Max-Plus Algebra-Based Morphological Wavelet Transform Watermarking for Highly-Parallel Processing with Mobile Embedded Processor

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Abstract This paper presents Max-plus algebra-based Morphological wavelet Transform (MMT) watermarking, which is a novel mobile-dedicated information data embedding method. The performance of watermarking processing is considered a very important factor in embedded processors, which are applied to mobile devices. This is because, in the case of embedding information data in digital contents for mobile application, real-time processing speed is more important than data security and image quality. The proposed MMT watermarking method can be defined by nonlinear operation (maximum or minimum search) and standard sum. Thus, while the proposed watermarking method only uses integer representation for all variables with embedding operation, the conventional watermarking method has to calculate complex numbers, trigonometric functions, and floating-points for restricting watermarked-image distortion. As a result, the proposed method can reduce the number of clock cycles to drastically less than those of conventional transform-based watermarking. The processing time of the MMT watermarking is about 1/28, 1/2720, and 1/4364 shorter than those of Haar Wavelet Transform (HWT), Discrete Cosine Transform (DCT), and Fast Fourier Transform (FFT), respectively. Furthermore, the practical-use processing time of the MMT watermarking with the evaluation board for the massive-parallel Single Instruction Multiple Data (SIMD) matrix processor is found to be about 96% shorter than that of the HWT watermarking method on the BeagleBoard-xM, which is used the ARM Cortex-A8. To compare the watermarked and extract image distortion, the PSNR values of MMT, DCT and HWT watermarking are calculated. The PSNR value of the proposed MMT watermarking is suitable for practical use with 5-bit watermark embedded information, which can keep maintain image quality for both watermarked and extract images. Consequently, the proposed MMT watermarking algorithm can achieve an efficient real-time watermarking scheme for mobile device applications.

Keywords: watermark, max-plus algebra, morphological wavelet transform, nonlinear operation, parallel processing, SIMD, mobile processor, image processing

1. Introduction

The rapid development of semiconductor-integration and embedded LSI technology is continuously improving in our mobile computing environment. Mobile devices like cellular phones and smartphones have spread across society. Thus, several types of mobile application and digital content are needed to satisfy user-requirements. Here, for expanding the usage of digital data, such as image and audio, digital watermarking technology has attracted attention over the years. For example, a digital advertisement or a URL for a website can be directly embedded into image, movie, and audio data [1]–[3]. Previously, the digital watermarking technique was often considered as a countermeasure against copyright infringement of digital contents. Thus, the following important requirements of digital watermarking have been written [4]: imperceptibility is that the watermarked data and the original data should be perceptually indistinguishable, robustness is that processing of the watermarked data cannot damage or even destroy the embedded information without rendering the processed data useless, and
security is that the embedded information can be detected, decoded and/or modified only by authorized parties. On the other hand, in case of the digital watermarking algorithm exploiting mobile applications, processing performance is considered to be the most important factor for embedded processors in mobile devices. The processing performance mainly includes the processing time and ease of data calculation. Because, in the case of embedding information data in digital contents for mobile application, real-time processing speed is more important than data security and image quality. From this background, we propose a Max-plus algebra-based Morphological wavelet Transform (MMT) watermarking as a novel data embedding algorithm for highly-parallel processing with a mobile embedded processor.

This paper is organized as follows. Section 2 introduces typical conventional watermarking methods. Section 3 explains the max-plus algebra-based morphological wavelet transform watermarking. Section 4 describes the processing results for some conventional processors and a massive-parallel SIMD matrix processor, and compares PSNR measurement results for image distortion. Finally, section 5 concludes this paper.

2. Conventional Watermarking Methods

Digital image watermarking can be classified as two types of embedding method, such as spatial domain and frequency domain. The spatial domain transform has more fragile data than the frequency domain transform, therefore the research of image watermarking is often centered in the frequency domain. This paper deals with three conventional frequency domain transform methods for watermarking processing. These algorithms represent a Discrete Fourier Transform (DFT), a Discrete Cosine Transform (DCT), and a Discrete Wavelet Transform (DWT). Nowadays, many researchers have proposed several watermarking methods that apply the above transform algorithms. Thus, this paper describes the basic concepts of DFT, DCT, and DWT watermarking methods [5].

