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PERFORMANCE CONSIDERATIONS FOR THE APPLICATION OF THE LOSSLESS BROWSE AND RESIDUAL MODEL

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Abstract. A hybrid lossless compression model employing both the (lossy) JPEG DCT algorithm and one of a selection of lossless image compression methods has been tested. The hybrid model decomposes the original image into a low-loss quick-look browse and a residual image. The lossless compression methods tested in the model are Huffman, arithmetic, LZW, lossless JPEG, and diagonal coding. For both the direct and the hybrid application of these lossless methods, the compression ratios (CRs) are calculated and compared on three test images. For each lossless method tested the hybrid model had no more than a nominal loss in compression efficiency relative to the direct approach. In many cases, the hybrid model provided a significant compression gain. When used in the hybrid model, lossless JPEG outperformed the other lossless methods over a broad range of browse image qualities.

1. Background

In many practical situations involving images, a small degree of error in the pixel values can be tolerated without a significant effect on the display. This suggests that there are advantages to a decomposition of images into a lossy component, or browse component, and an error or residual component. The decomposition of the original image into browse and residual images gives an end-user the ability to browse an image and determine whether the residual image should be transmitted and added to the browse image to reproduce the original image. This feature is not available with any direct lossless compression method. A hybrid compression model employing the (lossy) JPEG DCT algorithm with the lossless diagonal coding scheme has recently appeared in the literature [1].

Some of the standard lossless compression methods are Huffman, arithmetic, the Ziv and Lempel algorithms, predictive encoding, bit-plane encoding, and run-length encoding [2]. Each of these compression methods have many variations which are reported in the literature. Another lossless compression method is lossless JPEG which utilizes a combination of predictive encoding and Huffman [3]. A non-standard lossless compression method is diagonal coding [1]. Diagonal coding is a type of lossless variable length encoding designed to take advantage of the Laplacian distribution characteristic of the residual image. For efficient compacting of the coded bit stream, a special C source code program was written that operates at the bit level [4]. Operating at the byte level would destroy any advantages of this coding method. Lossy compression methods consist primarily of the Joint Photographic Experts Group (JPEG) algorithm [5] and fractal encoding [6].

2. The Lossless Hybrid Model

The hybrid model utilizes both a lossy and a lossless image compression technique to produce an overall lossless image compression. Such an arrangement takes advantage of the high compression ratios achieved by the lossy methods and the error-free compression of the lossless methods. The image is first compressed using a lossy compression method. The lossy compressed image is decompressed and compared on a pixel-by-pixel basis with the original image. The decompressed image is termed the browse image as it can be used to browse an image for suitability for the application intended. The difference between the original image and the decompressed image is termed the residual image. The residual image is compressed using a lossless compression method. The compressed browse and compressed residual images can be appended for calculating overall compression. The forward process described here and the corresponding reverse process are presented in Figures 1a and 1b.

Because of the general acceptance and effectiveness of (lossy) JPEG [3], all the results from our hybrid model investigations presented here use this method to produce the browse images. A similar investigation used fractal compression with LZW compression [7].

Our test results indicated that it is not feasible, in terms of compression overhead, to use secondary compression to significantly compress either the compressed browse or compressed residual. In most cases tested, secondary compression resulted in expansion of the compressed image file size [4]. As a result, secondary compression was not included in the hybrid lossless compression model presented here.

One compression measure used to gauge performance is the compression ratio (CR) defined as [8, p. 10]:

$$CR = (1 - (\text{Compressed Image Size} / \text{Original Image Size})) \times 100. \qquad (1)$$

The overall compression ratio achieved by the hybrid lossless compression model is a combination of the compressed browse image CR and the compressed residual image CR. Application of Equation (1) to browse, residual, and overall compression ratios leads to:

$$CR_{overall} = [CR_{browse} - 50] + [CR_{residual} - 50] \qquad (2)$$

where CR_{browse} and $CR_{residual}$ are the compression ratios of the compressed browse and residual images.

3. The Test Images

The hybrid model (Figures 1a, 1b) was tested and evaluated using three 8-bit, 256x256 pixel images in raw pixel grey map format. The three images (Figure 2) were selected based on their structurely different pixel distributions or histograms (Figure 3).

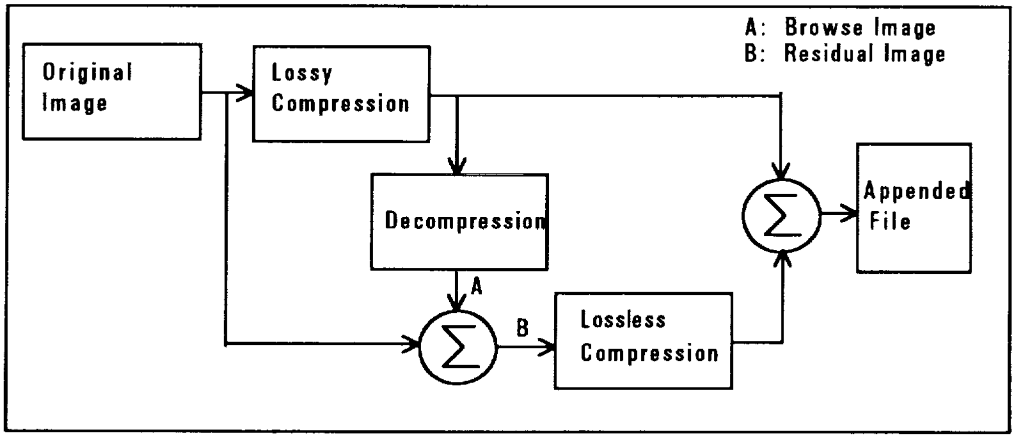

Figure 1a: Lossless Hybrid Model Compression.

