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APPLIED SEQUENTIAL-SEARCH ALGORITHM FOR COMPRESSION-ENCRYPTION OF HIGH-RESOLUTION STRUCTURED LIGHT 3D DATA

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ABSTRACT

A new image compression algorithm is proposed and demonstrated in the context of structured light 3D reconstruction. Structured light images contain patterns of light, which are captured by the sensor at very high resolution. The algorithm steps involve a two level Discrete Wavelet Transformation (DWT) followed by a Discrete Cosine Transformation (DCT) to generate a DC-Column and an MA-Matrix (Multi-Array Matrix). The MA-Matrix is then partitioned into blocks and a minimization algorithm codes each block followed by arithmetic coding. At decompression stage a new proposed algorithm, Sequential-Search Algorithm (SS-Algorithm) is used to estimate the MA-Matrix. Thereafter, all decompressed DC-Columns are combined with the MA-Matrix followed by inverse DCT and inverse DWT. The effectiveness of the algorithm is demonstrated within a 3D reconstruction scenario from structured light images.

KEYWORDS

Discrete Wavelet Transform; Discrete Cosine Transform; Minimize Matrix Size Algorithm; Sequential Search Algorithm; Structured Light; 3D reconstruction.

1. INTRODUCTION

In today's highly computerized and interconnected world, security of digital images/video has become increasingly more significant in applications such as pay preview TV, confidential video conferencing, medical imaging and industrial or military imaging systems. Many different image encryption techniques have been proposed in the literature. They include Bit Recirculation Image Encryption, Infinite Series Convergence method [3], Fuzzy PN code based Color Image Encryption method, Combinational Permutation method, Magnitude and Phase Manipulation method, SCAN based methods and Chaos based methods. Further, image encryption based on phase encoding by means of a fringe pattern uses cosine function, which adds to its argument the image to be phase encrypted [4,11]. Since these methods manipulate an entire data set without any presumption about compression at later time, the secure transmission of image has become more costly in terms of time, bandwidth and complexity [16]. Thus, users pay a price for security proportional to their desired level of security. Further, the use of compression after encryption fails to exploit the spatial and psycho-visual redundancies efficiently as the encryption of an uncompressed image removes intelligibility from the original image and hence incurring compression penalties. This results in a tradeoff between the competing requirements of encryption and compression [20]. Here a further requirement is introduced concerning the compression of 3D data. Rodrigues [13] demonstrated that while geometry and connectivity of a 3D mesh can be tackled by a number of techniques such as high degree polynomial interpolation or partial differential equations [14] the issue of efficient compression of 2D images both for 3D reconstruction and texture mapping for structured light 3D applications has not yet been addressed. Moreover, in many applications, it is necessary to transmit 3D models over the Internet to share CAD/CAM models with e-commerce customers, to update content for entertainment applications, or to support collaborative design, analysis, and display of engineering, medical, and scientific datasets. Bandwidth imposes hard limits on the amount of data transmission and, together with storage costs, limit the complexity of the 3D models that can be transmitted over the Internet and other networked environments [12,15].

The focus of this paper is on compression of structured light images. Such images contain patterns of light allowing 3D reconstruction. A possible scenario would be a surface patch compressed as a 2D image together with 3D calibration parameters, transmitted over a network and remotely reconstructed (geometry, connectivity and texture map) at the receiving end with the same resolution as the original data. The widespread integration of 3D models in different fields motivates the need to be able to store, index, classify, and retrieve 3D objects automatically and efficiently.

Siddeq and Rodrigues [12] proposed 2D image compression methods based on high-frequency sub-bands compressed by the Minimize-Matrix-Size Algorithm (MMS) and decompressed by the Limited-Sequential Search Algorithm (LSS). The advantages are high compression ratios with high-resolution 3D reconstruction. However, the complexity of the algorithm means very large execution times that could be in the order of minutes. A new algorithm was proposed [13] using JPEG, with decompression by a parallel SS-Algorithm. The execution time was reduced to a few seconds with higher compression ratios. Recently, a novel algorithm was proposed [22] for decompression of DCT coefficients called Fast Matching Search (FMS), which reduced execution time to milliseconds. Further, the FMS algorithm was applied to frequency sub-bands of DWT followed by DCT [23]. In this research we introduce a new method for compression and encryption by partition the DCT coefficients into blocks and applying the MMS-Algorithm on each block of pixels. Each block generates a unique key at compression stage. This key can be seen as a symmetric encryption key, as without the key the block cannot be decoded.