The DFT is considered to offer the possibility of controlling the frequencies of the image data. Specifically, the DFT can be calculated efficiently in practice using a Fast Fourier Transform (FFT) algorithm. While the FFT requires complex multiplications and additions, and is useful for watermarking purposes in order to perform phase modulation between the watermark image and the original image.

The DCT has been widely studied as a watermarking algorithm and is considered to embed information data inside JPEG images and MPEG videos. Embedding rules in the DCT domain are often robust to JPEG and MPEG compression. While the DCT often deals with trigonometric functions for computing coefficients, watermarking in the DCT domain offers the possibility of directly achieving the embedding operator in the compressed domain in order to minimize the computation time.

The DWT is identical to a hierarchical sub-bands algorithm. The original image is split into four quadrant bands after decomposition. The four quadrants contain approximation sub-band, horizontal detail sub-band, vertical detail sub-band, and a diagonal detail sub-band. This process continues until some final scale is reached. This paper applies a Haar Wavelet Transform (HWT) algorithm for watermarking processing. The HWT, which consists of addition, subtraction, and division operations, has the advantage of being easier to calculate than other DWT algorithms.

3. Max-Plus Algebra-Based Morphological Wavelet Transform Watermarking

Conventional wavelet transforms are known to be a method of signal analysis for executing signal decomposition/reconstruction. These methods can be classified into a linear operation [6]. The morphological wavelet transform, on the other hand, was introduced by Heijmans and Goutsias [7] as a method of nonlinear signal analysis. The morphological wavelet transform combines the inherent properties of the conventional wavelet transform and mathematical morphology. However, the original morphological wavelet transform deals with the field of formulation of real numbers and several complex mathematical equations. This concept is thus difficult to implement with general-purpose processors, especially several processors for low-power embedded mobile devices. A morphological wavelet transform, which utilizes the max-plus algebra concept, has been proposed [8] to overcome these problems. The Max-plus algebra-based Morphological wavelet Transform (MMT) can be defined by nonlinear operation (maximum or minimum search) and standard sum, and integer representation can be used for all variables. The max-plus algebra-based morphological wavelet transform has three novel features: lack of quantization error, high affinity with hardware implementation, and efficient edge image compression. Consequently, the algorithm for the max-plus algebra-based morphological wavelet transform is suitable for simple low-power processors. Despite the above high processing potential, there have not been many reports on the implementation or evaluation of this algorithm [9], [10]. Thus, we have reported several effective research results using the MMT application [11]–[13].

The MMT decomposes and reconstructs an orig-
inal image into several signals in accordance with to the patterns of scan windows. Figure 1 shows five basic patterns of a sampling window to execute the MMT. These sampling windows consisted of four or eight squares.

![Basic sampling windows]

**Fig. 1** Basic types of sampling windows

Figure 2 shows the watermarking flow using the max-plus algebra-based morphological wavelet transform for a $2 \times 2$ pixel sampling window case. Four pixel values are decomposed into four signals: scaled, horizontal, vertical, and diagonal. Then, all signals are gathered in accordance with the same signal group.

![Proposed watermarking concept underlying max-plus algebra-based morphological wavelet transform]

**Fig. 2** Proposed watermarking concept underlying max-plus algebra-based morphological wavelet transform

In contrast, the original image can be reconstructed from the four pieces. The decomposition operation in a sampling window can be represented in the following equations [14]:

$$a = \min(x, y, z, w)$$
$$b = y - x$$
$$c = z - x$$
$$d = w - x$$

The reconstruction operation can also be represented in the following equations [14]:

$$x = a + \max(-d, -h, -v, 0)$$
$$y = a + \max(h - v, h - d, h, 0)$$
$$z = a + \max(-d, -h, -v, 0) + h$$
$$w = a + \max(d - h, d - v, d, 0)$$

Here, the four variables $x, y, z,$ and $w$ correspond to the pixel values of the coordinates $(i, j), (i + 1, j), (i, j + 1)$ and $(i + 1, j + 1)$ in an original image. The variables $a, h, v,$ and $d$ are decomposed images, viz., scaled, horizontal, vertical, and diagonal signals. Since the decomposition and the reconstruction equations include minimum and maximum search, respectively, the MMT is classified as the nonlinear operation [8]. Figure 3 shows the results of decomposition processing for a $64 \times 64$ example image, which was decomposed by $2 \times 2, 4 \times 1, \text{and } 1 \times 4$ sampling windows. Each decomposed/reconstructed image includes a quadruple of signal values.

