Evolved Transforms for Improved Reconstruction of Lossy-Compressed NASA Images

Frank W. Moore
University of Alaska Anchorage
3211 Providence Dr.
Anchorage, AK, USA 99508
1-907-786-4819
fwmoore@uaa.alaska.edu

Brendan J. Babb
University of Alaska Anchorage
3211 Providence Dr.
Anchorage, AK, USA 99508
1-907-786-4819
brendanbabb@gmail.com

ABSTRACT
This paper describes a methodology for evolving image reconstruction transforms consisting of an arbitrarily large, user-selected number of wavelet and scaling numbers. Given images previously subjected to lossy compression using NASA's wavelet-based ICER compressor, these novel transforms are capable of reconstructing those images with less error than ICER's own reconstruction scheme. This advance has the potential to enhance the science value of all images subjected to lossy compression.

Categories and Subject Descriptors
I.2.1 [ARTIFICIAL INTELLIGENCE] Applications and Expert Systems, I.4.5 [IMAGE PROCESSING AND COMPUTER VISION] Reconstruction – *transform methods*

General Terms
Performance.

Keywords
Image reconstruction, evolution strategies, wavelets.

1. INTRODUCTION
In 2004, we began a series of research efforts to use various forms of evolutionary computation to evolve wavelet and scaling numbers defining image compression and reconstruction transforms capable of outperforming wavelets for lossy image compression and reconstruction. These efforts were focused upon producing transforms having the same number of wavelet and scaling numbers as a particular wavelet, but different values for each of those numbers. We extended our approach to multiresolution analysis (MRA) transforms [1], evolving different sets of wavelet and scaling numbers at each multiresolution level. Our results successfully improved upon state-of-the-art techniques across a wide range of application areas, including digital photography, fingerprints, satellite imagery, and ultrasound.

GECCO '14, Jul 12-16 2014, Vancouver, BC, Canada
ACM 978-1-4503-2881-4/14/07.

In 2010, we began Alaska NASA EPSCoR-funded research into the task of using the CMA-ES evolution strategy [2] to optimize reconstruction transforms for images transmitted from Mars rover *Spirit* under conditions subject to quantization error [3]. For lossy compression, *Spirit* exclusively used an "integer 2/6" wavelet transform from the ICER compressor [4], which is defined as follows:

LoD = [-1/2, 1/2]
HiD = [-1/8, 1/8, 1, 1, 1/8, -1/8]
LoR = [-1/8, -1/8, 1, -1, 1/8, 1/8]
HiR = [1/2, 1/2]

Here, LoD and HiD represent the scaling and wavelet numbers for the integer 2/6's compression transform, respectively, while LoR and HiR are the corresponding values from the reconstruction transform. ICER uses uniform "dead zone" quantization to achieve much greater compression than lossless techniques; unfortunately, quantization also introduces permanent and irreversible data loss.

The research described in this paper had two primary goals:

1. First, we wanted to evolve a reconstruction transform that could reduce the mean squared error (MSE) in images previously compressed, quantized, encoded, decoded, and dequantized using ICER's integer 2/6 wavelet. This transform could be applied to more than 100,000 lossy-compressed images received from *Spirit*, potentially allowing NASA to improve the science value of these images. Our targeted MSE reduction was 5%.
2. Second, we wanted to evolve a reconstruction transform that could be applied to images subjected to greater compression by ICER software, without incurring additional error in comparison to that achieved by ICER's reconstruction transform. This transform would allow future missions to transmit images at lower bit rates without sacrificing the quality ICER achieved at higher bit rates. Our goal was to achieve the same image quality at 0.96 bits per pixel (bpp) as ICER could achieve at 1.00 bpp.

2. THE KEY BREAKTHROUGH
After months of work, it became clear that our previously successful approach – evolving transforms having the same number of wavelet and scaling numbers as the wavelet transform upon whose performance we were attempting to improve – was simply not producing the stellar results to which we had grown accustomed. We should not have been surprised: ICER's designers had carefully matched compression transform, quantizer, encoder, decoder, dequantizer, and reconstruction

transform and had employed sophisticated progressive compression and error containment techniques to get the best lossy-compressed images possible for transmission over the severely bandwidth-constrained deep space channel.

What ultimately allowed us to achieve (and even exceed) the targeted MSE and BPP reductions was the realization that the size and shape of the reconstruction transform need not be constrained in any way by the size of the corresponding compression transform. For example, instead of evolving an inverse transform with only eight wavelet and scaling numbers (i.e., having the same shape as the integer 2/6 wavelet), we were free to evolve arbitrarily complex transforms having such unusual shapes as 12/12 or 15/15.

