Creating A High Resolution Image from Registration and Reconstruction of Spatially Shifted Low Resolution Images

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Abstract

In applications that demand high resolution images, it is often not feasible nor sometimes possible to acquire images of such high resolution by using current CCD camera with its inherent resolution. Instead, image processing methods may be used to construct a high resolution image from multiple, degraded, low resolution images. This paper presented a novel robust high resolution reconstruction method that consists of a high accuracy hierarchical registration, interpolation and postprocessing. This algorithm is found to be effective, robust and shows significant improvement over conventional interpolation algorithms. The success of this algorithm is demonstrated through various simulated and real images.

1. Motivation and Introduction

There has been a huge demand for high resolution imaging in such areas as aerial surveillance, medical, consumer and scientific imaging. Although a CCD camera with million pixels has already been developed, it is still necessary to increase the resolution further for VHD images (2000 X 2000 pixels). Current CCD technology has almost reached this barrier.[1] Therefore, new schemes are required to increase the resolution further. One promising approach to further improve resolution is to incorporate signal processing techniques into the imaging process.

The method presented on this paper consists of 3 steps: registration of multiple images, reconstruction of high resolution image and postprocessing for image enhancement. The complete flow of the algorithm is shown in Fig. 1. Image registration is a fundamental task in multiframe reconstruction process. The reconstructed image quality highly depends on the accuracy of registration. Fast and robust registrations have been proposed,[2,3] but there are limited to rigid shifts. The most conventional interpolation and match method[4,5] are able to achieve subpixel accuracy. However the accuracy of this method is affected by the quality of interpolation and fails when input images contain aliasing errors. We present a robust hierarchical registration algorithm which combines both phase correlation and spectrum cancellation[6] in frequency domain to achieve high accuracy of subpixel registration for images with both translational and rotational movements.

The proposed approach can achieve subpixel accuracy even when images contain aliasing errors due to undersampling. By using the Fast Fourier Transform of images as the registration domain, this method has smaller computational complexities as compared with the interpolation or convolution computations by orders of magnitude. A hierarchical searching further enhance the speed of this registration algorithm where a fast coarse search (phase correlation) is followed by an accurate fine registration (spectrum cancellation).

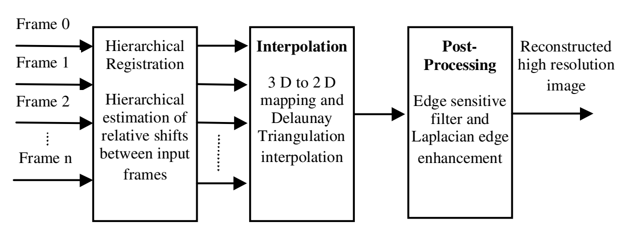

Figure 1. Steps in reconstruction of high resolution image from low resolution frames

The reconstruction algorithm present on this paper is a simple 2 steps approach in spatial domain. As a result of spatial domain image reconstruction, the ill condition problem in frequency domain image reconstruction can be eliminated completely. By using the shift information among low resolution images, a 3-D to 2-D mapping on the pixels is performed to form a non-uniform upsampled image. This image is then interpolated to a uniform high resolution using Delaunay triangulation interpolation. The reconstructed image quality is further enhanced by a postprocessing which involved an edge sensitive interpolation filter and a Laplacian edge enhancement. This algorithm is found to be efficient and shows significant improvement over conventional algorithms.

In section 2 of this paper, the hierarchical registration method, which involved the phase correlation and spectrum cancellation will be discussed. The reconstruction of high resolution and image enhancement algorithm will be given in section 3. In section 4, some simulated and real image results are provided to demonstrate the robustness and effectiveness of this algorithm. Finally, concluding remarks are made in section 5.

2. Hierarchical Registration

The hierarchical registration method consists of 2 level. The first level is a coarse phase correlation registration, where the rigid translation and subpixel rotation shifts are determined. This is followed by an accurate spectrum cancellation registration in the second level.

Let $f_1(x, y)$ represent the reference image and $f_2(x, y)$ is the spatially shifted frame. $F_1(w_x, w_y)$ and $F_2(w_x, w_y)$ are the Fourier transform of the above 2 frames respectively. If $f_2(x, y)$ is replica of $f_1(x, y)$ translated by (x_o, y_o) and rotated by θ_o, according to the Fourier Shift Theorem and the Fourier Rotation Theorem[7] their transform are related by

$$F_2(w_x, w_y) = e^{-j2\pi(w_x x_o + w_y y_o)} F_1(w_x \cos\theta_o + w_y \sin\theta_o, -w_x \sin\theta_o + w_y \cos\theta_o) \quad (1)$$