Generally, diagonal signals contain many high-frequency components. These signals can be often utilized in the information data watermarking operation. The horizontal low-frequency band and the vertical low-frequency band are located in the scaled signal group (LL). Similarly, the horizontal signal group, vertical signal group, and diagonal signal group represent the horizontal high-frequency band and the vertical low-frequency band (HL), the horizontal low-frequency band and the vertical high-frequency band (LH), and the horizontal high-frequency band and the vertical high-frequency band (HH), respectively. Diagonal signals in an HH area are simply overwritten with embedded information pixels, which are included in information data, to reduce processing time. A 5-bit embedding case is shown in Figure 4. Since the number of bits from MSB in a pixel can represent the main-information of the image, the upper 5 bits of the embedded information move to the lower 5-bit location in the diagonal signal.

Moreover, the MMT watermarking can repeat the transformation process for a multiscale spatial fre-
Fig. 3 Decomposition/reconstruction processing example for max-plus algebra-based morphological wavelet transform

Fig. 4 Embedding rule of max-plus algebra-based morphological wavelet transform (example of 5-bit information data)

3.2 Watermarking

Frequency decomposition of the original image. For example, for level three decomposition with three scale factors, the lowest frequency band at the lowest scale factor is found in the top-left corner. A watermark image is often embedded in the HH area because these signals include many high-frequency components of the original image. In contrast, the watermarked image can be reconstructed from the four pieces.

4. Experimental Results

This section reports several watermark implementation results for verifying the processing speed and the value of Peak Signal-to-Noise Ratio (PSNR). This paper deals with three types of embedded processor: a SH-2A processor, an ARM processor, a massive-parallel SIMD matrix processor. The massive-parallel SIMD matrix has been proposed as a novel mobile processor, which provides a better way of processing several types of multimedia applications [11],[12],[16]–[25]. We have developed and engaged in cooperative research on this processor.

4.1 Processor specification and processing results

For testing the efficiency of mobile-dedicated watermarking, three conventional watermarking methods (FFT, DCT and HWT) and the proposed MMT watermarking method were implemented in a typical embedded processor. Figure 5 shows four simulation results of the watermark-embedded performance by a SH-2A processor, which is a 200 MHz 32-bit typical Reduced Instruction Set Computer (RISC) microprocessor [26], and the horizontal logarithmic axis represents the processing time. A 64×64 pixel original image and a 32×32 pixel watermark image is used. The embedded information is 8-bits. While the proposed MMT watermarking method only uses integer variables for embedding operation and is defined as maximum or minimum search and standard sum, the three conventional watermarking algorithms have to calculate complex numbers, trigonometric functions, and floating-points for restricting watermarked-image distortion. Thus, the proposed method can drastically reduce the number of clock cycles more than FFT, DCT, or HWT watermarking. The processing time of the MMT watermarking is about 1/28, 1/2720, and 1/4364 shorter than those of HWT, DCT, and FFT, respectively.

Fig. 5 Conventional and proposed watermarking implementation results for SH-2A processor

Since the MMT is essentially suitable for pixel-level parallel processing, the processing time can be further reduced by choosing an appropriate SIMD processor. To efficiently process the multimedia applications, we have developed a massive-parallel SIMD matrix on the basis of a SRAM-embedded matrix,
which overcomes the limitations in parallelism of conventional architectures [11], [12], [16]–[25]. It achieves highly-parallel processing with low power consumption, and can thus target the mobile product applications. Moreover, since the massive parallel SIMD matrix uses a software-based architecture for several algorithm implementations, it is programmable for all processing functions required by multimedia LSI chips. It is explained in detail in the Appendix. For better verifying the more implementation performance of the proposed MMT watermarking and the HWT watermarking, which has the second processing capability for watermarking in Fig. 5, an evaluation board for a massive-parallel SIMD matrix and a BeagleBoard-xM [27] implementation results are evaluated. Figure 6 - (a) and (b) show a photograph and the system block diagram of the evaluation board. Main components are the massive-parallel SIMD matrix processor, a host CPU, a Direct Memory Access controller (DMA), and two SRAMs. Maximum clock frequencies of the SIMD matrix processor, host CPU and SRAM are 162 MHz, 81 MHz, and 81 MHz, respectively. The specifications of the massive-parallel SIMD matrix processor are 1,024-parallelism, 512-bit word-length, 2-bit-serial processing, and 150 mW power dissipation. The host CPU dispatches several tasks to the massive-parallel SIMD matrix and the DMA and executes serial operations.

