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Hardware Architecture for Lossless Image Compression Based on Context-based Modeling and Arithmetic Coding

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ABSTRACT

In this paper we present a novel hardware architecture for context-based statistical lossless image compression, as part of a dynamically reconfigurable architecture for universal lossless compression. A gradient-adjusted prediction and context modeling algorithm is adapted to a pipelined scheme for low complexity and high throughput. Our proposed system improves image compression ratio while keeping low hardware complexity. This system is designed for a Xilinx Virtex4 FPGA core and optimized to achieve a 123 MHz clock frequency for real-time processing.

I. INTRODUCTION

Lossless compression has been successfully used in reducing the bandwidth of communication networks and the storage requirement of digital data. Moreover, lossless image compression is increasingly significant since it is required by many upcoming applications, such as Tele-medicine, space related research, professional visual data studios [1], and next-generation lithography systems [2]. A lot of effort has been made to improve the compression methods both in software [3], [4], and hardware [5], [6]. While software implementation can often yield reasonably good compression ratios at the price of low speed, hardware implementation often suffers from unsatisfactory compression ratios. Furthermore,

hardware compressions of general and visual data are usually handled separately. This is not a very efficient approach due to the current trend of network convergence where visual and general data are transmitted along the same physical channel. This fact suggests a technology capable of fast adaptation to the nature of the data and delivering optimal compression ratios.

Given the above requirements, we propose an original reconfigurable FPGA architecture, shown in Fig. 1, to handle general and visual data using context-based modeling and arithmetic coding. We aim at producing an efficient combination of compression schemes for different data types with the final objective of achieving high compression ratio, high throughput and low complexity.

As part of this project, this paper focuses on a novel architecture for lossless gray-scale image compression, which uses context-based modeling, probability estimation and arithmetic coding.

II. LOSSLESS IMAGE MODELING ALGORITHM

The characteristics of images: large alphabet size, two dimensions and big size potentially imply high statistical model complexity and large memory usage. State-of-the-art compression schemes, e.g. CALIC [3], use complex edge detection technique and arithmetic coder to obtain optimal compression ratios. From the view of hardware implementation, however, a higher priority should be given to

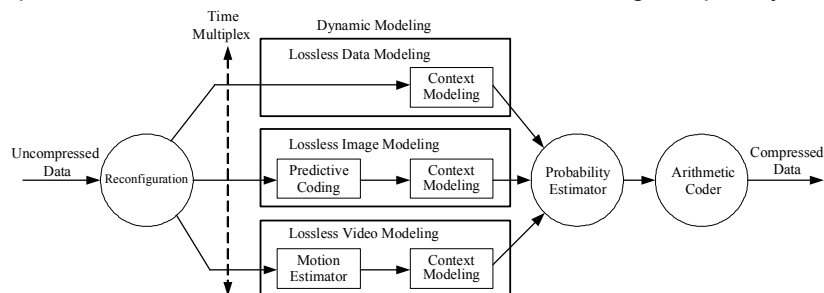


Figure 1: Architecture for the Universal Lossless Compression System.

controlling model complexity, which means that memory usage should be minimized and complex operations such as multiplication and division should be avoided if possible. Following these guidelines, we use a simple edge-detecting predictor and a binary arithmetic coder to obtain good compression ratio and hardware amenability.

Image modeling is divided into two phases: prediction and context modeling. In this work, the predictor is inspired by the GAP (Gradient-Adjusted Prediction) from CALIC, a software-based algorithm. However, our method is simplified as fewer contexts (512 vs. 576 in CALIC), and hence less memory, are used. It combines with the probability estimator and binary arithmetic coder to contribute in a new low-complexity scheme.

Fig. 2 shows the denotation of 7 neighboring symbols of the current symbol X , according to their geographical locations. They constitute the context of the current symbol X . In the prediction phase, we estimate the local edge feature by calculating the vertical and horizontal gradients intensity dv , dh , using the differences between context symbols vertically and horizontally. The predicted symbol value \hat{X} is a linear combination of its contexts, according to the gradient direction and magnitude. The predictor is designed to be suitable for hardware, involving only addition/subtraction and shifting. Thus we obtain the prediction error e , which is the difference between the original and the predicted symbol value. The prediction error e is also remapped from the range -2^{n-1} to 2^{n-1} , to the range 0 to 2^{n-1} to reduce the alphabet size.

