N94-28254

Comparison of the Lossy Image Data Compressions for the MESUR Pathfinder and for the Huygens Titan Probe

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Abstract : The commercial JPEG standard complies well with the specific requirements of exploratory space missions. Therefore, JPEG has been chosen to be the baseline for a series of spaceborne image data compressions (e.g. MARS94-HRSC, -WAOSS, HUYGENS-DISR, MESUR-IMP). One S/W-implementation (IMP) and one H/W-implementation (DISR) of image data compression are presented. Details of the modifications applied to standard JPEG are outlined. Finally a performance comparison of the two implementations is given.

1 Introduction

This paper introduces two lossy image data compressions designed for exploratory space missions. Both compressions represent task oriented modifications of the Joint Photographic Expert Group (JPEG) standard for still image data compression [1]. Accordingly, both are based on Discrete Cosine Transform (DCT).

For the NASA/ESA Cassini/Huygens Descent Imager Spectral Radiometer (DISR)[1] [2] the mission profile required the development of a dedicated compression hardware. Apparently, both the mission profile of the NASA Imager for MESUR Pathfinder (IMP)[2] [3] and the availability of a RISC central board computer supported a completely software oriented implementation. The modifications of the JPEG scheme can be categorized as :

(a) simplifications for H/W savings (DISR)

(b) improved data dropout robustness

(c) adaption of compression algorithms to the actual scene

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2 JPEG baseline scheme

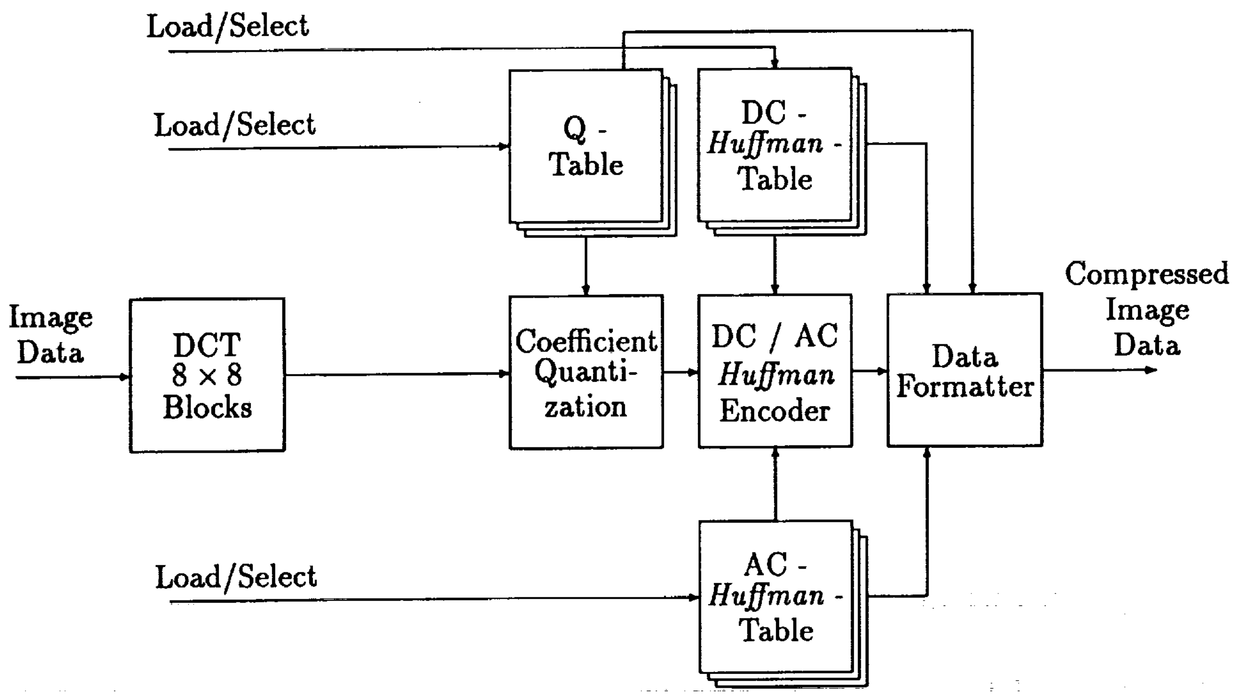

Figure 1: Data/control flow of JPEG sequential DCT baseline scheme

The JPEG standard describes a collection of image compression tools from which a subset can be selected to satisfy application specific requirements. JPEG offers four modes of operation (1) Sequential DCT, (2) Progressive DCT, (3) Sequential lossless and (4) Hierarchical mode. Sequential DCT (1) is well established and is implemented within numerous H/W- and S/W-applications. Therefore, the "baseline system" option of sequential DCT was selected as the compression scheme for IMP and DISR.