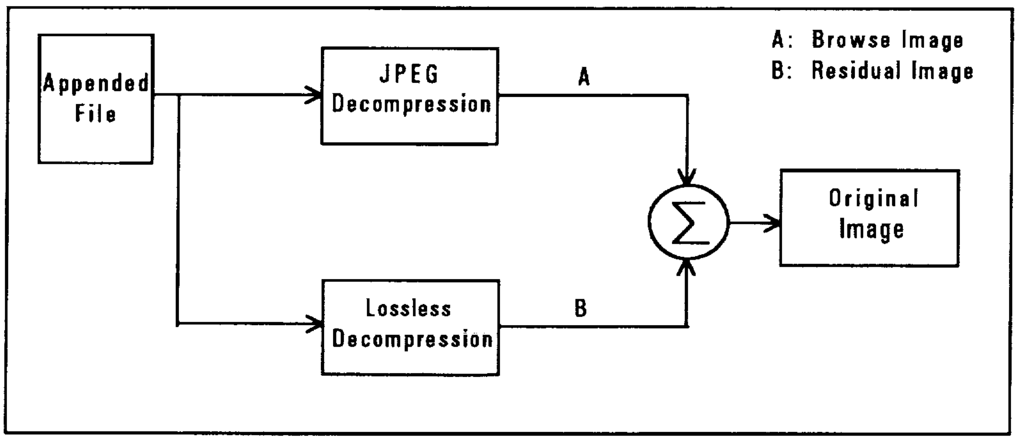

Figure 1b: Lossless Hybrid Model Decompression.

The lossy JPEG algorithm used in the model was developed by Andy C. Hung at the Portable Video Research Group (PVRG), Stanford University [5]. The quality factor used when compressing an image determines the amount of compression achieved and the resolution of the image when it is decompressed. The higher the quality factor, the greater the compression and the less the resolution upon decompression. Figure 4a graphically displays the quality factor versus compression ratio achieved for the three test images. One common measure of the resolution of the decompressed image as compared to the original image is termed the root mean square error (e_{rms}) as defined by:

$$e_{rms} = \frac{1}{N}\left[\sum_{x=0}^{N-1}\sum_{y=0}^{N-1}|g(x,y)-f(x,y)|^2\right]^{0.5} \tag{3}$$

where, for NxN pixel images, f(x,y) is the array of pixel values for the original image while g(x,y) is the array of pixel values for the decompressed image [9, pp. 256-257]. Figure 4b graphically displays a plot of quality factor versus e_{rms} for each of the three test images. As the quality factor is increased, the e_{rms} of the decompressed image decreases as expected. The decompressed test image LENA is displayed in Figure 5 after compression at various quality factors. Note that as the quality factor increases, the resolution of the decompressed image decreases. At quality factors greater than 250, the decompressed image begins to exhibit distinct blockiness due to the processing of 8x8 pixel blocks by the JPEG algorithm.

The residual image resulting from the pixel by pixel differences in the original image and the decompressed image exhibits a Laplacian distribution with a mean of zero [2, p. 60]. The residual image distribution, or histogram, has a reduced variance compared to the original image and is also significantly less correlated. The shape of the residual image histogram is dependent upon the quality factor used to compress the original image using lossy JPEG. As previously discussed, the higher the quality factor used, the more compression achieved; however, the decompressed image will less resemble the original image. This results in a residual image containing a wider range of pixel values. As a result, the residual image histogram will exhibit a wider Laplacian distribution. Figure 6 displays residual image histograms of LENA for various quality factors. Note that as the quality factor used to compress the original image of LENA is increased, the distribution of the corresponding residual image widens.

