Big Data Compression Using Anamorphic Stretch Transform

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Abstract

The proliferation of image data is a major contributor to the big data and the problems associated with its storage and transmission. In this paper, we present applications of the recently introduced Anamorphic Transform to enhancing the performance of two popular image compression methods, JPEG and JPEG 2000. The transformation increases the spatial coherence resulting in superior compression without sacrificing the image quality. We present examples showing improved compression of various types of images contributing to big data including medical, security and surveillance, astronomy, and satellite images.

Keywords: Big data compression; Anamorphic Stretch Transform; Shape based image compression; Diffractive data compression; Space bandwidth compression; Image communication.

1. Introduction

The ever increasing number of pixels in image sensors and the pervasiveness of graphics in internet traffic is a major contributor to big data. To deal with the storage and transmission of high resolution images and videos in the cloud, new advances in data compression are paramount [1-4]. Today, JPEG [5] and JPEG 2000 [6] are commonly used standards for image compression. To reduce the data size, JPEG and JPEG 2000 use frequency decomposition via the discrete cosine transform (DCT) [5] or wavelet transform [6] as well as the frequency dependence of the human psychovisual response.

Recently a physics-based data compression technique has been introduced [7-9]. By reshaping the signal before sampling, the Anamorphic Stretch Transform increases the coherency of the waveform so it can be re-sampled at a sampling rate lower than the Nyquist rate of the original signal without losing information. Consequently, it reduces the size of the digital representation of the information. The reshaping emulates propagation through a diffractive element with a specific warped refractive index profile followed by a nonlinear operation. The transformation has been implemented in analog domain for real-time optical data compression [7]. Such a need arises in scientific research and medicine where large numbers of real-time measurements must be made in order to find statistically rare but important information. For example, for rare cancer cell detection in blood, screening of millions of cells in a high speed flow stream is required. Such problems has fueled development of record throughput real-time instruments such as a new type of camera that allowed the detection of cancer cells in blood with sensitivity of one cell in a million [10] and new spectrum analyzers enabling the discovery of Optical Rogue Waves [11]. These instruments produce a fire hose of temporal data approaching 1 Tbit/s. The challenges of managing such big data loads led to the development of the Anamorphic Stretch Transform, an analog time-domain transformation for capturing and compressing high speed temporal signals in optical domain.

The discrete implementation of this technique, dubbed Discrete Anamorphic Stretch Transform (DAST) represents a new solution to image compression [8,12]. The transform reshapes the image before uniform re-sampling in such a way that sharp features are naturally stretched more than coarse features. This causes sharp features to experience higher sampling density than coarse features. This feature selective reshaping is achieved through a mathematical restructuring of the image and not through modification of the sampling process as in compressive sensing (CS) [13-17]. This technique does not need feature detection and is non-iterative.

Here we show examples of DAST image compression to various types of images contributing to big data. In particular, we show applications in digital pathology, security and surveillance, astronomy, and satellite imaging. In these examples, we use pre-compression using DAST to enhance the performance of JPEG, and JPEG 2000 formats.

2. Anamorphic Transformation

The Discrete Anamorphic Stretch Transform (DAST) is mathematically defined as:

\[
\tilde{B}[n,m] = \sum_{k_1,k_2=-\infty}^{\infty} e^{j\Phi[k_1,k_2]} \cdot B[n-k_1,m-k_2],
\]

(1)

where \( \tilde{B}[n,m] \) is the transformed image, \( B[n,m] \) is the original image brightness (intensity), and \( n \) and \( m \) represent the two dimensional discrete spatial variables. The transform convolves the image with the Kernel \( \exp(j\Phi[n,m]) \) where \( \Phi[n,m] \) is a nonlinear phase profile. The symbol \( | \cdot | \) is nonlinear absolute operator which extracts the brightness out of the complex amplitude.

After the transformation, the reshaped image is uniformly re-sampled at a rate below the Nyquist rate of original image. As shown below, the reshaping is such that it increases the spatial coherence (i.e. it compresses the intensity bandwidth), hence, sub-Nyquist resampling does not cause loss of information. In the decoder side, phase discrimination is used to recover the original image [7-9].

A specific class of the nonlinear phase profile \( \Phi[n,m] \) leads to increased spatial coherence enabling image compression. To
identify the profile, we employ a mathematical tool that shows the image intensity bandwidth and the image data size after the transformation by equation a). Since the intensity bandwidth is the inverse of coherence length, this tool identifies the specific $\Phi[n,m]$ that leads to increase in coherence. This mathematical tool is called Stretched Modulation (SM) Distribution:

$$S_M[n,m,p,q] = \sum_{k_1,k_2} \tilde{B}[p+k_1,q+k_2] \cdot \tilde{B}^*[k_1,k_2]$$

$$\cdot \tilde{K}[p+k_1,q+k_2] \cdot \tilde{K}^*[k_1,k_2] \cdot e^{i(nk_1+mk_2)},$$

(2)

where $\tilde{K}[p,q]$ is the Fourier transform of the Kernel $\exp(j\Phi[n,m])$, and $p$ and $q$ represent the two dimensional discrete frequency variables. At $n=0$, the Distribution is equal to the autocorrelation of the image complex spectrum and its width is the output brightness bandwidth. The half range of the spatial features over which the SM Distribution is non-zero is the image record length.

