The Application of Vector Quantization to Image Compression for Satellite Imaging Systems

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Over the past few years it has become more and more common to use satellites for imaging applications. The imaging may be performed in the visual realm using cameras, or may infrared or electro-optical using multi-sensor arrays. One thing that all these imaging techniques have in common is the large amount of data that must be stored and/or transmitted per image. If many images are being gathered over a relatively short time, then storage and power requirements may become too large for small satellite systems.

Take, for example, a system which might be used to acquire visual images of the earth's surface. A typical system might have 512 pixels horizontally by 512 lines vertically by 8 bits per pixel. If this image were to be stored for later transmission it would require 262,144 bytes of storage. At transmission time 2,097,152 bits of information would have to be transmitted. Color images would contain 8 bits each for red, green, and blue, so these numbers would increase by a factor of three. If these images were to be acquired in real time, say at thirty frames per second, then the transmission rate for monochrome images would be about 63 Mbits per second or 188 Mbits per second for color. Both the storage and transmitter power required are excessive for small satellites.

All satellites, but especially small satellites, are constrained in the amount of onboard storage available and the amount of power available for data transmission. If these images could be compressed by a reasonable amount, in such a way that the resulting images contained essentially the same information as the original, then many more images could be stored for future transmission and the power required to transmit each image could be reduced significantly.

Lossless compression schemes [1] have been used for a number of years for data transmission and storage in the computer industry. An advantage of lossless compression is that after the compressed image has been restored, the new image looks exactly like the original. Disadvantages of these techniques are: first, the amount of compression achieved and the transmission rate are variable, depending on image content, and second, the amount of compression is not very significant for the application of interest. For most images that contain a reasonable amount of information the lossless compression ratios achieved might range from 1.05:1 to 2:1.

By allowing the reconstructed image to be slightly different than the original image it is possible to obtain compression ratios much higher than lossless techniques, on the order of 8:1 to 50:1 and higher. Also, it is easier using these techniques to provide a constant transmission rate. One such technique which has become quite popular is the Discrete Cosine Transform (DCT). [2] It has been successfully utilized in the aerospace industry, where cost is not as significant a factor as in commercial or small satellite applications. The DCT algorithm transforms an image into the spatial frequency domain, finds the spatial frequencies of dominant energy, and reallocates bits to the dominant energy spatial frequencies. The new bit allocations and the code (or side information) on how to unpack the bits are sent to the receiver. The disadvantages of the DCT method are:

1). High complexity and cost for both transmitter and receiver.

2). Susceptibility to noise; for low bit error rates (BER), entire frames may be lost.

The Vector Quantization algorithm, which is presented next, overcomes these deficiencies.

Vector Quantization

Approximately five years ago Dr. R.D. Gray from Stanford revived a mathematical tool known as Vector Quantization (VQ) [3,4,5,6]. This process has been applied in several fields and has proven fruitful in providing significant advances in quantizing many different types of signals. For example, it has been used to allow reasonably high quality speech transmission at only 800 bits per second (bps) while standard pulse code modulated speech requires 64,000 bps.

Recently, the VQ tool has been successfully applied to image compression [7,8]. Dr. R. Baker received his Ph.D. under Dr. R.D. Gray at Stanford University, later coming to Utah where he transferred VQ image compression technology to the state of Utah.

The VQ algorithm divides an image into small segments, each on the order of 4 pixels by 4 pixels. On transmission, a 4 x 4 pixel segment is compared to a prearranged set (called a codebook) of 4 x 4 segments. The address of the prearranged segment that most closely corresponds to the real data is sent to the receiver. At the receiver, which also has a copy of the codebook, the address tells the receiver to display the closest match in the codebook at the appropriate image position. Note that the closest match is not exactly the actual data so that there is some quantization error.

Data compression results because the address, typically 8 bits for a 256 segment codebook, is much less than the 128 bits

(4 pixels x 4 pixels x 8 bits) which comprise the raw data segment. Thus, in this example, there is a compression ratio of 128/8.