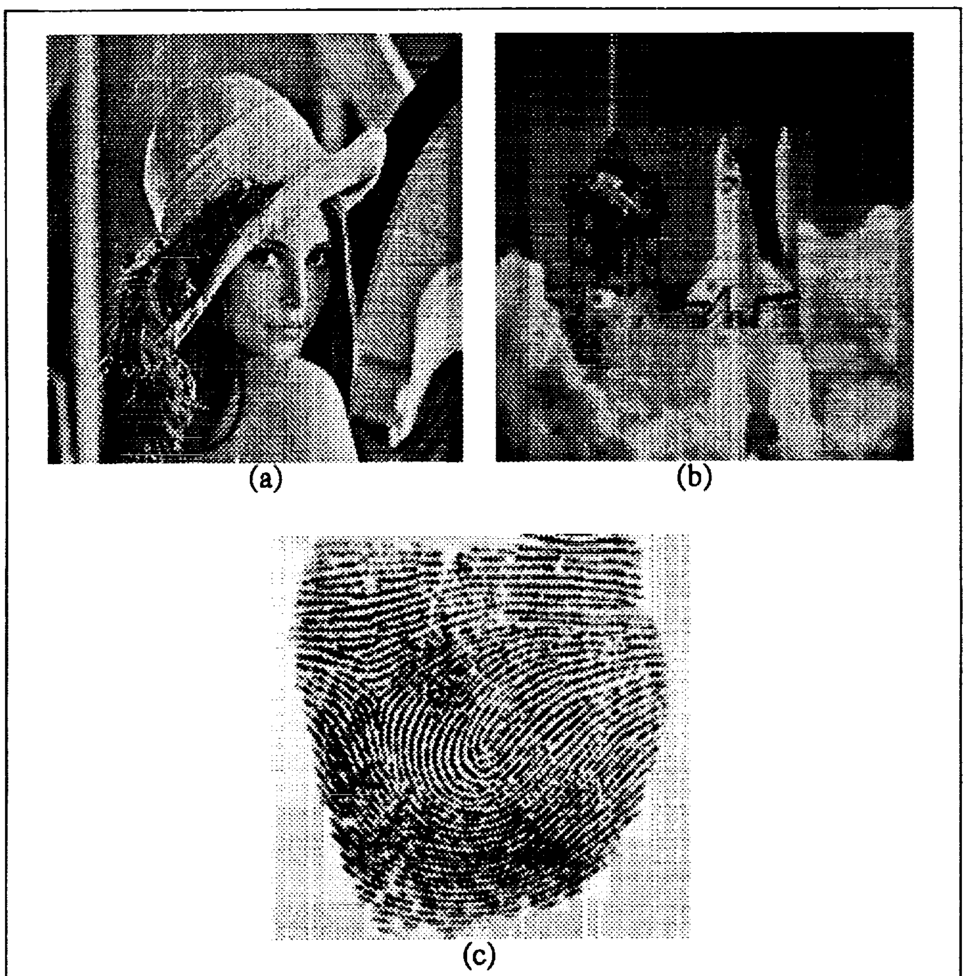

Figure 2: Three Test Images (a) LENA, (b) SHUTTLE, (c) FINGERPRINT.

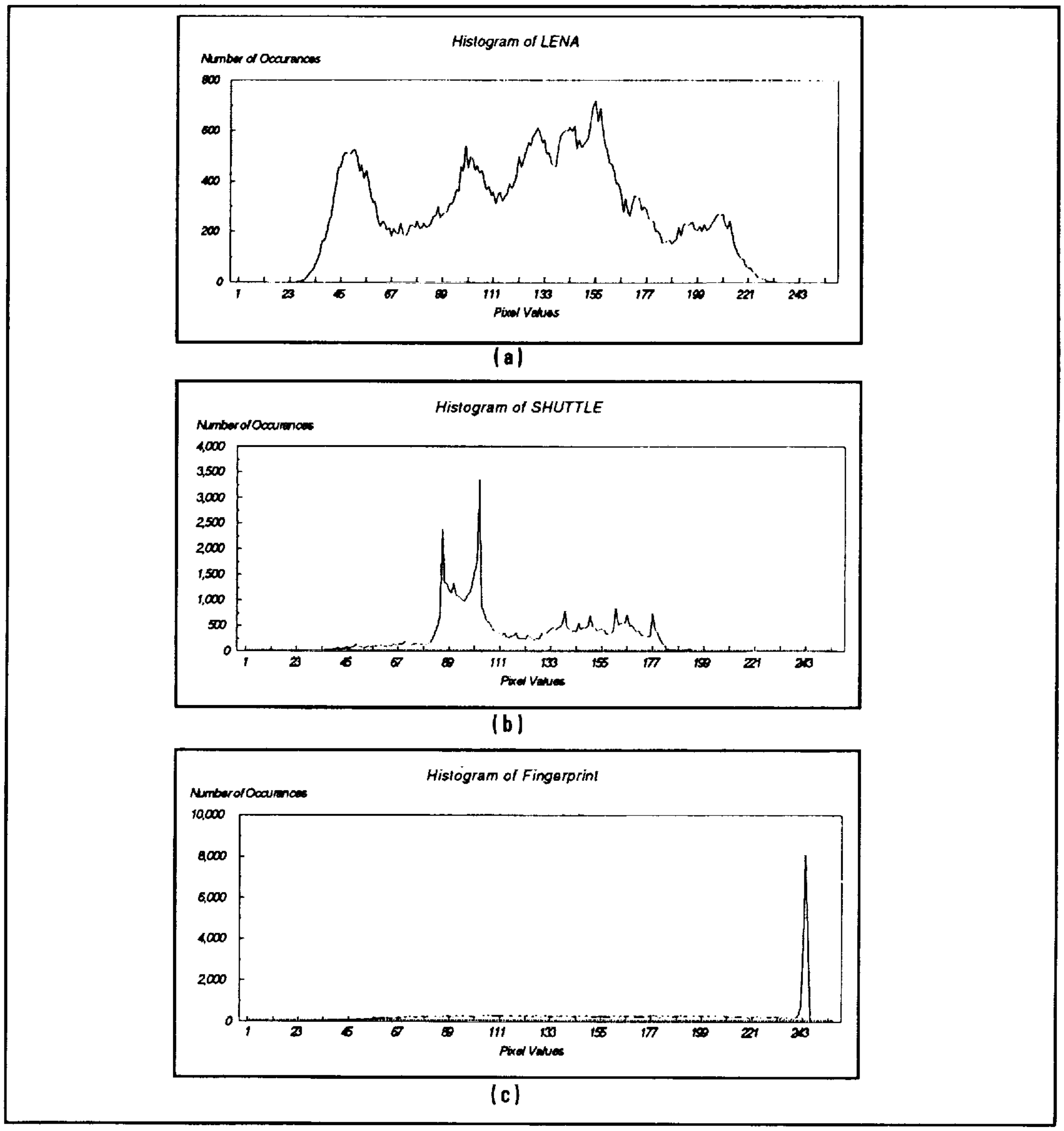

Figure 3: Histograms of the Three Test Images (a) LENA, (b) SHUTTLE, (c) FINGERPRINT.

