Chapter 6

Conclusions and Future Work

In this chapter, we present several conclusions based on our analysis in Chapter 4 and the results presented in Chapter 5. These conclusions are based on 14 grayscale images (including 10 natural and 4 rendered images), with different frequency content, compressed at four different compression ratios using the popular scalar biorthogonal wavelets and seven multiwavelets with vastly different characteristics. Our conclusions are as follows.

6.1 Conclusions

1. Balancing is essential to the multiwavelet transform. To keep the transform non-expansive, the multiwavelet transform is implemented similar as a 4-channel scalar filter bank with interleaving (equivalent to the polyphase input vectorization fed into the vector multiwavelet filter bank). For unbalanced multiwavelets, the shift-varying characteristic gives rise to non-smooth basis functions that drastically affect image compression performance at low bit rates. Moreover, the unbalanced multiwavelets' non-ideal magnitude characteristics degrade the compressed image quality further. On the other hand, the balanced multiwavelets have smooth basis functions under all integer shifts and they have relatively better magnitude characteristics.

This is reflected in our results; the balanced multiwavelets resulted in PSNR values 0.2–1 dB higher than the unbalanced multiwavelets. Also subjectively, the balanced multiwavelets clearly outperformed the unbalanced multiwavelets.

2. Our analysis shows that shift-invariance and desirable magnitude response characteristics are the most significant determinants of image compression performance for the balanced multiwavelets tested. A departure from shift-invariance and ideal magnitude response produces checkerboarding and tiling artifacts in the compressed image.

   Balancing does not automatically ensure shift-invariance or good magnitude and phase characteristics. In general, a higher balancing order indicates better performance. But we do not observe a one–one relationship between the balancing order and the PSNR values (although Bmw_{12} has a balancing order of 3, it gives slightly lower PSNRs than $\mathrm{SA}_4^\flat$ and $\mathrm{Ort}_4^\flat$ which are balanced to order 2).

   We expect that the next most important characteristic that affects image compression performance is the length of the synthesis bank filters. Short reconstructions filters are essential to minimize the ringing artifact. Further, a good symmetric extension technique is necessary to avoid border artifacts.

   We cannot exactly assess the impact of the good group delay characteristics on performance since the balanced multiwavelets we tested have fairly equivalent phase characteristics. However, for these multiwavelets, we suspect that the group delay characteristics have relatively less impact on the compression performance.

3. The best multiwavelet PSNR results fall short of the best scalar wavelets by 0.2–0.7 dB. This performance gap is explained by the difference in their energy compaction efficiencies. The balanced multiwavelets discussed in this paper have a balancing order less than or equal to 3, while $\mathrm{B}_{9/7}$ and $\mathrm{B}_{22/14}$ have higher vanishing orders. (The biorthogonal scalar wavelet $\mathrm{B}_{22/14}$ has a vanishing order of 5 and 7 for its analysis and synthesis wavelets, respectively while $\mathrm{B}_{9/7}$ has 4 vanishing moments for both its analysis and synthesis wavelets. Once again we notice that the higher vanishing order

of $B_{22/14}$ gives a performance improvement of only about 0.1–0.2 dB relative to $B_{9/7}$). Subjectively, the best balanced multiwavelet (SA_4^b) gives results comparable to the best scalar wavelets, $B_{9/7}$ and $B_{22/14}$. So we expect that higher order balanced multiwavelets will outperform their scalar counterparts in image compression applications.

4. For most images the HVS-based scheme improves the perceived image quality for the SA_4^b multiwavelet at low bit rates although the corresponding PSNR values are lower by 0.2–0.8 dB. Furthermore, the SA_4^b multiwavelet decomposition with the HVS model outperforms JPEG2000.

6.2 Directions for Future Research

Our conclusions suggest the following avenues for further research.

1. The design of new balanced multiwavelets with more desirable properties, i.e. shift-invariance, better magnitude response characteristics, higher balancing order, short filter lengths, etc., would be a promising research area for image compression.

2. This thesis studies only the characteristics of multiwavelets. A similar analysis of these filter bank characteristics for multiwavelet packet based compression might offer further insight and performance improvement. It would be interesting to see how the balanced multiwavelets perform in a multiwavelet packet decomposition. Perhaps, highpass branch characteristics (such as group delay) of the multiwavelet would become important determinants of the compression performance.

3. A related research area would include the analysis of biorthogonal multiwavelet filter bank characteristics and their effect on image compression performance (as compared to the orthogonal multiwavelets in this thesis).

4. This thesis evaluated the performance of the HVS-based scheme for grayscale images.

An extension of this analysis for color images would be another interesting direction to pursue.