A NOVEL WAVELET MEASUREMENT SCHEME BASED ON OVERSAMPLING

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Abstract: In this paper, a novel wavelet image measurement scheme is developed inspired by the Haar wavelet oversampling. It is equivalent to the dyadic Haar wavelet decomposition, but has a simpler hardware implementation architecture. It contains three basis patterns and one fixed selection template, which enables parallel computations. The measurement scheme is verified by simulation results and a hardware implementation is proposed. This measurement scheme records the difference of neighboring pixels, which is independent of illumination conditions.

1 INTRODUCTION

Starting with Haar's work (Haar, 1910) at early 20th century, wavelet becomes a more and more popular tool in signal processing. Its ability to localize both time and frequency and provide multi-resolution representation of image enables its wide applications in many fields of signal and image analysis, such as speech recognition, image compression, image segmentation, image denoising/enhancing, and etc. Most of the researches focus on the software-based wavelet transform (Antonini et al., 1992) (Lewis and Knowles, 1992) (Porwik and Lisowska, 2004) (Raviraj and Sanavullah, 2007), though the transform requires extensive computational resources for the real-time implementation. Later a number of techniques for realizing the wavelet transform in hardware systems are developed. The use of Digital Signal Processors (DSPs) provides a quick and flexible way to compute the wavelet transform (Haapala et al., 2000). However, it requires significant area and power resources. Besides, an analog-to-digital converter to quantize the analog input is required for such digital processors.

In recent years, some researchers try to integrate the wavelet transform in image sensors, where the transform is implemented in the analog domain directly on the focal plane (Luo and Harris, 2002) (Mosqueron et al., 2006) (Shoushun et al., 2006). Analog circuits perform area-efficient and low-power computation directly on the focal plane, eliminating the need for an external processor (Olyaei and Genov, 2007). The wavelet embedded image sensor combines image acquisition, signal processing and quantization in a compact architecture, yielding high computational throughput. Their performance is often beyond that of modern digital processors, allowing to perform complex image processing operations in real time. Those wavelet sensors are mostly developed based on the Haar wavelet transform, because Haar wavelet transform requires only shift and addition operations, which are suitable for the hardware implementation.

The fixed circuit design of the standard wavelet transform has limited scalability due to the prior determined level of the wavelet decomposition. High decomposition levels are usually too complicated to be realized in the digital circuit design. In this paper, we propose a novel wavelet image measurement scheme developed based on the Haar wavelet oversampling. It is equivalent to the dyadic Haar wavelet decomposition, but has a simpler structure for the hardware implementation. This measurement scheme records the difference of neighboring pixels, which is independent of illumination conditions. It truly captures the ratio between the various features of an object. Besides, the difference is generally much smaller than the absolute pixel value, hence less bits are required after quantization, reducing the throughout significantly. Furthermore, the parallelism of imaging architecture guarantees the real-time processing property.

The organization of this paper is as follows. Combined with the conventional 1D Haar wavelet trans-

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formation, the concept of oversampling is introduced in Section 2. In 2D space, the dyadic Haar wavelet transform is introduced. Based on this transform, we propose a novel image measurement scheme, whose results can be transformed to dyadic Haar wavelet coefficients easily. This equivalence is verified both by the mathematical proof and simulation results. In Section 4, the simulation results are presented and a schematic hardware implementation is proposed. Finally, a conclusion is drawn based on the discussion above.

2 WAVELET MEASUREMENT IN 1D SPACE

Wavelet transform converts a 1D-signal into a series of wavelet coefficients using basis functions that are bounded in frequency as well as in space domains. There exists a variety of wavelet transforms, which range from the oldest Haar wavelet, the general Daubechies wavelets to the more complicated biorthogonal wavelets. Among all the wavelet transforms, the discrete wavelet transform using Haar wavelet functions is one of the most promising technique in image coding and sensor design due to its simplicity and small computation costs.

However, the classical Haar wavelet transform has several limitations, for instance, the lack of translational shift invariance. If the input data is updated with new samples, the majority of the coefficients changes and needs to be recalculated. Aiming at the incremental update, Z. Struzik proposes an extended formulation of the Haar wavelet decomposition (Struzik, 2001). It oversamples the decomposition by calculating coefficients on a shift invariant grid. Oversampling on the position axis can be done to the highest resolution required or any required lower resolution. Fig. 1 shows an oversampled grid for an 8-point signal, in which the highest available resolution is used. In the figure, MA denotes the the moving average filtering operation and DMA denotes the convolution of the derivative operator and the moving average filter. The oversampling scheme provides a representation with shift invariant coefficients and incremental update on new samples. It also provides a possibility to extend the Haar representation over higher order (Struzik, 2001).