4. Testing the Lossless Hybrid Model

The hybrid model (Figure 1a) was tested using lossless compression techniques previously mentioned. Huffman, arithmetic, diagonal, and lossless JPEG were used to compress the residual image ((B) shown in Figure 1a). A comparison between the compression results achieved by the direct lossless compression methods and the hybrid model is graphically displayed in Figures 7a, 7b, and 7c for each of the three test images at various quality factors. The corresponding results for LZW are summarized in Figure 8. For ease of reading, it should be noted that the right-most 3-D bar in each column represents the compression achieved with that particular direct lossless compression method (not using the hybrid model). The graphical results of using diagonal coding

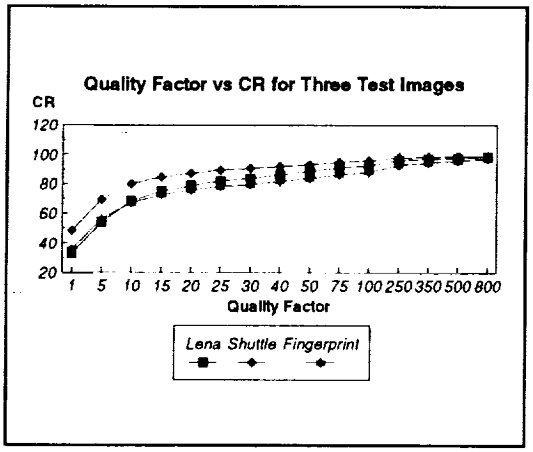

Figure 4a: Comparison of Quality Factor vs CR for the Three Test Images.

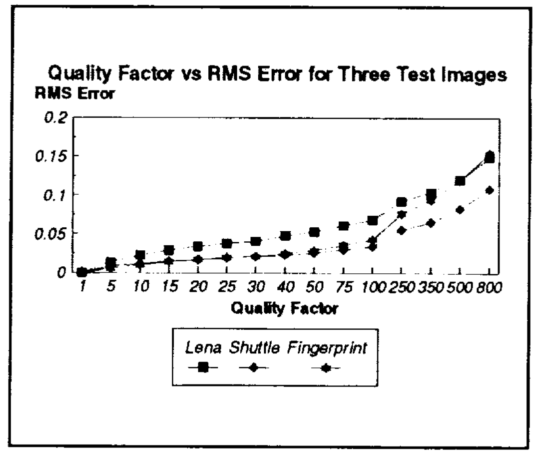

Figure 4b: Comparison of Quality Factor vs e_{rms} for the Three Test Images.

in direct lossless compression is limited to a CR of -30% for each of the images due to the degree of expansion diagonal coding produces when used in the direct compression application. Diagonal coding produced CRs of -76%, -111%, and -144% when used to compress LENA, SHUTTLE, and FINGERPRINT directly. In all cases, the hybrid model achieved greater compression ratios on all three test images than did the direct lossless compression methods with the exception of the direct application of the lossless JPEG method. From a comparison of Figures 7a, 7b, 7c, and Figure 8, LZW does not appear to be a wise choice for lossless compression in the hybrid model. LZW does not surpass the performance of the other methods for any quality factor tested. The residual images do not contain long repetitive strings of pixel values which are necessary for LZW to achieve high compression results. This is not surprising since the LZW method is designed primarily for compressing text, not visual graphics [8, pp. 23-24]. For this reason the LZW results will not be included in the discussion of comparisons which follow.

The CR for diagonal coding is not superior to the set of lossless methods at any quality factor (see Figures 7a, 7b, 7c); however, it does achieve close to the same compression results as Huffman, arithmetic, and lossless JPEG at some quality factors. As the quality factor used to compress the original image is increased, the compression achieved using diagonal coding decreases. This is due to the residual image distribution widening, thereby resulting in longer diagonal codes. At some point, diagonal coding will result in the expansion of the residual image file size. Diagonal coding resulted in an expansion of the residual image size when used to compress FINGERPRINT at a quality factor of 500 (see Figure 7c). It may be noteworthy that the execution time for the diagonal coding method was qualitatively observed to be shorter relative to the execution times for the computationally intensive Huffman, arithmetic, and lossless JPEG algorithms.

Using only the CR as the criterion for comparison, the results indicate that for low quality factors (≤50) arithmetic coding is the best choice for lossless compression of the residual images while at higher quality factors (>50) lossless JPEG is the best choice. Due to the wide diversity in