A critical factor in VQ transmission is developing an accurate codebook. This is done a priori by choosing statistically representative segments (codebook entries) from a finite set of images, which are representative of the actual data that will be transmitted. Previous research has shown that a well designed codebook is very robust and can be used for a wide variety of image data.

The advantages of the VQ algorithm are:

1) Low cost and minimal complexity for the receiver electronics, requiring only a few PROMS. Therefore, in volume production, the unit receiver cost is potentially very low. The transmitter is less complex than that used with the best DCT implementation. Research using the absolute value (or 'L1') distortion measure indicates high performance, while significantly reducing the required hardware.

2) The VQ algorithm is very insensitive to bit errors. Recent studies indicate that usable images can be received with a BER of only 10^{-3}. A high BER causes loss of only part of the image. Address errors cause only segment errors, not errors over the entire image.

Application of VQ to Satellite Imaging

Based on the fact that both digital storage and power are at a premium on small satellites, image compression would appear to be a fairly valuable technique for imaging systems. If limited power and storage were a factor, then images which had been compressed by a factor of 20 would then require 1/20 the power to transmit or 1/20 the storage required by the original image. If, on the other hand, performance were an issue, it would be possible to acquire and transmit 20 images in the same time as required for one image before compression.

A very flexible system would be one in which the amount of compression could be controlled by an observer on the ground. Very high compression ratios could be used in a monitoring or scanning mode. This would allow large numbers of images to be transmitted to the ground station at a high rate. If one of these images contained information of interest, then the ground observer could command the imaging system to acquire another image of the area of interest at a lower compression rate or at no compression at all. In this manner large areas of the earths surface could be viewed in a scanning mode while still making it possible to acquire high resolution images when needed.

Ongoing VQ Programs at USU

A closely related group of research projects utilizing VQ image compression are presently being carried out in the Electrical Engineering Department at Utah State University.

ComNet Project. Recently, a research project called 'Low Bit Rate Image System' was begun in the Electrical Engineering Department. The project is designed to use IBM/AT based equipment with video cameras, image digitizers, and monitors to demonstrate the VQ process over 9600 bps telephone lines used by ComNet. Funding has been provided by the Electrical Engineering Department at USU, ComNet, and a non-profit educational development company (LEARN, Inc.). This work is well under way and will be documented in the literature over the next several months [9,10].

Image Processing Testbed. A state-of-the-art image processing testbed is being jointly developed by the Electrical Engineering Department at USU, the Center for Space Engineering at USU, and Stewart Radiance Laboratories. The testbed will be used for advanced research in the areas of multi-sensor arrays and image processing. The system will contain hardware for image acquisition and display, external communication channels, and a powerful processing unit utilizing multiple INMOS Transputers [11]. This testbed will allow research into advanced VQ techniques as well as other areas of image processing such as edge enhancement, pattern recognition, image filtering and enhancement, and data fusion. Work done in this area will also be documented in the literature in the near future [12,13].

Real-Time color TV compression. Work is beginning on a system which has been coined 'T1TV', which will make it possible to transmit real-time digitized color television over a T1 line (1.544 Mbits per second). The processor required to perform image compression at this rate must be able to perform over 15.5 billion operations per second. A custom low-power CMOS VLSI chip set is being developed to perform the VQ algorithm in real-time. This same VQ processor can be applied to large multisensor arrays (512 x 512 x 8 bits x 80 frames/second) to cut data rates from 168 Mbits/second to 10 Mbits/second and even lower.

Results from each of these projects may well allow efficient image acquisition for small satellites. A reasonably fast acquisition system could be developed using technology from either the transputer testbed system, or a modified version of the custom real-time processor. Being designed in low-power CMOS circuitry, such a system could provide for relatively rapid image acquisition while still requiring less power than the transmission of uncompressed images.

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