The sequential DCT mode consists of a "baseline system" and an "extended baseline system". Contrary to the "extended baseline system" the "baseline system" represents a minimum of coding flexibility, defined by the capability of the decoder. This scheme is splitted into a sequence of DCT-operation, coefficient quantization and *Huffman* coding (see Figure 1). Finally a data formatter organizes the compressed data.

DCT based transform coding is well suited for compression of pixel data with high correlation between adjacent pixels. Application of the DCT to a $N_1 \times N_2$ array of pixel intensity values (image domain) maps these values into a $N_1 \times N_2$ array of coefficients (frequency domain). Because of the DCT energy packing nature most of the image energy now is concentrated into a small number of neighbouring and highly decorrelated coefficients. The residual majority of coefficients represents a small fraction of image energy only.

Moderate savings of computing time (DCT operation) and limitation of error propagation are the rationals for the subdivision of the image array into nonoverlapping blocks each of

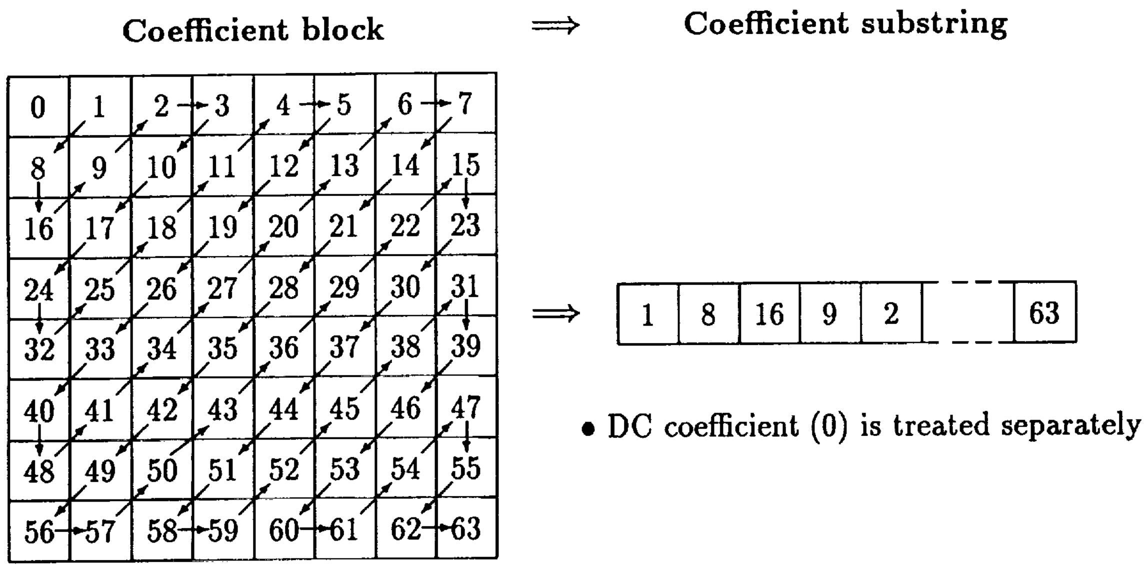

Figure 2: Rearranged coefficient block

size $M \times M$ pixels. However, signal to noise ratio degrades with decreasing block size. $M = 8$ and $M = 16$ provide a reasonable compromise between these contradictory constraints.

In order to increase the coder efficiency the coefficients of the two-dimensional array are rearranged in zigzags to a one-dimensional string representation (Figure 2) [4]. The distance between coefficient locale and the upper left corner reflects the spatial frequency. The coefficient values have the tendency to decrease with increasing spatial frequency. Coefficients with values below a coefficient dependent low bound are set to zero in the case of quantization. Therefore zigzag rearrangement increases the length of "zero" sequences.