Fig. 6 Photograph and block diagrams of massive-parallel SIMD matrix evaluation board

In this test, the original image was 5-bit embedded information data because 5-bit-embedded information results are suitable for practical use of mobile applications. (This reason will be described in section 4.2.) The BeagleBoard-xM exploits the ARM Cortex-A8 at 1 GHz, which is a well-known conventional embedded processor. Figure 7 shows three sets of processing results of the HWT and the MMT watermarking methods with the evaluation board for the massive-parallel SIMD matrix and the BeagleBoard-xM. The ARM Cortex-A8 has the VFPv3 architecture [28], which can handle single or double floating-point values. Thus, the processing time of the MMT watermarking method, which is executed on the BeagleBoard-xM, is about 9% smaller than that of the HWT watermarking method on the BeagleBoard-xM. On the other hand, the massive-parallel SIMD matrix can achieve highly parallel pixel processing. The processing time of the proposed MMT watermarking method with the evaluation board for the massive-parallel SIMD matrix is found to be about 90% shorter than that of the HWT watermarking method on the BeagleBoard-xM. From above results, the proposed MMT watermarking can achieve efficient highly-parallel fast image watermarking processing.

Fig. 7 HWT and MMT watermarking implementation results for a BeagleBoard-xM and a massive-parallel SIMD matrix evaluation board

4.2 Comparison between watermarked and extract image distortion

This section shows some example images of the proposed MMT watermarking method. For comparison with the Peak Signal-to-Noise Ratio (PSNR) value, which is the most common distortion measure in the field of image coding for the watermarked and extract images, four test Portable Gray Map (PGM) pictures are used.

Figures 8, 9, and 10 show three 64 x 64 pixels watermarked images and a 32 x 32 pixels extract image. These figures, - (a) to (d), show eight watermarked and corresponding extract images, in which the embedded information bits are varied from 1 to 8. These original images are taken from a standardized sample image. The chosen images have several different characteristics for contents. Figure 8 shows a woman against an interior background. Figure 9 shows an airplane against a natural background. Figure 10 shows some houses in a field. An extract image (Fig. 11) has widely varying pixel values for clarifying differences in extracted watermark images.

Figures 12 and 13 show the image quality expressed in PSNR. In general, a loss of image quality is hard for the human eye to notice when the overall PSNR is more than 30 dB [29]. Figure 12 shows PSNR values of watermarked images for Figs. 8, 9, and 10 from 1- to 8-bit embedded information. In this case, PSNR values of sample images are almost equal to each other.
Fig. 8 Watermarked images of a woman processed by the max-plus algebra-based morphological wavelet transform watermarking method: Results (a) to (h) are obtained by 1- to 8-bit embedded information data, respectively.

Fig. 9 Watermarked images of an airplane processed by the max-plus algebra-based morphological wavelet transform watermarking method: Results (a) to (h) are obtained by 1- to 8-bit embedded information data, respectively.

If the value of PSNR is higher than 30 dB, the watermarked image can be applied with several embedded digital appliances. Thus, our proposed algorithm is suitable for practical use, such as 1 to 5-bits. The PSNR values of an extracted watermark image from 1- to 8-bit embedded information are shown in Fig. 13. The quality of the obtained image can achieve over 30 dB from 5 to 8-bits. Thus, the value of PSNR with 5-bit watermark embedded information can maintain high image quality for both watermarked image and extract image. Furthermore, the size of the extracted watermark image, which is indicative of the quantity with the MMT watermarking, can be calculated by multiplying the embedding bit width by the number of pixels. Thus, the size of gray-scale extract images in Fig. 11-(a) to (h) are 128 to 1,024 bytes, respectively.