3. RESULTS

To establish a baseline, we subjected a representative training set of 150 losslessly transmitted Mars images to a lossy image compression and reconstruction scheme commonly used by MERs: specifically, we applied the five-level MRA compression transform, quantization, encoding, decoding, dequantization, and five-level MRA reconstruction transform software used by ICER at 1.00 bpp, and measured the MSE in reconstructed images (relative to the original training set).

To accomplish goal 1 from above, we evolved several transforms having novel shape, culminating in a five-level 18/18 MRA reconstruction transform. Note that the evolved transform has a different number of scaling and wavelet numbers (i.e., a different shape) than the wavelet for which it has been evolved: in this example, instead of the wavelet inverse transform's 6 scaling numbers and 2 wavelet numbers, the evolved transform has 18 scaling numbers and 18 wavelet numbers (18/18), each of which is a floating-point value. Also note that unlike a wavelet transform, the evolved transform may have different wavelet and scaling numbers at each MRA level (e.g., a five-level 18/18 transform is defined by 180 different floating-point values). The evolved transform was trained on images previously compressed, quantized, encoded, decoded, and dequantized by ICER software at 1.00 bpp. Our best evolved transform was able to reduce the MSE in reconstructed images by an average of 7.76% in comparison to the baseline described above. This patent-pending technology [5] will allow NASA to go back through its entire library of images previously subjected to lossy compression and reconstruct them with less MSE, thus potentially improving the science value of these images.

To accomplish goal 2 from above, we repeated the experiment using ICER's compression transform, quantization, encoding, decoding, and dequantization software, but we subjected the images from the training set to a greater amount of compression; for example, instead of compressing the images at 1.00 bits-per-pixel (bpp), we compressed the images at a 0.936 bpp rate, thus reducing the compressed file sizes by 6.4%. Instead of using ICER's inverse wavelet transform to reconstruct these images, however, we evolved another 18/18 five-level MRA reconstruction transform (with different wavelet and scaling numbers than the transform evolved to accomplish goal 1). This evolved transform was capable of reconstructing images compressed at 0.936 bpp with 99.99% (ever so slightly less) MSE, averaged across the 150 test images, as ICER introduced to images compressed at 1.00 bpp. Our technology [5] will thus allow future missions to send a larger number of images over severely bandwidth-limited deep space communication channels without sacrificing image quality.

The specific results reported above were achieved using 1024x1024-pixel MER images with 4096 possible greyscale values (12 bpp). However, the methodology described in this paper is not limited to images of this size or resolution.

The primary advantage of the approach described in this paper is that it can be used with any existing wavelet-based lossy compression scheme. Signals may be compressed at lower bit rates without reducing the quality of the reconstructed signal, or may be compressed at the same bit rates with less error in the reconstructed signal.

Lossy signal compression is ubiquitous. MP3 audio signals, JPEG 2000 images, FBI fingerprint images, satellite images, medical images, multispectral images, and hyperspectral images are all routinely subjected to lossy compression. By reducing error in reconstructed signals (goal 1), our technology improves the quality of those signals without requiring additional bandwidth; by allowing signals to be compressed at lower bit rates without negatively impacting the quality of the corresponding reconstructed signals (goal 2), our technology significantly reduces signal storage and transmission costs. This technology thus has a diverse range of potential beneficiaries, including hospitals, clinics, and doctors; audio and video retailers; defense organizations and contractors; space organizations and contractors; law enforcement organizations; internet service providers; cell phone data, photos, and video; any organization with a large archive of lossy-compressed images; and any organization seeking to reduce its lossy image storage and transmission costs.

4. ACKNOWLEDGMENTS

The research described in this paper was funded by an Alaska NASA EPSCoR Cooperative Agreement Notice for Research. Additional support was provided by the University of Alaska Anchorage (UAA) INNOVATE program. Technical guidance was provided by scientists at NASA Jet Propulsion Laboratory (JPL). The authors are particularly grateful to Drs. Denise Thorsen (Alaska Space Grant Director), Aaron Kiely, (JPL), Matthew Klimesh (JPL), and Helena Wisniewski (UAA) for their support.

5. REFERENCES

[1] Mallat, S. 1998. *A Wavelet Tour of Signal Processing*, Academic Press.

[2] Hansen, N. 2006. The CMA Evolution Strategy: A Comparing Review. In *Towards a New Evolutionary Computation: Advances in Estimation of Distribution Algorithms*, 75-102, Springer.

[3] Gersho, A. and Gray, R. 1991. *Vector Quantization and Signal Compression*, Springer.

[4] Kiely, A. and Klimesh, M. 2003. The ICER Progressive Wavelet Image Compressor. In *IPN Progress Report 42-155*.

[5] Moore, F. and Babb, B. 2014. Evolved Transform for Processing Data, US Patent Application 61/944241 (pending), Feb. 25, 2014.