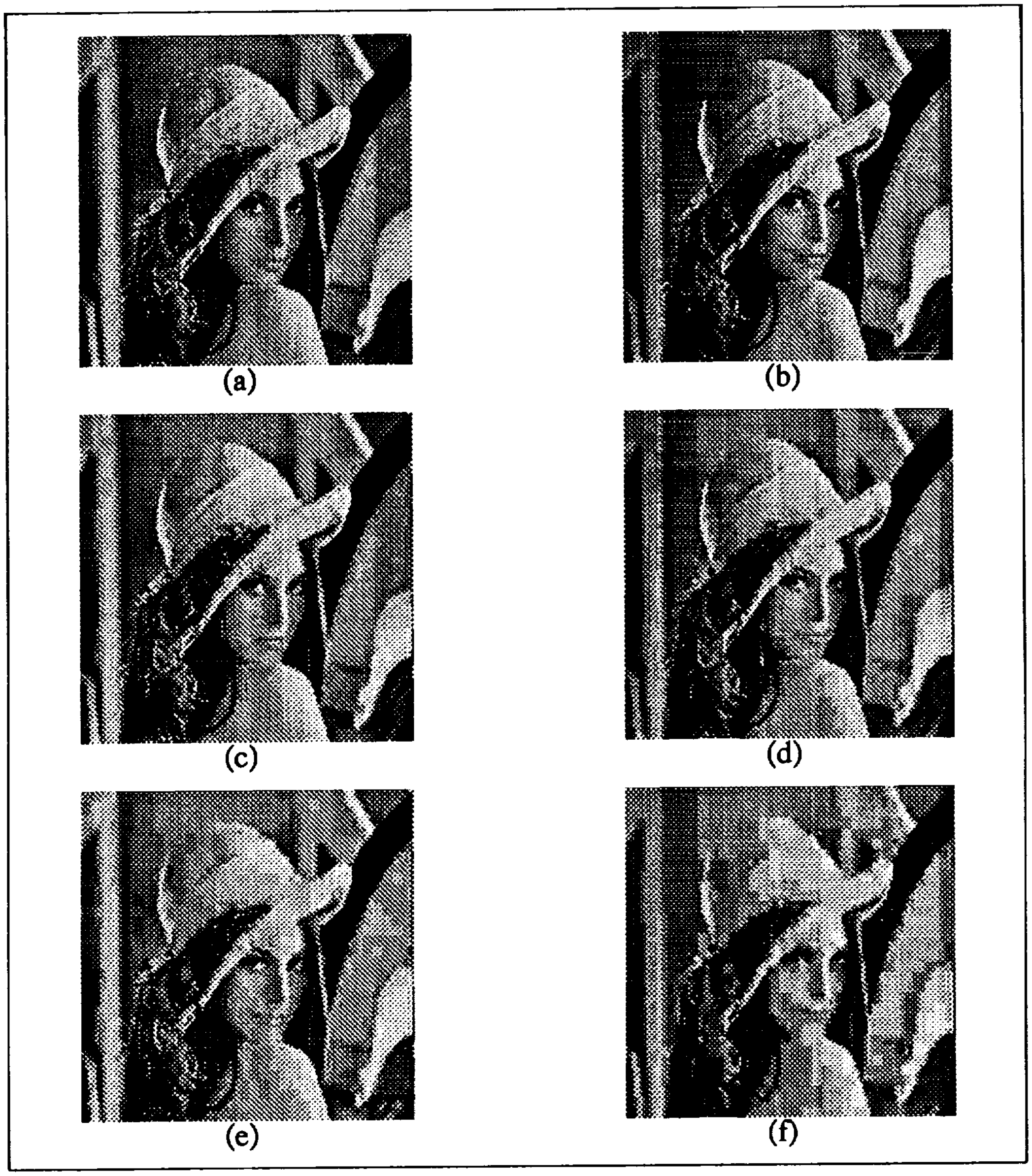

Figure 5: Decompressed LENA at Various Quality Factors (a) Original Image, (b) Q=100, (c) Q=250, (d) Q=350, (e) Q=500, (f) Q=800.

the histograms of the images tested, the observations made here regarding hybrid model performance would ostensibly be qualitatively applicable to a large host of images.

5. Additional Performance Considerations of the Hybrid Model

The hybrid model, using the lossless JPEG, achieved a lower CR on LENA and SHUTTLE than did the direct application of the lossless JPEG; however, the model did achieve a greater CR than direct lossless JPEG on FINGERPRINT at quality factors of 50 and 100 (see Figure 7c). Nonetheless, the hybrid model enjoys the advantage of producing a compressed