Inspired by this oversampling scheme, we develop a new measurement scheme. It eliminates the redundancy in the oversampled representation, while still records all the information needed for restoring the Haar wavelet coefficients as well as the oversampled representation. Fig. 2 shows the measurement scheme with a 1D sensor array. This measurement scheme is suitable for hardware implementation and records the difference of adjacent input signals. Obviously, the Haar wavelet coefficients can be obtained by a simple recursive calculation. In this sense, this measurement is equivalent to the Haar wavelet coefficients.

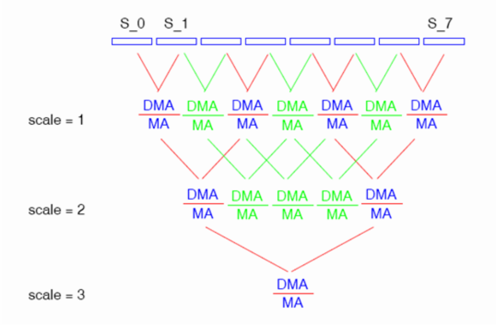


Figure 1: Oversampled scheme of Haar wavelet transform.

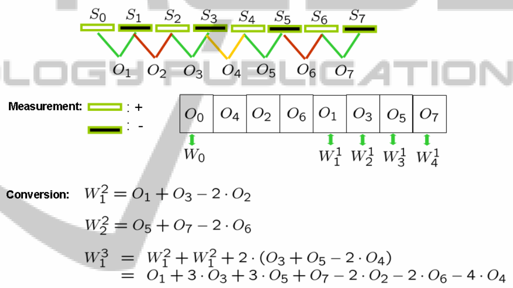


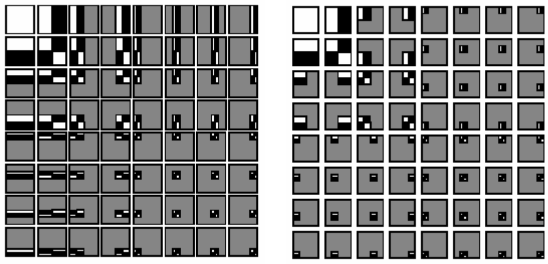
Figure 2: Measurement scheme with 1D sensor array.

3 WAVELET MEASUREMENT IN 2D SPACE

The standard 2D Haar wavelet decomposition is obtained by computing a 1D Haar transform on each row, followed by a 1D Haar transform on each column (or conversely). Fig. 3(a) shows the basis functions of the standard 2D Haar wavelet transform. Pixel values are added where the white color appears and subtracted where the black color appears. From the figure, we conclude that the standard Haar transform generates different spectral coefficients on different decomposition levels. A naive extension of the previous 1D measurement is not working in 2D case. We have to turn to some alternative wavelet decomposition method.

3.1 Dyadic Wavelet Transform

It is well known that the dyadic wavelet transform is a more efficient representation for the entropy cod-



(a) (b)

Figure 3: Haar wavelet transform in 2D space (a): Basis functions of the standard Haar wavelet transform; (b): Basis functions of the dyadic Haar wavelet transform.

ding in image compression. It is a slightly modified 2D Haar wavelet transform, whose basis functions are shown in Fig. 3(b). The alternation between rows and columns are applied within each decomposition steps, leading to a multi-scale version of three independent basis patterns. The wavelet basis functions can be interpreted as three independent forms in different scales:

$$\Psi^H = \frac{1}{4}\begin{pmatrix} +1 & -1 \\ +1 & -1 \end{pmatrix} \tag{1a}$$

$$\Psi^V = \frac{1}{4}\begin{pmatrix} +1 & +1 \\ -1 & -1 \end{pmatrix} \tag{1b}$$

$$\Psi^D = \frac{1}{4}\begin{pmatrix} +1 & -1 \\ -1 & +1 \end{pmatrix} \tag{1c}$$

This structure avoids the sequential operation along rows and columns in the standard Haar wavelet transform, providing a possibility to implement a parallel measurement.

