Smart Pixel Implementation of a 2-D Parallel Nucleic Wavelet Transform for Mobile Multimedia Communications

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Abstract

A novel Smart Pixel Opto-VLSI architecture to implement a complete 2-D wavelet transform of real-time captured images is presented. The Smart Pixel architecture enables the realisation of a highly parallel, compact, low power device capable of real-time capture, compression, decompression and display of images suitable for Mobile Multimedia Communication applications.

1. Introduction

The development of the next generation of personal communication systems (PCS) demands highly compact low power devices capable of image capture and display as well as very low bit rate coding and transmission [1, 2]. Smart Pixel (SP) arrays are uniquely able to fulfil all of these requirements. An architecture to implement a 2-D wavelet transform (WT) algorithm on an array of SPs is presented. The SP array is used to carry out complete forward and inverse WTs in real-time on images captured in-situ within the array. Coupled with a low bit rate codec, such as Shapiro's embedded zerotree wavelet (EZW) coding scheme [3, 4, 5], the SP array is capable of performing image capture and compression whilst decompressing and displaying images transmitted from a remote location, all in real-time. A basis for the future Smart Pixel Mobile Multimedia Communicator (SPM^{3}C) can, thus, be established through the use of the Opto-VLSI architecture proposed.

Most WT algorithms use complex orthogonal filters like Daubechies' as these have been proven to have the best spatial-frequency localisation properties [6, 7]. A simpler filter pair derived from a triangular wavelet is proposed as a better choice for application in M^{3}C systems. The space limitations on a single substrate in general mean that the more complex filters can not be well represented. In contrast, the triangular filters, due to their simplicity, are well suited to compact high-speed SP implementation. In addition, given a limited dynamic range for calculations within the array, the triangular filters have been shown to produce better results than the more commonly used filters like Daubechies' [2, 8].

2. Nucleic Wavelet Transform

Within the SP array, all of the pixels are connected via lateral nearest neighbour connections creating a mesh structure of processing elements. Such a mesh structure is well suited to the implementation of a highly parallel, 'nucleic' WT scheme. The term 'nucleic' refers to the way in which pixels are organised to facilitate the computation of complete WTs over multiple resolution scales. During a complete WT a large number of coefficients are obtained in different frequency sub-bands and at different scales [9]. For optimum efficiency all of the coefficients should be stored on the array throughout the computation of the WT so that no time is wasted transporting them elsewhere. The nucleic scheme organises the coefficients during the WT such that they can all be positioned within the array, while maintaining an optimum efficiency for the transform at every scale.

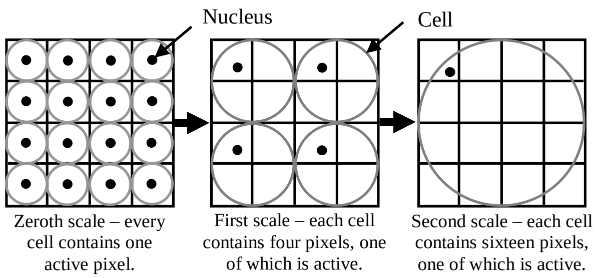

Figure 1. Wavelet image decomposition over two scales in the nucleic scheme.

Figure 1 demonstrates the nucleic arrangement for wavelet decomposition on a generic 4x4 array. Initially all of the elements in the array contain 'nuclei' i.e. they are all active. At each subsequent scale of the decomposition, however, the number of active elements reduces by a factor of four. The remaining active elements can then be amalgamated with the inactive elements surrounding them to form larger 'cells', each cell containing only one nucleus (active element).