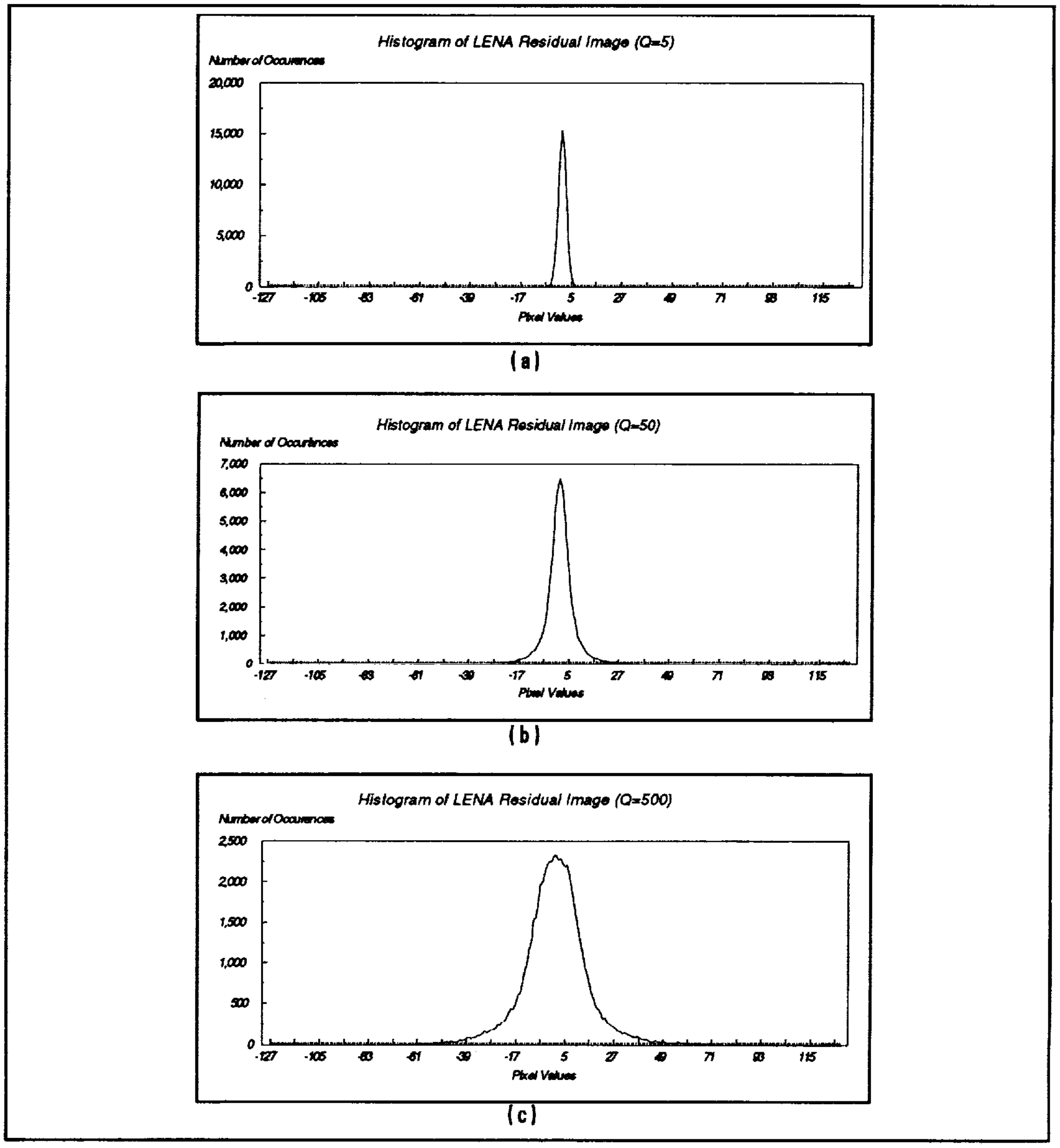

Figure 6: Residual Image Histograms of LENA (a) Q=5, (b) Q=50, (c) Q=500.

browse image which is significantly more compressed than the direct lossless JPEG compressed image. For instance, using a quality factor of 100 to compress LENA produces a quick-look lossy compressed browse image with a file size of 4823 bytes (compression ratio of 92%). The best lossless JPEG predictor algorithm produces a direct lossless compressed file size of 43322 bytes (compression ratio of 34%) (see Figure 9). The Q=100 LENA browse image produces an image that is visually lossless with no visual distortions (see Figure 5). If a lossless image is desired then the residual image of 40353 bytes can be transmitted and added to the browse image to produce an exact replica of the original image.

As previously discussed, the quality factor will impact the Laplacian distribution of the residual image. As seen from Figure 9 for LENA, the compressibility of both the browse and residual images depend on the quality factor. At low quality factors, minimal compression is achieved on the browse image; however, the residual image becomes highly compressible. As the quality factor is increased, the browse image is more compressible, but the residual image compresses less. These observations also apply to SHUTTLE and FINGERPRINT [4]. Since the overall lossless image is the sum of the compressed browse and residual image data (see Equation 2), achieving maximum overall compression would ostensibly depend on finding some optimal quality factor. In this section, we will examine this issue as well as the sensitivity of the overall CR to the quality factor for the images chosen.

Figures 10a, 10b, and 10c show the overall CR versus quality factors using the hybrid model on LENA, SHUTTLE, and FINGERPRINT respectively. Consistent with the conclusions reached at the end of the previous section, the focus of the comparisons will now be on the application of the arithmetic algorithm and lossless JPEG in the hybrid model. Note that for sufficiently high quality factors the lossless JPEG outperforms arithmetic. Under these conditions, the JPEG predictor is better able to accurately predict pixel values for residual image distributions and therefore produces higher compression ratios. This ostensibly is a result of a higher 2-D correlation of pixel values within the corresponding residual images at higher quality factors (see Figure 4b). As seen from Figures 10a, 10b, and 10c, for quality factors greater than approximately 50, the arithmetic method becomes less effective as the quality factor increases. At the higher quality factors, lossless JPEG achieves asymptotically higher compression ratios. Except at very low quality factors, the test results show that the overall compression ratio achieved by the hybrid model, when using lossless JPEG to compress the residual image, is relatively insensitive to the quality factor used to compress the original image. Therefore the data suggests that for the hybrid JPEG case, the trade-offs which dictate the best JPEG quality factor can be limited to subjective browse image quality and the associated browse compression ratio, but not the overall compression ratio.