3.2 2D Oversampling-based Measurement

Inheriting the spirit of the oversampling scheme, we propose a novel measurement scheme in 2D space. It contains three different basis patterns. Those patterns are independent of each other, which leads to a parallel architecture in hardware implementation. As we know, the oversampling scheme has severe redundancy. In this measurement, only the dyadic wavelet coefficient related measurements are reserved. The selection principle is a matter of art, which induces a delicate symmetric template. Combining the three patterns with a selection template, the 2D oversampling-based measurement is determined. Fig. 4 shows the measurement scheme for a 4×4 sensor array.

The chessboard-like patterns represent the different manners interpreting the sample value from each

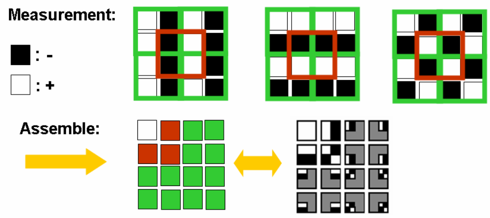
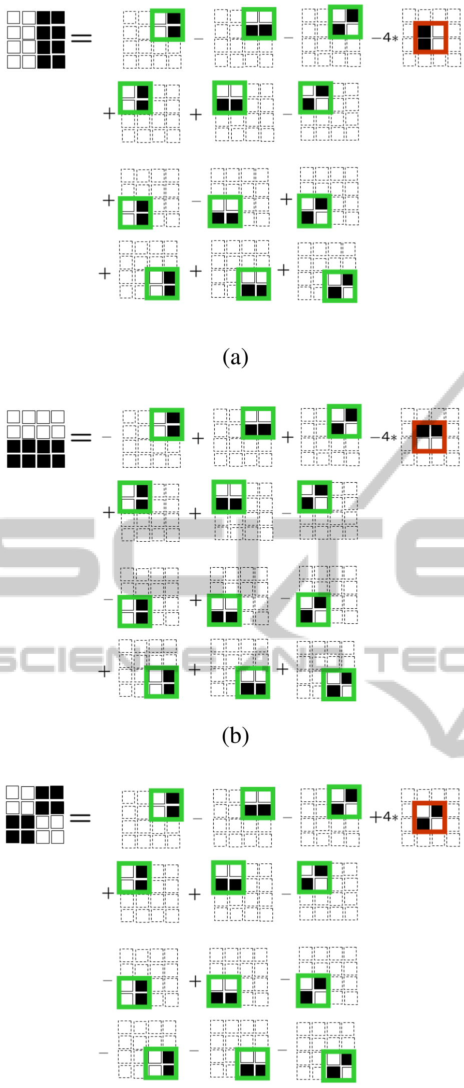


Figure 4: Measurement scheme for 2D sensor array.

sensor. White color means counting the sample value as positive, while the black color means counting it as a negative sample value. For 4×4 sensor array, the selection pattern has two levels. The green blocks are the first level and the red blocks are the second level. Each block contains four pixels, whose signed summations constitute the measurements. The acquired measurements can be reassembled in a similar form as dyadic wavelet coefficients. Obviously, the first level measurements are consistent with the first level dyadic wavelet coefficients. The second level dyadic wavelet coefficients can be derived by a linear combination of the derived measurements. The relationship is shown in Fig. 5.

Similarly, in the 8×8 and 16×16 cases, the dyadic wavelet coefficients in higher levels can be computed recursively. The three different patterns remain the same for larger sensor arrays. They are constructed by repeating the basis functions defined in Eq. 1 respectively. The selection template distribution obeys strict rules and is highly symmetric. This architecture benefits the hardware implementation. The independence of three patterns provides a parallel architecture shown in Fig. 6. Compared with the traditional dyadic wavelet transform, this measurement has a simpler structure, which avoids complicated switch operations in hardware design. The pattern number and the rule for selection template construction remain unchanged when the size of sensor array increases, which simplifies the circuit design process. All the computation can be carried out simultaneously, leading to less process time. Besides, only the difference of adjacent pixels is recorded, which captures the true features of an object and eliminates the affect of the illumination condition. Since the variance of the difference value is generally smaller than the variance of absolute value, the throughout can be reduced after the quantization step.