In the context modeling phase, context selection is essential to reduce memory usage. We use 6 context symbols to compare with the predicted value \hat{X} to obtain a texture pattern t , representing the local texture feature. Also, to indicate the activity of errors in a context, a coding context is generated with the local gradients dv , dh and an previous prediction error e of W . The coding context is quantized into 8 levels to form a coding context index QE . Combining the texture pattern and coding context, a set of 512 compound contexts are formed by 6 bits texture pattern t and

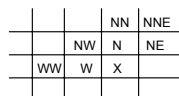


Figure 2: Neighbouring Pixels in Prediction and Modeling

3 bits coding context index QE . These contexts are used to generate an error feedback to adjust the bias of prediction, which will be discussed in the next section. The 8 coding contexts are also used to encode symbols in the probability estimator presented in Section IV.

III. LOSSLESS IMAGE MODELING ARCHITECTURE

We present our new hardware architecture of the image modeling module in Fig. 3, where the prediction part is illustrated in the solid-line box and the context modeling part is the rest.

Implementation of the modeling can be done in two pipelines running in parallel.

- Line 1: a) Calculate prediction error $e = X - \tilde{X}$, where \tilde{X} is the adjusted predicted value;
 b) Update sum and number of prediction errors in each compound context;
 c) Map prediction error e to \tilde{e} ;
 d) Update coding context index QE ;
 Line 2: a) Update context with new symbol;
 b) Calculate gradients dv , dh ;
 c) Calculate primary prediction value \hat{X} and quantized coding context QE ;
 d) Calculate texture pattern and update context index;
 e) Calculate the mean of errors \bar{e} in context for error feedback, and obtain an adjusted predicted value $\tilde{X} = \hat{X} + \bar{e}$.

Line 1, indicated by solid line in Fig.3, operates on the current symbol and yields the prediction error \tilde{e} and coding context index QE for the probability estimator. Line 2, indicated by dash line, calculates the prediction value and context index

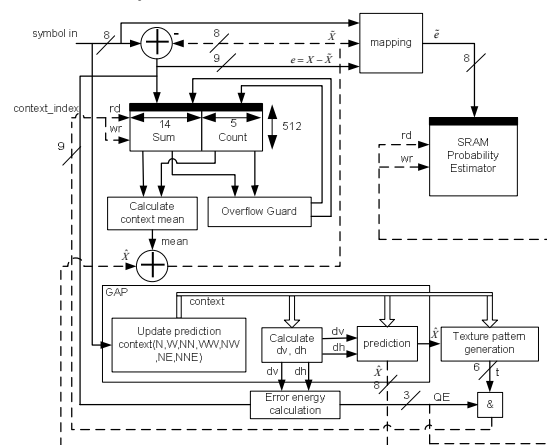


Figure 3: Architecture of Image Modeling Module

for next symbol. So the Line 1 operation for the next symbol can utilize the result of Line 2 from current symbol when the two lines work in parallel. Consequently, pipelining can be achieved by breaking the operation into small pieces and executing them simultaneously, resulting in a reduction of clock period. Managing the context memory and the error feedback technique, which calculates the mean of errors in a context, are the most difficult parts. The details are given below.

In the compression process, we need to store 3 lines of image pixel values in memory as context and use 3 pointers to indicate symbol locations in each line. At the end of processing each line, the 3 pointers to each line have to be rotated in a certain order so that the oldest line will be discarded and the newly formed line will be saved.

An error feedback technique is used in the prediction schemes to adjust the prediction in a certain context, because the mean of errors \bar{e} is the most probable prediction error in each context. This error feedback can help with reducing the bias of the primary prediction. The mean of errors \bar{e} in a context is simply given by

$$\bar{e} = \text{sum} / \text{count} \quad (1)$$

where *sum* and *count* are the sum and occurrence of errors in the context, respectively. In order to calculate the mean, *sum* and *count* in each context are stored in memory, as shown in Fig. 3. For memory efficiency, we only use 5 bits to store the error occurrence. When the *count* reaches its maximal value 31, it is halved by right-shifting one bit; meanwhile *sum* is halved so as to maintain the mean \bar{e} . Thus we only need 13 bits ($2^5 \times 2^8 = 2^{13}$) plus one sign bit to store the sum of errors safely. This rescaling function is completed by the block of *Overflow Guard*. Experimental results prove that this rescaling technique slightly improves the compression ratio by “aging” the observed data. However, division is always a difficult problem in hardware, especially when the dividend can be as large as 13 bits. To make this division practical, we bound the dividend *sum* by 10 bits for two reasons: firstly experiments on our image test set show that the chance of the sum being larger than 1023 is less than 0.001%; secondly, extraordinary large errors tend not to reflect the true behavior of the context because prediction errors should be moderately small given an adequate predictor. We

use the most significant bits of the divisor *count* in the division, with the dividend being rescaled accordingly to maintain the same result. Consequently, we only need a lookup table of 1KByte ($2 \times 512 = 1024$) to complete fast division. Although the result of division is only an approximation, it does not affect the compression performance in our experiments.