The nucleic scheme can easily be applied to a SP implementation. Figure 2 illustrates how the transform coefficients are arranged in the SP array over the first and second scales of a decomposition of an NxN image. After the first scale of decomposition in the forward WT coefficients from four frequency sub-bands are obtained (LL, LH, HL, HH). These sub-bands are arranged into 'cells', each cell containing one coefficient from all four of the sub-bands. Sub-sampling is achieved at the same time, whereby every other pixel value is discarded prior to the next scale of the decomposition. At each subsequent scale of the decomposition, only the coefficients from the lowest sub-bands (LL) are operated upon. The pixels storing these low-low filtered coefficients are, thus, the nuclei for the next scale. All pixels storing coefficients from the higher sub-bands (LH, HL, HH) are switched into a transparent mode allowing data to pass through them freely. As the decomposition progresses the cells become larger, containing more transparent pixels holding the high frequency sub-band coefficients from the previous scale. Each cell always retains one active pixel, the nucleus, in the top left corner, which contains the low frequency sub-band coefficient from the current scale ready for decomposition at the next scale.

The inverse transform can also be easily performed using the nucleic scheme. The only differences in the computation of the inverse WT compared to the forward are that the inverse filter coefficients are used and the filtered sub-bands are summed to obtain the reconstructed coefficients. The arrangement of the coefficients on the array during the inverse transform is the opposite of that illustrated in Figure 2. Initially the cells are large and the majority of the array is transparent, as the reconstruction progresses more pixels are activated and the cells become smaller until finally the whole array is active and contains the completely reconstructed image.

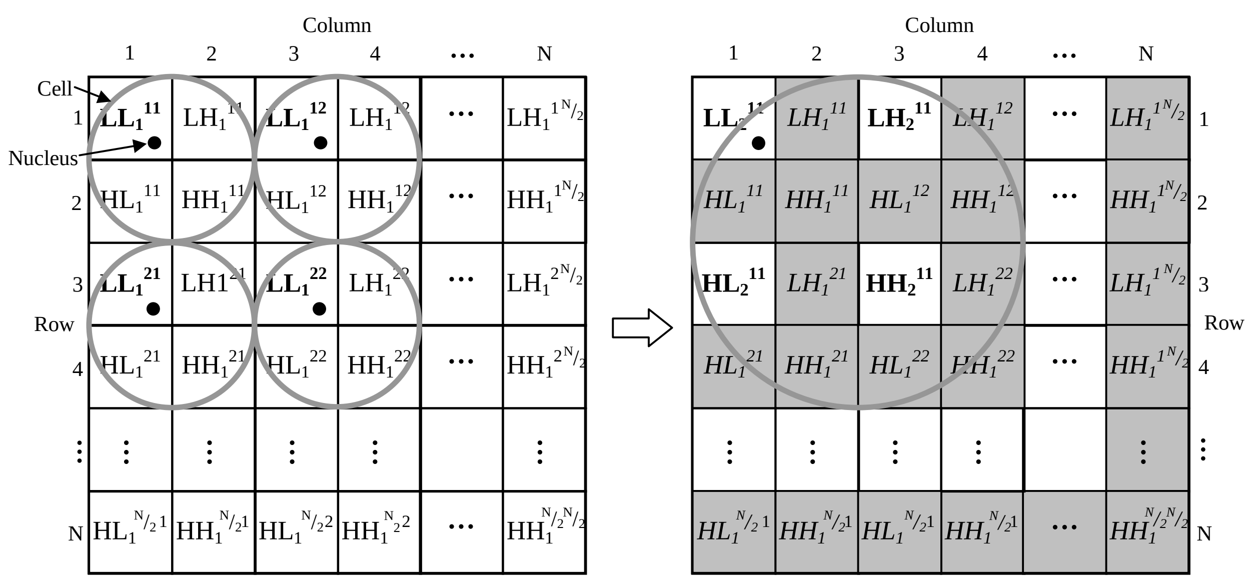

Figure 2. Decomposition of an NxN image in the nucleic scheme. LL_s^{xy} **represents a low-low filtered coefficient obtained at scale** s **of the decomposition in cell** x,y**. Grey pixels are transparent.**

Using the nucleic organisation on the SP array allows a complete multi-scale WT to be computed very efficiently. Assuming there is a negligible delay in shifting data through the transparent pixels then the transform algorithm can work with equal effectiveness at any scale. The time complexity of a 2-D WT, using filters of length L, on the SP array is O(L) independent of the image size. Thus, the time complexity of a complete K scale decomposition is merely O(KL).

