler with 6 dB peaking. In Fig. 6 the comparison between the nonlinear scaler from [2] and the novel proposed nonlinear scaler is shown. It is clearly visible that peaking increases the amplitudes of all existing frequency components particularly in the baseband. Both nonlinear approaches in Fig. 6 create new higher harmonics while the new procedure uses the available frequency range even more efficiently.

The output images of the simple diamond scaler and the proposed nonlinear scaler are depicted in Fig. 7. The diamond scaler in the upper half already shows a very high quality compared to other scaling methods such as simple bi-directional or more complex bi-cubic scalers which are not presented in this paper. The bottom picture using the proposed nonlinear detail processing clearly depicts sharp edges without distortions. The behaviour with additional white noise shows Fig. 8. In the lower picture of Fig. 8 a reduction of smaller amplitudes can be recognized. The noise is hardly increased by this proce-
Figure 5 - Spectra of up-scaled car image by factor 2.4; top: diamond scaler; bottom: diamond scaler with 6 dB peaking.

Figure 6 - Spectra of up-scaled car image by factor 2.4; top: nonlinear scaler from [2]; bottom: nonlinear scaler from Fig. 2.

Figure 7 - Car image part after up-scaling by factor 2.4; top: basic diamond scaler; bottom: nonlinear scaler from Fig. 2.

Figure 8 - Car image part with additional gaussian noise (S/N=27dB) after up-scaling by factor 2.4; top: diamond scaler; bottom: nonlinear scaler from Fig. 2.
dure for detail enhancement compared to the noise in the input image. Other material was tested with excellent results, including other scaling factors and different noise levels.

6. CONCLUSION AND FURTHER INVESTIGATIONS

The proposed approach for image up-scaling with nonlinear edge enhancement is suitable for any rational factors. The basic diamond scaling achieves already good results. Up-scaling offers an additional available frequency space which can be filled by nonlinear processing. The basic diamond up-scaler has been extended by a new method for the creation of higher harmonics. Experiments show very good results regarding the subjective image quality. Even at images with additional noise the edge enhancement could be noticed whereby the noise hardly increased.

However the presented nonlinear up-scaling method may be further simplified without degrading the output quality significantly. In further investigations we will first explore the function of the proposed algorithm for more pictures and particularly for video sequences. In additional we will aim at lower computational costs to use the proposed algorithm in real time environments on programmable platforms.

REFERENCES