(a) (b) (c)

Figure 5: Second level dyadic wavelet functions.

4 SIMULATION AND HARDWARE DESIGN

This measurement scheme is equivalent to the dyadic Haar wavelet decomposition. In this section, we simulate the measuring process and compare the results with the coefficients of the dyadic Haar wavelet transform. The measurements can be converted to dyadic Haar wavelet coefficients in any level, which guarantees the flexibility of postprocess. Furthermore, we propose a design guideline for a CMOS sensor design.

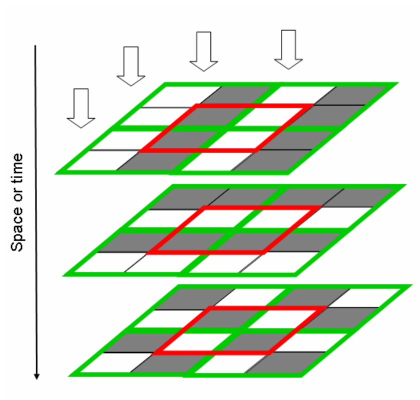


Figure 6: Parallel architecture.

4.1 Simulation Results

The measurement process is simulated with a given matrix, and a test image in order to verify its accuracy. We start with a given 4×4 matrix:

$$A = \begin{pmatrix} 64 & 2 & 3 & 61 \\ 9 & 55 & 54 & 12 \\ 17 & 47 & 49 & 20 \\ 40 & 26 & 27 & 37 \end{pmatrix} \tag{2}$$

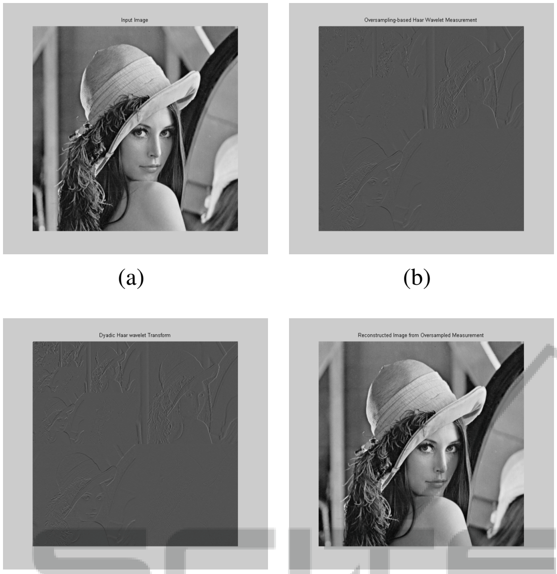
The oversampling-based measurement is given as:

$$M = \begin{pmatrix} 32.6875 & 0.2500 & 4.0000 & -4.0000 \\ -3.2500 & 0.7500 & -4.0000 & 4.7500 \\ 0.5000 & -0.5000 & 27.0000 & -25.0000 \\ -0.5000 & 1.2500 & -11.0000 & 9.7500 \end{pmatrix} \tag{3}$$

In order to verify the equivalent of the measurements and the dyadic Haar wavelet decomposition, we convert the measurements based on the relationship given in Fig. 5. The derived matrix is the same as the results applying the dyadic wavelet transform directly.

$$W = \begin{pmatrix} 32.6875 & -0.1875 & 4.0000 & -4.0000 \\ -0.1875 & 0.1875 & -4.0000 & 4.7500 \\ 0.5000 & -0.5000 & 27.0000 & -25.0000 \\ -0.5000 & 1.2500 & -11.0000 & 9.7500 \end{pmatrix} \tag{4}$$

Fig. 7 shows a simulation example with an image input. The value of the novel measurement scheme is compatible to the dyadic Haar wavelet transform with the highest level. Through recursive computations, the measurement matrix can be converted to the dyadic Haar wavelet coefficients. The equivalence is verified. Then an inverse dyadic Haar wavelet transform is applied to the coefficients, the reconstructed image is shown in Fig. 7(d).



(a) (b)

(c) (d)

Figure 7: 2D measurement simulation (a): Test image; (b): Oversampling-based measurement; (c): Converted to dyadic wavelet coefficients; (d): Reconstructed image.

4.2 Hardware Design

This measurement scheme can be applied in different sensor systems together with certain postprocessing blocks, such as noise removal, image coding/compression and etc. Its fixed template simplifies the complexity of hardware implementation.