3. Smart Pixel Architecture

A complete two-dimensional WT is usually calculated by sequential convolution of the rows and columns of the image with a pair of suitably chosen quadrature mirror filters (QMFs) followed by half rate subsampling at each scale. In most VLSI implementations FIR filters are used for these convolutions [10]. The filter coefficients derived from the triangular wavelet basis allow significantly simpler filter implementation. The transform coefficient, Y_i, is the convolution of the pixel input value, X_i, with the coefficient, W_s, of an FIR filter of length L:

$$Y_i = \sum_{s=1}^{L} X_{i-s} W_s \qquad (1)$$

If a symmetric kernel of length 2P is used to form the filter, however, then by using the property $W_s = W_{-s}$ the convolution in equation (1) can be rewritten as:

$$Y_i = \sum_{s=1}^{P} X_{i+s} W_s + \sum_{s=1}^{P} X_{i-s} W_s + X_0 W_0 \qquad (2)$$

A bidirectional scheme can thus be employed, which avoids the inherent border problem of linear convolutions [11]. The complete convolution is obtained through scaling the pixel inputs by each of the FIR filter coefficients in turn and then accumulating the sum of these products in a storage register in each pixel. Due to the space limitations within the SPs, however, this scaling is not easily achieved for complex real valued filters. The simple 3-tap triangular filters are, therefore, proposed as a suitable alternative. The coefficients of the triangle filters are either 0, ±0.5 or ±1. The scaling can thus be realised by 1-bit intra-register right shifts and no filter coefficients need to be stored within the array. Convolutions with the 3-tap triangular filters can be implemented within the SPs using three shift registers and a full adder. Figure 3 illustrates the SP's functionality and interconnections for implementation of the WT using triangular filters.

The use of a bidirectional scheme with the symmetric 3-tap filters allows the complete 1-D transformation to be obtained for one plane of the image after a single cycle. The 2-D transform is computed simply by repeating the convolutions in the perpendicular direction. Depending on whether the low pass or high pass filters are used for the convolutions the output transform coefficients, Y_i, are referred to as L or H respectively, or LL, LH, HL and HH in the 2-D case as in Figure 2. Functional simulations for both still and moving images have been performed which demonstrated a satisfactory quality of compression and reconstruction using this scheme [2].

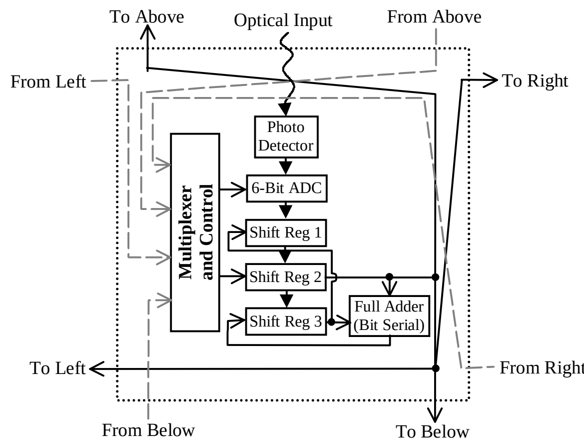

Figure 3. Logical Architecture for computation of the WT within the Smart Pixel.

4. Smart Pixel Layout

The design of an M^3C system calls for an architecture capable of image capture, processing and display on a single pixel array. Every processing element in this array must, therefore, be capable of carrying out the following functions:

- Detection and conversion of the incident light level to a suitable input value.
- Local processing to implement the forward and inverse wavelet transform algorithms.
- Optical modulation of reconstructed output values to a suitable grey level.