As suggested by SM Distribution [8,12], for image compression the Kernel’s Phase Derivative (PD) function should have a superlinear profile such as the tangent function which corresponds to the following Kernel phase profile [12]:

$$\Phi[n,m] = \frac{a_1}{b_1} \cdot \ln(\cos(b_1 \cdot n)) + \frac{a_2}{b_2} \cdot \ln(\cos(b_2 \cdot m)).$$

(3)

where $a_1$, $b_1$, $a_2$ and $b_2$ are real numbers, $\ln$ is natural logarithm, $\cos$ is Cosine function and $b_1,n$ & $b_2,m < \pi/2$. The parameters $a_1/b_1$ and $a_2/b_2$ are normalized to the image size.

To study the effect of DAST on an example image we use a 1 Mega pixel raw image shown in left panel of Fig. 1(b). Designed DAST Kernel PD profile is shown in Fig. 1(a). The right panel in Fig. 1(b) shows the image after the transformation, described mathematically by Equation a). To understand how the space-bandwidth product is compressed after DAST, in Fig. 1(c) we compare the intensity bandwidth of the original image with the transformed one. As it can be seen, the intensity bandwidth is reduced (image coherence increased) however, as shown in right panel in Fig. 1(b), the spatial size of the image is almost unchanged. Hence space-bandwidth product is reduced which results in image data compression.

3. Applications in Big Data

Text Here we study some emerging Big Data applications in which DAST can prove to be advantageous. The observed improvements are not unique to the specific images used here, but rather illustrate the general property of the Anamorphic Stretch Transform. The DAST Kernel Phase Derivative (PD) profile normalized to the image size used for image compression examples in this paper are shown in Fig. 1(a).

3.1 Medical Image Compression

Here, we compare JPEG 2000 compression alone with the case of DAST pre-compression followed by post-compression using JPEG 2000 for digital pathology image compression [18-21]. In this example, the image under analysis is a histologic specimen of stained tissue [22]. The original color image file size is 1.08 MB and 360 kilo pixels in TIF format. Compressed images are shown in Fig. 2. The total compression factor for the both cases is 220. In the case of DAST pre-compression, the 220 is obtained by 3.66x compression by DAST followed by 60x compression by JPEG 2000. This is compared with 220x is obtained by JPEG 2000 alone. To numerically compare the performance, we calculate the Peak Signal to Noise Ratio (PSNR) for the two cases. PSNR for the case of JPEG 2000 alone is 17.5 dB versus 22.2 dB for the case of using DAST pre-compression. This shows that the case with DAST pre-compression has a higher quality than JPEG 2000 alone while two cases having the same total compression factor and hence the same compressed file size.
3.2 Astronomy Image Compression

Here we show improvement of JPEG compression enabled by DAST. As an example we use the image of Andromeda galaxy. The PD profile of the normalized DAST Kernel for this example is shown in Fig. 1(a). The original gray-scale image in this example has file size of 328.32 kB and 640x513 pixels in TIF format. Here we compare two cases, JPEG compression alone and the case with DAST pre-compression followed by JPEG. The total compression factor in the both cases is 62. Results are shown in Fig. 3. As seen, the resolution in the case with DAST pre-compression is higher while having the same compression factor. Figure 3 demonstrates that pre-compression with DAST improves the performance of JPEG as well as application of DAST to astronomy image compression.

3.3 Security and Surveillance

Here, we present an example to study the performance of DAST compression combined with JPEG for security and surveillance applications. The PD profile of the normalized DAST Kernel for this example is shown in Fig. 1(a). The original gray-scale image [23] has file size of 180.635 kB and 180635 pixels in TIF format. Here we compare two cases, JPEG compression alone and the case with DAST pre-compression followed by JPEG. The total compression factor...
Applications. To numerically compare the image compression DAST can prove advantageous in security and surveillance in Fig. 4. Figures 4 demonstrate that pre-compression with JPEG alone while having the same total compression factor. In this example, the output data size for the case of JPEG alone was 81.4% versus 97.1% for the case of using DAST pre-compression. This shows that pre-compression using DAST has improved the structural similarity of the compressed image to the original image.

3.4 Satellite Image Compression

In the last example presented here, we compare the performance of our image compression method when combined with JPEG format for applications in satellite image compression. In this example, the original colorful satellite image [24] has file size of 1.38 MB and 460 kilo pixels in TIF format. Results are shown in Fig. 5. In both cases, we have compressed the images by 56 times. Our method clearly shows superior performance when combined with JPEG over DAST alone while having the same total compression factor. Figure 5 demonstrates that pre-compression with DAST can prove advantageous in satellite image compression applications.

References