Data compression is achieved by

1. coefficient quantization, which reduces the accuracy and therefore the number of bits per coefficient (lossy operation)

2. coding which optimizes (reduces) the average word length of coefficient representation (lossless operation)

The baseline system operation of coefficient quantization is based on the model of an uniform quantizer. It uses an individual quantization step width for each coefficient of the substring and for the DC value.

Quantization values are set individually using performance criteria such as human visibility or any kinds of image signal qualities. They are stored using a zigzag arranged quantization table (Q - Table). JPEG offers the selection of one out of four possible Q-Tables. The selection is fixed for the complete image. Compression amount is user controlled by a factor called *quality level*. Depending on this factor the quantization values of the actual Q-Table are rescaled before the quantization starts.

The baseline system distinguishes the coding of the single DC-coefficient and the $M^2 - 1$ AC-coefficients. While there is only one DC-coefficient for each coefficient block it is sufficient to code the DC magnitude only. Accordingly coding of the AC-coefficients involves both, coding of the coefficient magnitude as well as coding of the coefficient position.

3 Requirements derived from mission profiles

	mission target	experiment operation time	averaged data rate	total amount of data	image rate	implementation
DISR	Titan	$\approx 2.5h$	450 bps	4 Mbit/mission	10/s	H/W
IMP	Mars	30 d - 1 a	600 bps	50 Mbit/d	0.2/min	S/W

Table 1: Mission profiles

The major aspects of the mission profiles are summarized in Table 1. IMP will be launched in 1996 and will land on Mars in 1997. During a 30 days primary and a second operation which is extended to one year IMP will take different kinds of images (single images, panorama) and will monitor the rover operation. Analysis of preceding images will be used to define both the best suited imaging mode and compression mode. Requirements for the IMP image data compression are

(a) a 256×256 image has to be compressed within 5 minutes

(b) automatic operation, but human interaction

(c) self adaption to spatially varying image statistics, target compression factor selectable, image quality adjustable

(d) compliance with RISC board computer capability

Due to the moderate image rate (see (a)) no dedicated H/W is needed. Unfortunately, this comfortable and flexible situation is not applicable to the Huygens Camera.

Cassini with its daughter probe Huygens will be launched in 1997 and will arrive at Saturn moon Titan in 2006. After release by the orbiter the probe will descend through Titan's atmosphere down to its surface within approximately 2.5 hours. Only during this descent DISR will take, preprocess, compress and transfer images. Due to this mission profile the image data compression concept for DISR has to comply the following requirements :

(a) a 256×256 pixel image has to be compressed in less than 0.1 s

(b) completely automatic operation, human interaction via telecommand is impractical because of signal propagation time (70 min. one way, 150 min. operation time)

(c) self adaption to spatially varying image, fixed set of target compression factors

(d) compliance with environmental requirements as board area ($225cm^2$), mass ($210g$), peak power ($0.6W$) and averaged power consumption ($0.4W$ @image frequency = 10 images/s)

Driven by these tough requirements a dedicated hardware solution has been implemented for DISR.