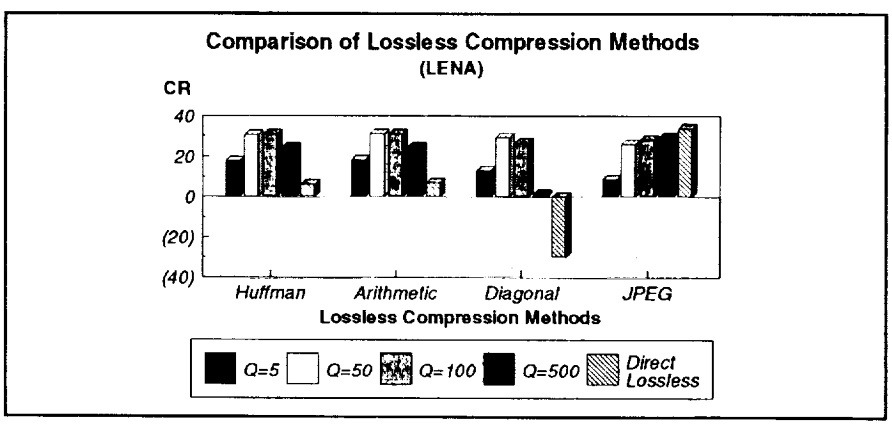

Figure 7a: Comparison of Hybrid Model with Lossless Compression Methods for LENA at Various Quality Factors.

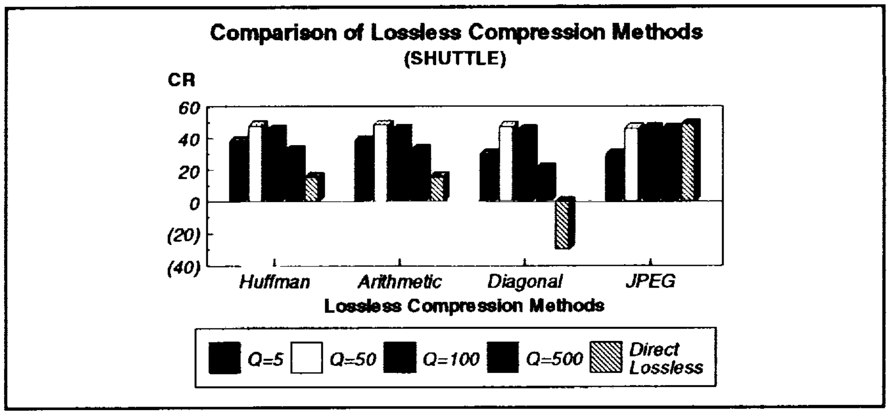

Figure 7b: Comparison of Hybrid Model with Lossless Compression Methods for SHUTTLE at Various Quality Factors.

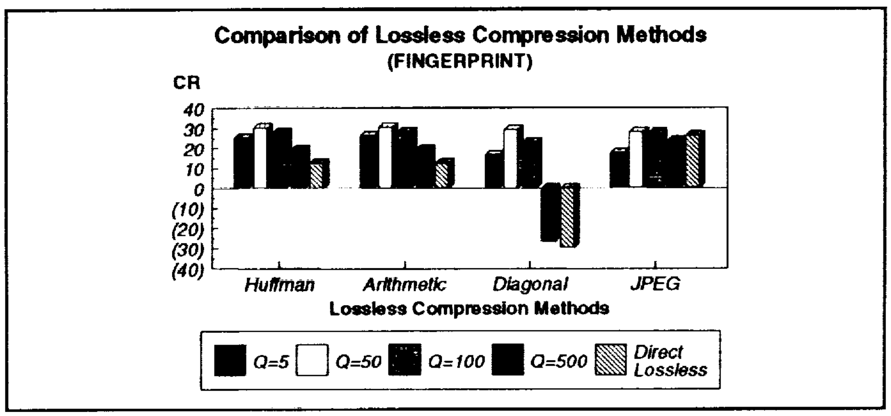

Figure 7c: Comparison of Hybrid Model with Lossless Compression Methods for FINGERPRINT at Various Quality Factors.

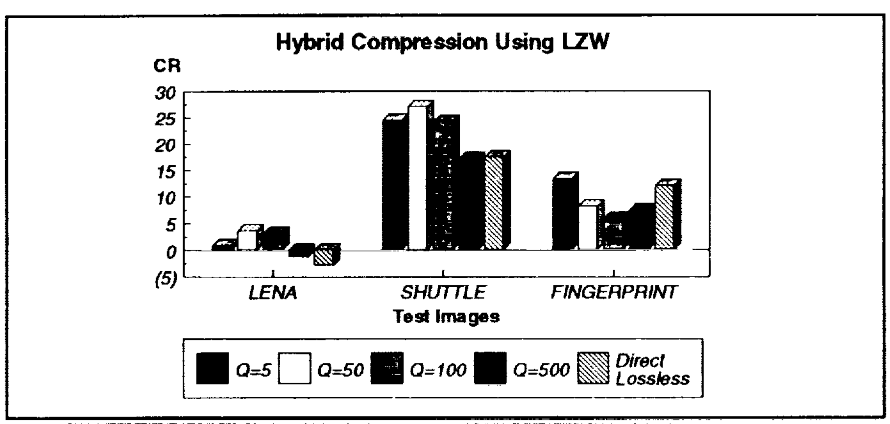

Figure 8: Compression Achieved Using LZW in Hybrid Model for Three Test Images at Various Quality Factors.