Here, we propose a schematic of hardware implementation in a CMOS sensor array in Fig. 8. It contains four main parts: pattern control unit, sensor array, measurement template and AD converter.

The pattern control unit generates the control signal with respect to three patterns, such as sample/hold signal and sign control signal. The sign control signal is generated by logic circuits for each basis pattern.

A modified S/H circuit is described in Fig. 9. It is set up based on the conventional APS design (Chi et al., 2009) with a sign control function, which counts the accumulated photons as a positive or negative output voltage. Clocks S/H are non-overlapping. If SC (stands for sign control) is low during the sample phase S and goes high during the hold phase H, the amount of charge transferred is $C(V_{ij}^{int} - V_{ref})$, where V_{ij}^{int} is the voltage collected in the sample phase. V_{ref} is defined as the pixel voltage when there is no light. Conversely, if SC is high during the sample phase S and goes low during the hold phase H, the amount of charge transferred is $C(V_{ref} - V_{ij}^{int})$.

The main computation unit is the measurement template unit. It contains basic measurement elements arranged as the selection template defined above. A basic measurement element is shown in Fig. 10, which computes the weighted sum of adjacent pixel in an image. The capacitor is set to $4C$ in order to get a normalized measurement. The output of the amplifier is given as:

$$M_{ij} = \frac{1}{4}\sum_{i,j}(V_{i,j}^{int} - V_{ref}) \cdot SC_{ij}. \tag{5}$$

where SC_{ij} is either $+1$ or -1. In the end, the measured differences are quantized through a AD converter. This hardware design is only an example of this measurement realization, in which the measurement process is done consecutively. It contains a switch circuits transferring one basis pattern to another. The measurement scheme can also be carried out simultaneously, which means implementing the measurement template concerning each pattern layer-by-layer. It avoids the switch operation between the three patterns, hence it is faster, but the manufacture cost for the chip is also higher. With different applications, certain circuits should be changed accordingly.

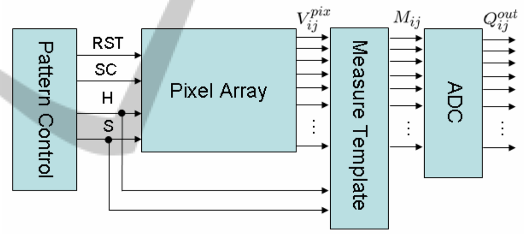


Figure 8: Hardware architecture.

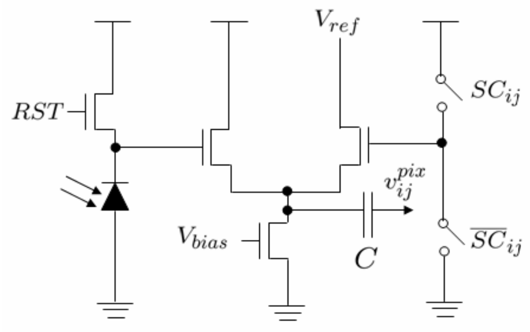


Figure 9: S/H circuit with sign control.

5 CONCLUSIONS

In this paper, we propose an oversampling-based wavelet measurement scheme. It records only the difference of adjacent pixels, capturing the true character of an object. It eliminates the redundancy which

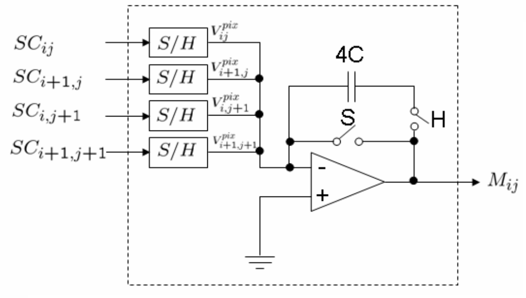


Figure 10: Basic measurement element.

occurs commonly in the oversampling system and restores only the measurements equivalent to the dyadic wavelet decomposition. The measurement scheme can be carried out by combining three independent chess-board like patterns with one fixed selection template. The hardware architecture is much simpler than the traditional wavelet transform. The independent pattern structure provides a possibility of parallel computations. Combined with certain postprocess units, it can be used in different applications, especially the occasions requiring real-time image acquisition and processing.

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