4 IMP image data compression

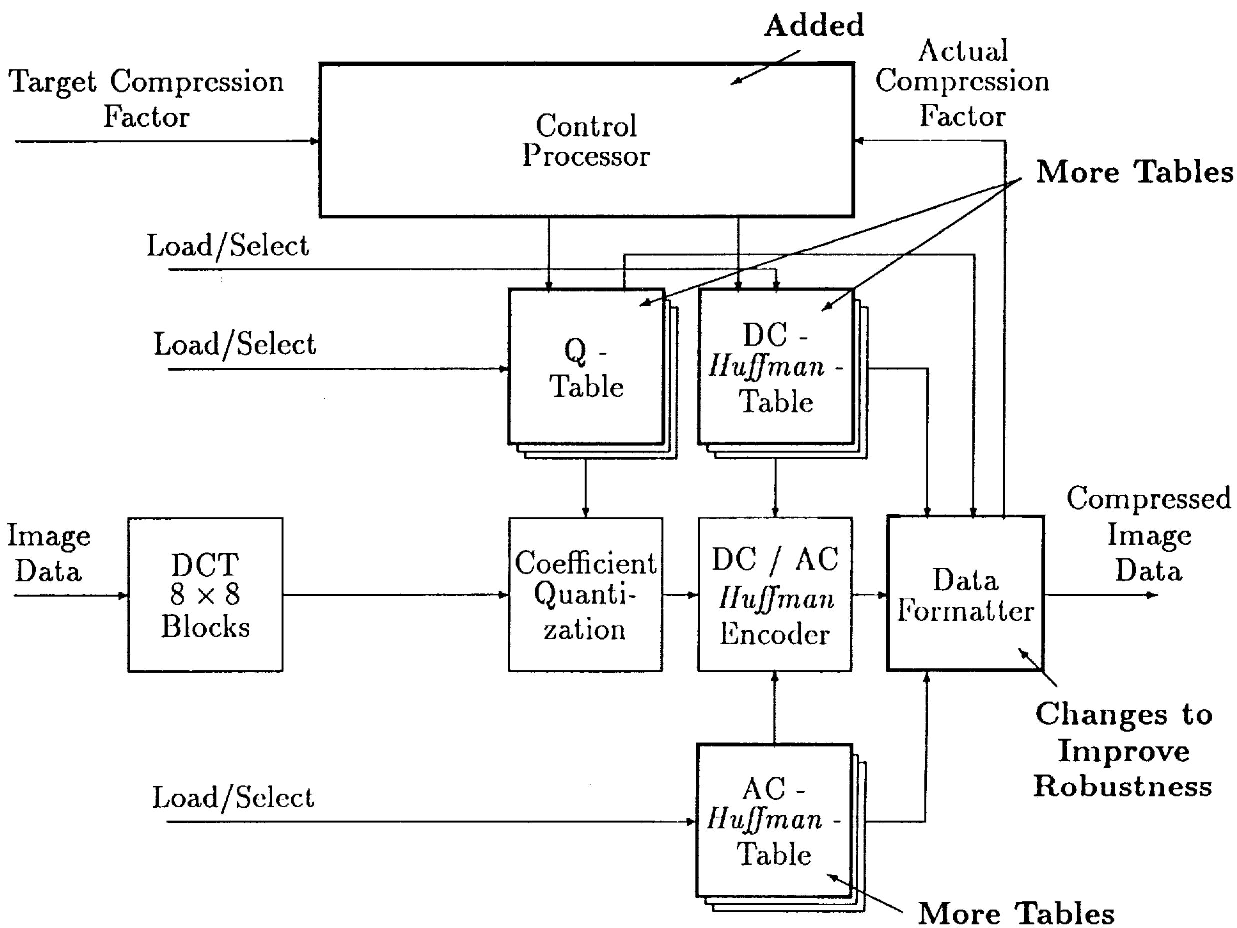

Figure 3: Data/control flow of IMP image data compression scheme

The IMP compression is a pure S/W solution based on the JPEG baseline system. According to mission specific requirements baseline system algorithm has been stripped down to serve only monochrome images. Further all not applicable parameters have been removed from the output data format.

Generally, entropy/redundancy reduction increases the tendency of error propagation in case of telemetry dropouts. To cope with this serious problem the following modifications have been implemented :

(a) **JPEG** : $Q-$ table loadable, table contents are included in each compressed image data set

IMP : 16 loadable $Q-$ tables, selectable by telecommand, multiple table references instead of full table contents are included in each compressed image data set.

(b) **JPEG** : *Huffman* table individually generated for each image is included in each compressed image data set.

IMP : 16 loadable *Huffman* tables, selectable by telecommand or automatically for highest compression ratio. Multiple table referencing as (a)

(c) **IMP** : in order to restrict error propagation to block boundaries a specific image position identifier has been added

Further, an optional feedback path has been implemented for the iterative adjustment of the compression factor to a given target value.

Arithmetic coding as proposed by JPEG improves coding efficiency. Error robustness requires additional synchronization means, which degrades the performance of arithmetic coding. Whether a reasonable balance does exist, shall be investigated by simulations being in progress.