By rotating f_1 by θ, the transform will become $F_1(w_x\cos\theta + w_y\sin\theta, -w_x\sin\theta + w_y\cos\theta)$. Now let

$$G(w_x, w_y;\theta) = \frac{F_2(w_x, w_y)}{F_1(w_x\cos\theta + w_y\sin\theta, -w_x\sin\theta + w_y\cos\theta)} \quad (2)$$

with θ taken as a variable, obviously for $\theta = \theta_o$

$$G(w_x, w_y;\theta_o) = e^{-j2\pi(w_x x_o + w_y y_o)} \quad (3)$$

If $\theta = \theta_o$ the problem is reduced to the tracking of a purely translational movement. The procedure is first determine the angle $\theta = \theta_o$ for which $G(w_x, w_y;\theta)$ reduces to the form Eq. 3, then the rigid translation shift x_o and y_o can be found by phase correlation.[3] The cross power spectrum of the 2 images is defined as

$$\frac{F_1(w_x, w_y)F_2^*(w_x, w_y)}{\left|F_1(w_x, w_y)F_2^*(w_x, w_y)\right|} = e^{(w_x x_o + w_y y_o)} \quad (4)$$

Therefore, by inverse transforming Eq. 4, an impulse centred on (x_o, y_o) is obtained, hence the rigid translation is immediately determined.

Using θ and (x_o, y_o) found in 1st level, the images are aligned and the second level registration is performed to find the subpixel shifts. Assume that the aligned second image $f_2(x, y)$ is subpixel shifted in the spatial domain by (Δ_x, Δ_y) with respect to the first frame $f_1(x, y)$. Then the relationship description of the two images in the discrete frequency domain is:

$$F_1^c(w_x, w_y) = \exp(j\Delta_x w_x + j\Delta_y w_y) F_2^c(w_x, w_y) \quad (5)$$

The superscript 'c' denotes the continuous spectrum.

Next, consider the case when images are undersampled M times in the x direction and N times in y direction, respectively. From the aliasing relationship, we have

$$F_i(w_x, w_y) = \frac{1}{MN}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} F_i^c\left(\frac{w_x + 2\pi m}{M}, \frac{w_y + 2\pi n}{N}\right) \quad i = 1,2 \quad (6)$$

With M = N = 2, the undersampled image frames have the following spectra:

$$4F_i(w_x, w_y) = F_i^c\left(\frac{w_x}{2}, \frac{w_y}{2}\right) + F_i^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2}\right) + F_i^c\left(\frac{w_x}{2}, \frac{w_y}{2} + \pi\right) + F_i^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2} + \pi\right) \quad i = 1,2 \quad (7)$$

Therefore, if the second frame image has a shifted sampling reference (Δ_x, Δ_y) and is undersampled with M = N = 2, the spectrum of the second frame is related to that of the first frame as follows. Using Eq. 5 and Eq. 7,

$$\begin{aligned}
4F_2(w_x, w_y) &= F_2^c\left(\frac{w_x}{2}, \frac{w_y}{2}\right) + F_2^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2}\right) + F_2^c\left(\frac{w_x}{2}, \frac{w_y}{2} + \pi\right) + F_2^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2} + \pi\right) \\
&= \exp\left(\frac{j\Delta_x w_x}{2}, \frac{j\Delta_y w_y}{2}\right) F_1^c\left(\frac{w_x}{2}, \frac{w_y}{2}\right) \\
&+ \exp\left[j\Delta_x\left(\frac{w_x}{2} + \pi\right) + j\Delta_y \frac{w_y}{2}\right] F_1^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2}\right) \\
&+ \exp\left[j\Delta_x \frac{w_x}{2} + j\Delta_y\left(\frac{w_y}{2} + \pi\right)\right] F_1^c\left(\frac{w_x}{2}, \frac{w_y}{2} + \pi\right) \\
&+ \exp\left[j\Delta_x\left(\frac{w_x}{2} + \pi\right) + j\Delta_y\left(\frac{w_y}{2} + \pi\right)\right] F_1^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2} + \pi\right)
\end{aligned} \quad (8)$$

Next, consider the case when the undersampled frame image is artificially shifted. Suppose the first image frame $f_1(x, y)$, undersampled as explained above, is shifted by $(\delta_x/2, \delta_y/2)$. The scale factor is due to the down sampling with M = N = 2. Then the Fourier transform of the shifted image is,

$$\begin{aligned}
\hat{F}_1(w_x, w_y) &= \exp\left(\frac{j\delta_x w_x}{2} + \frac{j\delta_y w_y}{2}\right) F_1(w_x, w_y) \\
&= \exp\left(\frac{j\delta_x w_x}{2} + \frac{j\delta_y w_y}{2}\right)\left\{F_1^c\left(\frac{w_x}{2}, \frac{w_y}{2}\right) + F_1^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2}\right)\right. \quad (9) \\
&\left. + F_1^c\left(\frac{w_x}{2}, \frac{w_y}{2} + \pi\right) + F_1^c\left(\frac{w_x}{2} + \pi, \frac{w_y}{2} + \pi\right)\right\}
\end{aligned}$$

Subtracting Eq. 9 with proper scaling from Eq. 8 and if the estimate of the shift is exact, i.e., $\delta_x = \Delta_x$ and $\delta_y = \Delta_y$, only the low frequency part of the difference spectrum, i.e., the principal spectrum located at the origin (0, 0) is completely eliminated. Hence, the registration is to find δ_x and δ_y, which minimize the error function in Eq. 10 around the low pass region of the images.

$$E = \sum_m \sum_n \left\| F_2(m,n) - \hat{F}_1(m,n) \right\|^2 \qquad (10)$$

where $(m, n) \in$ Low Pass Region

3. Reconstruction and Enhancement Process

After the registration, frames are aligned in a 3D form as shown in Fig.2.