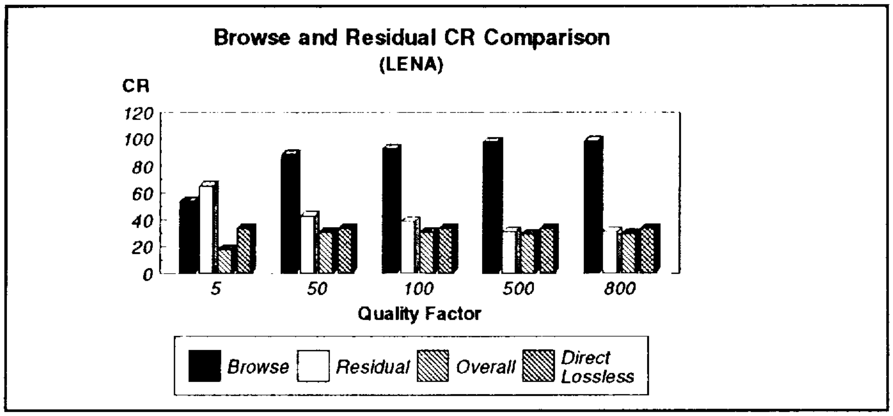

Figure 9: Browse and Residual CR Comparison with Direct Lossless Compression for LENA.

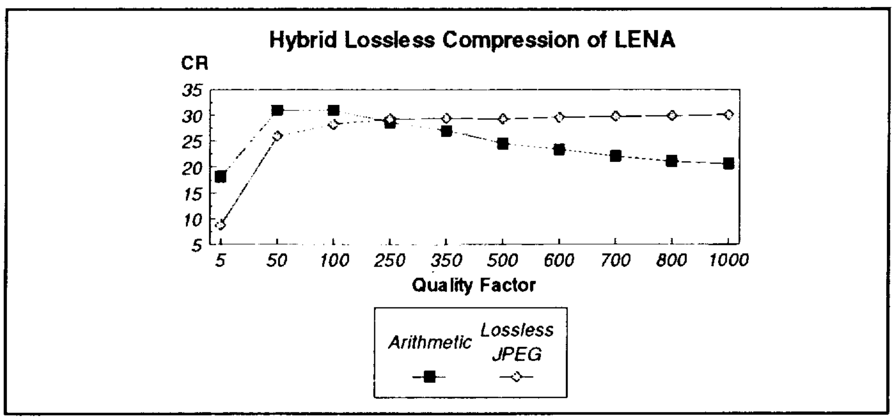

Figure 10a: Lossless Hybrid Compression of LENA Using Arithmetic and Lossless JPEG.

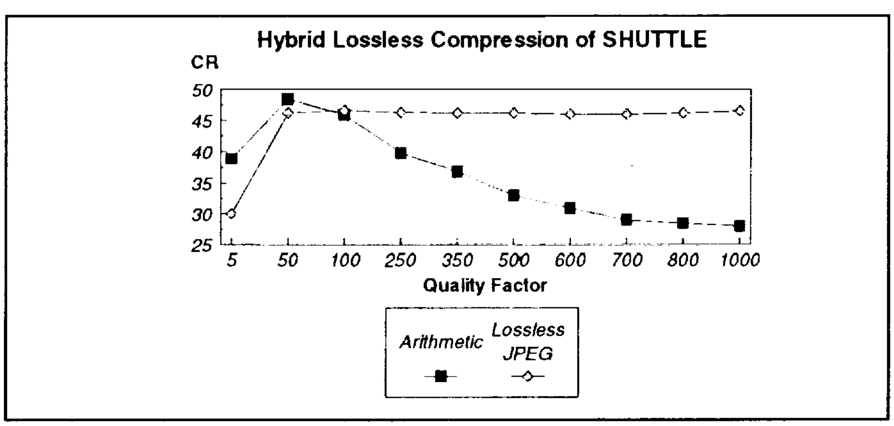

Figure 10b: Lossless Hybrid Compression of SHUTTLE Using Arithmetic and Lossless JPEG.

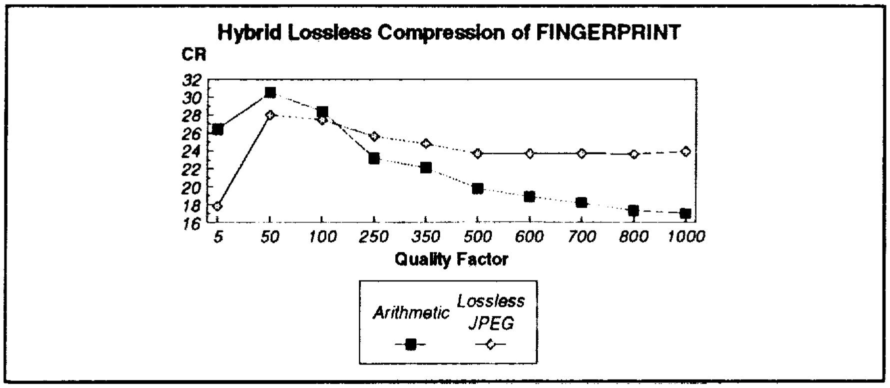

Figure 10c: Lossless Hybrid Compression of FINGERPRINT Using Arithmetic and Lossless JPEG.

6. Conclusions

Using the CR as a criterion for comparison, the results presented here indicate that the (lossy) JPEG DCT-based hybrid model has merit as a lossless image compression method. The results indicate that for low quality factors ($\leq$50) arithmetic coding is the best choice for lossless compression of the residual images while at higher quality factors (>50) lossless JPEG is the best choice. With the exception of lossless JPEG, the substitution of the other lossless compression methods (Huffman, arithmetic, LZW, and diagonal coding) into the hybrid model produce compression results that generally outperform their direct compression counterparts. CRs obtained for the lossless JPEG in the hybrid model were not predictably better than the CRs obtained by direct application of lossless JPEG. Nonetheless, the hybrid model has the advantage of decomposing the image into browse and residual components.

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