5 DISR image data compressor

As stated before the DISR task is characterized by a rather high image rate of 10 images per second. Phase A/B studies have shown that the handling of this rate requires the design of a specific H/W processor[5]. This design was based on the Thomson DCT Processor STV3200, which provides sufficient radiation hardness.

Again, the processing scheme is rather similar to JPEG. Modifications are mainly directed to hardware savings. The most prominent modifications are :

(a) **JPEG** : 8×8 blocks

DISR : 16×16 blocks, provides a slightly improved compression ratio at the expense of a slightly degraded error robustness

(b) **JPEG** : Individual Q-value for each coefficient of a block

DISR : Coefficient quantization is subdivided into coefficient qualification by threshold (th) and quantization of the remaining coefficients. Coefficients are quantized using one unique (adjustable on image level) Q-value. Deletion map provides efficient coding of deleted coefficients.

(c) **JPEG** : *Huffman* coding

DISR : Run lenght coding

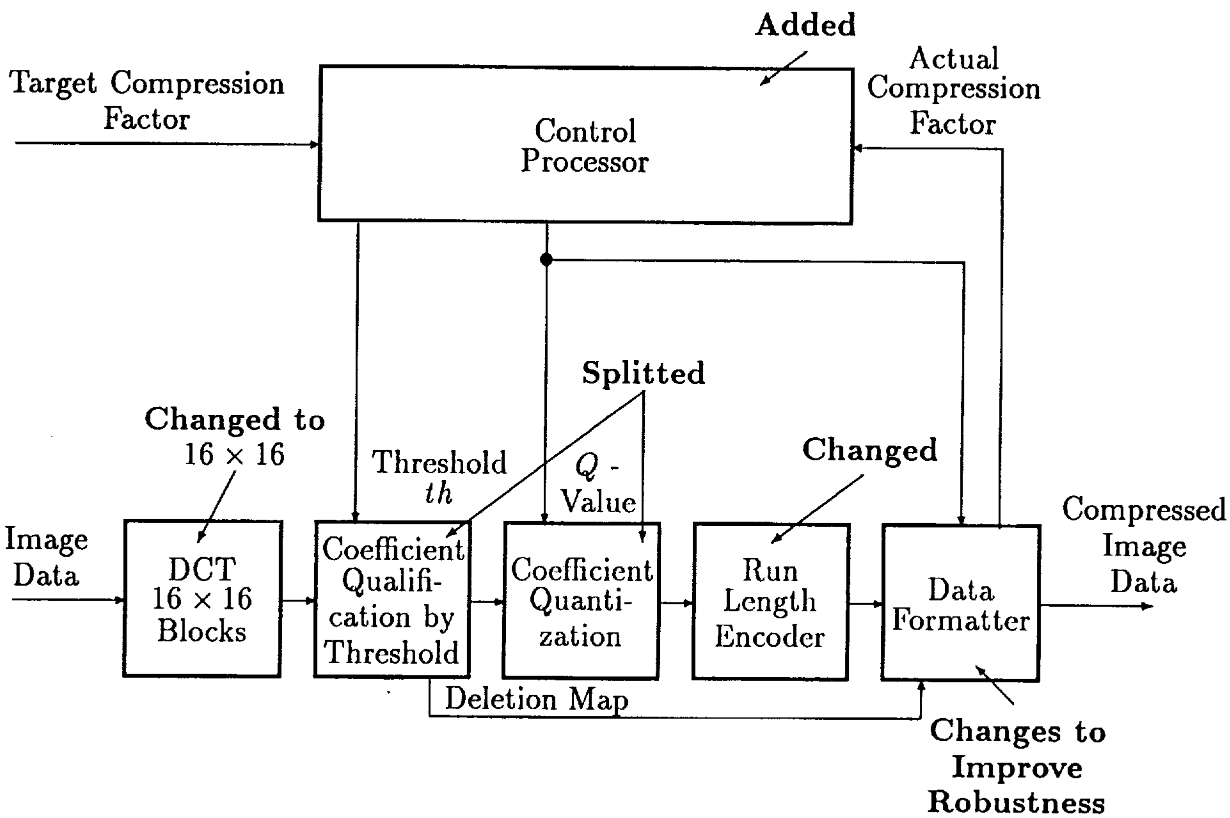

Figure 4: Data/control flow of DISR image data compression scheme

Quantization value Q and threshold th are feedback controlled by the control processor. They are iteratively adjusted until the best approximation of the target compression factor is reached. Iteration time is included in the DISR compression time of less than 0.1 s.