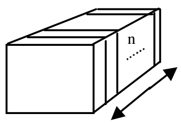

Figure 2. Alignment of low resolution frames

Pixels on these frames are then mapped into a single 2D image using the shift information obtained early. As a result a nonuniform upsampled image is formed. In order to arrive at a uniformly sampled image, we thus need to perform interpolation from these nonuniformly placed sampled. This problem has been discussed in the literature.[8-10] The nonuniform cubic spline interpolation based on Delaunay triangulation[11] is used in our algorithm. However, this interpolation has low pass effect, where it smoothed out the edges of the reconstructed high resolution image.

In order to overcome this problem and to enhance the high resolution image, a postprocessing which includes nonlinear edge sensitive interpolation filter[12] and Laplacian edge enhancement is applied to the image. The Laplacian edge enhancement is a process of subtracting Laplacian image (2 dimensional second differentiation of image) from the original image. This Laplacian enhancement is shown in Fig. 3.

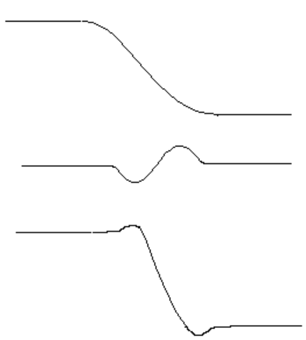

Figure 3. Laplacian enhancement

4. Results

In this section we provide examples for improving the resolution of computer simulated low resolution pictures and real images captured by CCD camera. In both cases the relative shifts between images are unknown.

To obtain the test images, an original image (148 X 148) is interpolated to a large image (592 X 592) by appending zeros in the DFT domain. This image is then downsampled 8 times to form 64 low resolution images. Fig. 4(a) shows one of the low resolution Lena image (74 X 74), which is enlarged to the same size of reconstructed image for comparison purpose. Using only 8 of these 64 images as the input images to our algorithm, a high resolution image (148 X 148) is constructed and is shown in Fig. 4(b). Fig. 4(c) shows the original Lena image.

Figure 4(a): Simulated low resolution Lena image

Figure 4(b): Reconstructed high resolution Lena image

Figure 4(c): Original Lena image

Figures 5 and 6 show 2 examples of this method applied to real images. There may be arbitrary displacements (both translation and rotation) between successively taken frames due to trembling of camera. Fig. 5(a), 5(b) and 6(a) are fractions of captured images, which are enlarged to the same size as the enhanced high resolution image for comparison purpose. Using 8 frames for each example as the input images, the reconstructed images are shown in Fig. 5(c) and 6(b) respectively. These reconstructed images show significant improvement on the resolution and sharpness of captured image and the text on figure 5(c) is now readable.

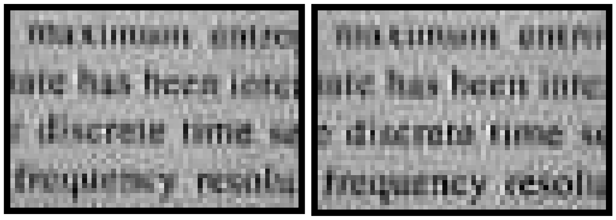

Figure 5(a) and 5(b): Low resolution captured input images

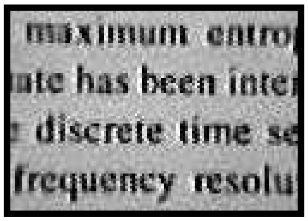

Figure 5(c): Reconstructed high resolution image

Figure 6(a): Low resolution captured image

Figure 6(b): Reconstructed high resolution image

5. Conclusion

In this paper we have presented an algorithm for creating high resolution image from a sequence of low resolution images. The addressed spatial domain interpolation is simple and effective. With the help of postprocessing, the algorithm is able to enhance the resolution while maintaining the sharpness and edge features of the object captured. The incorporation of robust, fast and accurate hierarchical registration within the system itself allows enhancement of images that are captured in real situation where the image priory information is unknown. The results show that the algorithm is capable of reconstructing a high resolution and quality image from spatially shifted (both rotation and translation) low resolution captured images even when the input images contain aliasing error. The algorithm has been successfully implemented using MATLAB, and is being implemented on a DSP controlled CCD camera. A typical application of the proposed system is enhancing images of digital still cameras, digital imaging equipment for consumer and medical applications.

6. References

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Biography

Loh Kok Heng received his B.Eng in 1999 with 1st Class Honors from the school of Electrical Engineering in Nanyang Technological University, Singapore. He is currently pursuing a Master of Engineering degree in Nanyang Technological University, Singapore in collaboration with BITwave Private Limited. His research area covers algorithm development for multiframe image enhancement and real time implementation using DSP.