For verifying the effectiveness of the proposed MMT watermarking in detail, PSNR values of several watermarked algorithms are used. To compare the watermarked and extract image distortion, three watermarking algorithms are used and processing results are shown in Figs. 14, 15, and 16. The three watermarking algorithms (MMT, DCT and HWT) seem to have practical processing-time capability on an embedded processor from section 4.1. Values around 30 dB belonging to the bar diagrams of both watermarked and extract images are the DCT- and the MMT-based watermarking processing, which have embedded information data of 4 and 5-bit width and 5 and 6-bit width, respectively. The HWT-based watermarking cannot achieve 30 dB in any bit width images. While the DCT-based watermarking performs only slightly better than the proposed algorithm in terms of embedding information bits, the MMT-based watermarking algorithm can be executed extremely fast from section 4.1. Furthermore, the PSNR values of extract images, which are transformed by the DCT, suffer a downturn in growth. The DCT algorithm tends to have digit-overflow of pixel data, which is caused by floating-
Fig. 12  Comparison of PSNR values for three watermarked images

Fig. 13  PSNR values of an extracted watermark image from 1- to 8-bit embedded information

point calculation, if the original image is embedded with more information data of the watermarked image. On the other hand, the MMT watermarking can transform the original image and watermarked image exclusively by integer arithmetic. As a result, the proposed MMT watermarking method can achieve an efficient and practical watermarking scheme.

5. Conclusion

We propose a max-plus algebra-based morphological wavelet transform watermarking, which is a novel mobile-dedicated information data embedding method. For verifying processing performance, three conventional watermarking algorithms (FFT, DCT, and HWT) and the proposed MMT watermarking are simulated by a SH-2A processor. Thus, the proposed MMT watermarking can reduce the number of clock cycles drastically to about 1/28, 1/2720, 1/4364 smaller than those of HWT, DCT, and FFT, respectively. Furthermore, the practical-use processing time of the MMT with the evaluation board for the massive-parallel SIMD matrix is found to be about

96% shorter than that of the HWT watermarking method on the BeagleBoard-xM, which uses the ARM Cortex-A8. In the watermarked and extract image distortion, the PSNR value of the proposed MMT watermarking is suitable for practical use with 5-bit watermark embedded information, which can maintain high image quality for both watermarked and extract images. This research mainly focused on binary images to verify image distortion. In reality, mobile applications often use compressed images, which are processed by JPEG or MPEG algorithms, and image data tends to be smaller than binary data. The proposed MMT watermarking has the potential to select a data-embedding signal group and scaled factor flexibly in accordance with the image compression ratio for practical use. As a result, the proposed MMT watermarking method can achieve an efficient real-time watermarking scheme for mobile device applications.
Fig. 16 PSNR values of watermarked and extracted images from 1- to 8-bit embedded information for Haar wavelet transform watermarking

Appendix

The massive-parallel SIMD matrix processor is a kind of parallel mobile embedded processor. To increase the degree of parallel processing and flexibility, the massive-parallel SIMD matrix applies bit-serial and word-parallel mode of operation and a close connection between 1,024 2-bit Processing Elements (PEs) and synchronous dynamic random access memory (SRAM) arrays. The number of implementable PEs is still relatively small. We have developed and engaged in cooperative research on a massive-parallel SIMD matrix core based on a SRAM embedded architecture, which can overcome the limitations in parallelism of conventional architectures.

The above core achieves performance of 40 GOPS for 16-bit additions at a clock frequency of 200 MHz and power dissipation of 250 mW. A 1M-bit SRAM capacity of 1,024 words with a 512-bit length or 2,048 words with a 256-bit length for data registers and 1,024 or 2,048 2-bit PEs, connected by a flexible switching network, are integrated on small area of 3.1 mm² with 90 nm low-power CMOS technology [16].

Figure 17 is a block diagram of the typical massive-parallel SIMD matrix core. A 1M-bit SRAM is provided with up to 2,048 2-bit PEs that are connected by a vertical and a horizontal switching network. A vertical channel (V-ch) connects the PEs, while a horizontal channel (H-ch) connects the SRAM-register and PEs. The data transfer between different PEs, whose distance is a power of two rows, can be operated through a V-ch path in one cycle. The SRAMS at the left and right have different bank structures and independent H-ch paths. Two pieces of data are read from both SRAM banks, and several arithmetic and logical operations are carried out in the PEs. The results from PEs can be re-stored to either the SRAM area in the same cycle using “read-modify-write” operation.

Since the massive-parallel SIMD matrix consists of a simple SRAM-based architecture, the processed-data width and magnitude of parallelism can be changed and optimized flexibly in accordance with the needs of applications.

The massive-parallel SIMD matrix processor has been used to implement linear and nonlinear operation-based multimedia applications, such as Huffman-encoding [20], DCT processing [19], face detection [22], and fast multiplication [21].

Fig. 17 Block diagram of massive-parallel SIMD matrix architecture

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[27] http://beagleboard.org/hardware-xM


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