6 Performance

By simulations it has been verified that the IMP S/W implementation delivers JPEG equivalent image quality combined with improved error robustness. Figure 5 shows the signal to noise ratio

$$SNR\,[dB] = 10 \log \frac{\sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} f_o(n_1,n_2)^2}{\sum_{n_1}^{N_1-1} \sum_{n_2}^{N_2-1} (f_o(n_1,n_2) - f_r(n_1,n_2))^2}$$

f_o : pixel intensity of original image

f_r : pixel intensity of reconstructed image

versus the compression factor c for the well known "Lena" image and a mars surface image which was derived from a viking mission. The DISR H/W implementation shows slightly

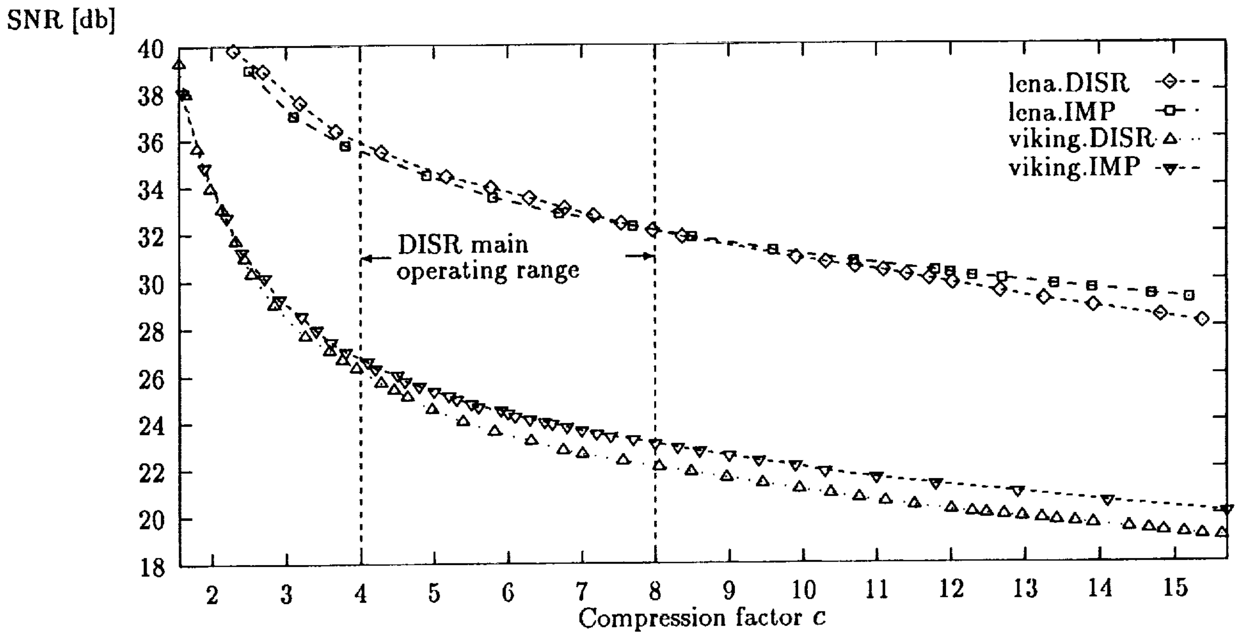

Figure 5: Comparison of IMP and DISR $SNR[dB]$ performance versus c

degraded image quality, but increased error robustness, too. For a compression factor greater than 4 the compression quality expressed by $SNR[dB]$ versus c is degraded to less than 1 dB. But a visual comparison of the decompressed images shows more visible blocking effects. This is caused by suboptimal coefficient quantization and suboptimal redundancy reduction. Still, these slight performance degradations have to be balanced against the substantial higher compression speed.

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