The outputs of the modeling module are the mapped error \tilde{e} and the coding context index *QE* which are sent to the probability estimator.

IV. PROBABILITY ESTIMATOR AND BINARY ARITHMETIC CODER

The probability estimator adaptively calculates the probability of symbol occurrence in each context in a SRAM. It enables the application of a simple and fast binary arithmetic coder and the decomposition of the coding procedure into bit level operations, and hence full pipelining and high throughput.

Each context is represented by a balanced binary tree with 2^n (n is the bits per pixel) nodes associated with each symbol in the alphabet. A number of bits are used to store the symbol frequency count in each node. Initially, all the symbols in the alphabet are assigned an equal probability, e.g. $1/256$ in an alphabet of 256 symbols. When one symbol is received, the value of the corresponding tree node increases to reflect the probability distribution of symbol occurrence. There are 8 coding contexts for image compression, corresponding to 8 “dynamic” trees and one “static” tree for coding the *escape* symbols. *Escape* happens when a valid probability of a symbol cannot be found, e.g. when its probability is 0, in which case the symbol is “escaped” to the “static” tree and is sent as it is. *Escape* is undesirable as it does not achieve any compression. It takes place when some symbol counts reach the maximal frequency count, e.g. 14 bits for ($2^{14} - 1$), in which case all the symbol counts in the tree will be halved. Consequently, the counts of symbols that have not been seen before will be rescaled from 1 to 0, resulting in *escape* when those symbols occur later for the first time. Therefore, the frequency count bits have to be carefully chosen. Experimental results of average compression bit rates under different frequency count bits are shown in Fig. 4. Note that when too

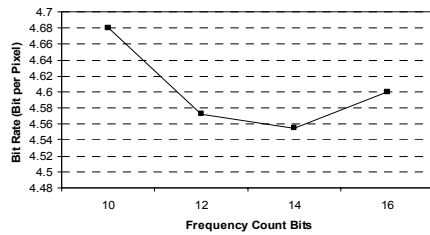


Figure 4: Average Bit Rates under Different Probability Precision

few bits are used, more *escapes* happen; when too many bits are used, fewer *escapes* happen but the probability distribution is so skewed that more bits are needed to encode the symbols with small probability. Therefore we choose 14 bits for the symbol counts.

As tree node value increment works from the root down to the leaves through the tree, a symbol can be fully encoded by the binary decision (left or right) taking place in each level of the tree.

The binary arithmetic coder is driven by the binary decision bits and the probability data from probability estimator. More details regarding the arithmetic coder can be found in [7].

V. IMPLEMENTATION AND PERFORMANCE COMPARISON

In this section we present the experiment results of the proposed lossless image compressor. We compared the performance of different image compressors in Table. 1, using a set of grey-scale test images of size 512*512 pixels. JPEG-LS (LOCO-I) [4] and SLP (Switched Linear Prediction) are low complexity compression schemes using Golomb-Rice coder. Clearly, the proposed scheme outperforms JPEG-LS and SLP in terms of compression ratio with comparable low complexity, though yields slightly bigger compression ratio compared to software CALIC since fewer contexts and simpler hardware-amenable modeling techniques are used in our system.

Table 2 is the device utilization summary of the hardware implementation on a Xilinx Virtex4 FPGA

Table 1. Bit Rates Comparison of a few Selected Schemes

Image	JPEG-LS	SLP(M0)	CALIC	proposed
barb	4.86	4.79	4.59	4.68
boat	4.25	4.28	4.12	4.18
goldhill	4.71	4.74	4.61	4.65
lena	4.24	4.17	4.09	4.14
mandrill	6.04	5.99	5.9	5.93
peppers	4.49	4.49	4.35	4.39
zelda	4.01	3.97	3.84	3.90
average	4.66	4.63	4.50	4.55

Table 2: Device Utilization Summary

	Modelling	Probability Estimator	Arithmetic Coder
No. of Slices	508	297	1123
No. of Slice Flip-flop	224	124	283
No. of 4 input LUT	912	561	2131
No. of bonded IOBs	31	60	53
No. of GCLK	1	1	1

chip. Memory usage for modeling is 3.7KBytes, for probability estimator is 4KBytes. The design was synthesized and optimized using Xilinx ISE 8.1 and achieved a clock frequency of 123 MHz, and a throughput of 123Mbits/sec. The low complexity means that a multi-core solution could be used to scale up the performance.

VI. CONCLUSIONS

A novel hardware architecture for context-based lossless image compression is proposed in this paper. As a result, lossless compression is achieved efficiently with low complexity hardware design. Our experiments show improvement in terms of compression ratio when comparing to other low complexity schemes. The combination of different modeling modules optimized for various data types, has the potential of achieving a high efficient universal lossless compressor.

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