Figure 4 illustrates the layout of the circuitry in the SP to realise this functionality. The optical detection required for image capture is carried out in-situ by the photodetector (PD). The ADC converts the input into a digital value for use by the rest of the processing circuitry. The shift registers and adder are used to carry out the wavelet transform as outlined above.

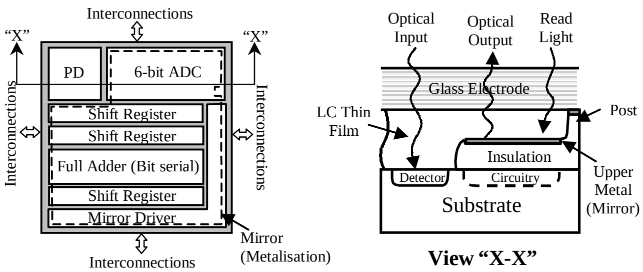

Figure 4. Schematic of the Smart Pixel.

For the display a thin film of ferroelectric liquid crystal (FLC) is placed between the backplane and a front glass electrode. A metal mirror is built on the top metalisation level of the backplane, covering the circuitry. The addition of polarisers then allows amplitude light modulation by the FLC [12]. Grey levels are obtained by temporal or space-division multiplexing of the mirror.

5. Time Complexity Analysis

The SP architecture presented in this paper is capable of performing both the forward and inverse WTs using a highly efficient parallel implementation. The images are captured in situ on the array, thus, no communication cost is incurred moving data to the SPs prior to the transformation. The time complexity for computing a complete, K scale WT using FIR filters of length L on the parallel SP array is, therefore, O(KL). This is in contrast to the time complexity of $O(KN^2L^2)$ incurred when a normal pipeline architecture is used to implement a K scale WT on an NxN image.

Using the parallel nucleic scheme a complete set of convolutions for one dimension of the WT can be computed with six intra-pixel parallel loads, two inter-pixel 6-bit copies, two 1-bit intra-register right shifts and two 6-bit serial additions. This requires approximately 32 cycles, thus a complete 2-D, 3-scale wavelet transformation can be computed in under 200 cycles. A complete 3-scale forward or inverse WT can thus be completed in less than 2μs using a CMOS technology with a 10ns clock. This is more than sufficient for the real-time capture, compression, decompression and display required for multimedia communications.

Figure 5 illustrates how the order of complexity, in terms of the number of multiplication and addition operations, varies with the size of an NxN image for a complete 3 scale WT using length 3 filters. The complexities of both the parallel nucleic and the pipeline architectures are plotted on a log scale for comparison.

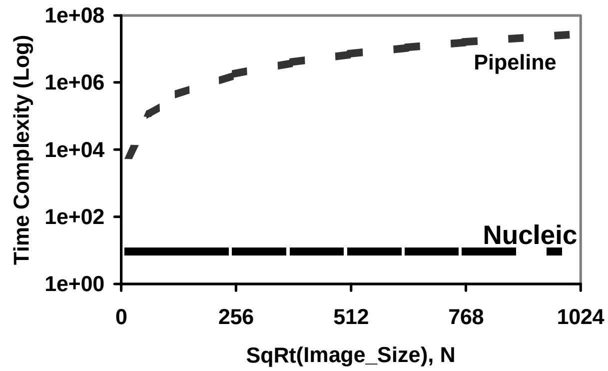

Figure 5. Graph comparing the time complexity of the nucleic WT scheme to that of a pipeline WT scheme.

6. Conclusions

An architecture capable of exploiting the highly parallel processing capability of a SP array to realise a real-time implementation of the forward and inverse WT has been demonstrated. The proposed SP architecture enables embedded, simultaneous image capture and display on a single substrate. Rapid multi-scale WTs can, therefore, be performed in both the forward and reverse directions in turn, achieving a unique design capable of both image capture and decomposition, as well as reconstruction and display on a single SP array. The Opto-VLSI architecture presented thus establishes the basis for the future Smart Pixel Mobile Multimedia Communicator (SPM^3C).

7. Acknowledgements

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