2. THE PROPOSED COMPRESSION-ENCRYPTION ALGORITHM

The proposed algorithm uses two transformations: a two level DWT converts an image into seven frequency sub-bands. The low-frequency sub-band is divided into 2x2 non-overlapped blocks and a DCT is applied to each block. The DCT is very important to increase high-frequency domains by converting LL2 into DC-coefficients and AC-coefficients (DC-Column and MA-Matrix). The Minimize-Matrix-Size Algorithm is applied to MA-Matrix for encryption and then subject to arithmetic coding together with DC-Column as depicted in Fig. 1.

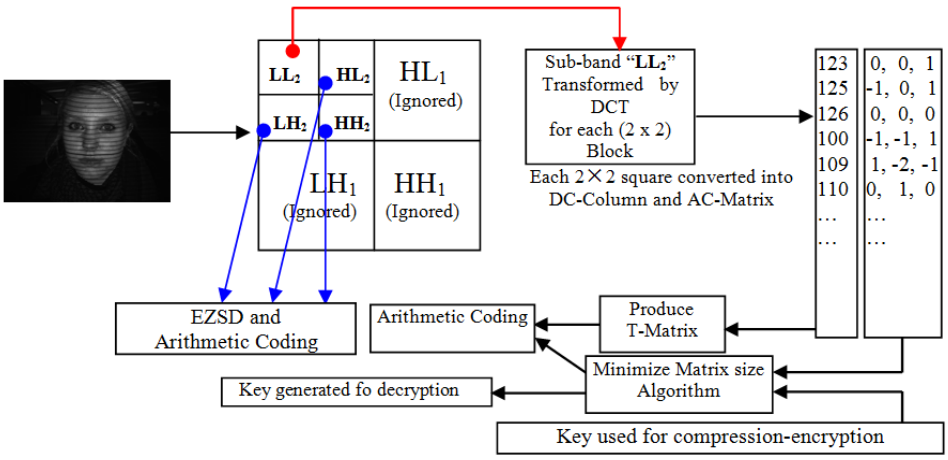


Figure 1.Layout of proposed Compression-Encryption algorithm

2.1. Discrete Wavelet Transform (DWT)

DWT analysis divides a signal into two classes (i.e. Approximation and Detail) by signal decomposition for various frequency bands and scales [1,2]. DWT utilizes two function sets: scaling and wavelet, which are associated with low and high-pass filters. In other words, only half of the samples in a signal are sufficient to represent the whole signal. The wavelet transform has some important properties; many of the coefficients for the high-frequency components (LH_1, HL_1 and HH_1) are zero or insignificant [5,6,10]. This reflects the fact that much of the important information is contained in the LL_2 sub-band. In particular, the Daubechies wavelet transform has the ability to reconstruct approximately the original image by just using second level sub-bands (LL_2, HL_2, LH_2 and HH_2), while other sub-bands can be ignored. This property allows higher compression ratios [18,19].

2.2. Discrete Cosine Transform (DCT)

A second transform is applied to each 2x2 block of pixels of LL_2 sub-band as show in Fig. 2. The energy in the transformed coefficients is concentrated about the top-left corner of the matrix of coefficients. The top-left coefficients correspond to low frequencies: there is a 'peak' in energy in this area and the coefficients values rapidly decrease to the bottom right of the matrix, which means the higher-frequency coefficients [7,9]. The DCT coefficients are de-correlated, which means many of the small values (coefficients) can be discarded without significantly affecting image quality. A compact matrix of de-correlated coefficients can be compressed much more efficiently than a matrix of highly correlated pixels [8,17].

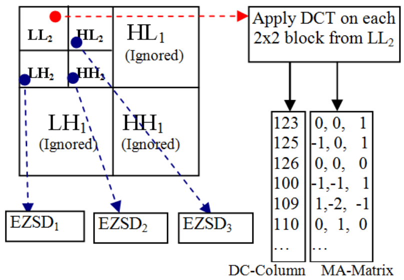


Figure 2. LL_2 sub-band quantized and transformed by DCT for each 2x2 blocks

Quantization is performed by matrix-dot-division and then truncating the result, by dividing each 2x2 coefficient from LL2. The quantized matrix removes insignificant coefficients. In the proposed method the high frequency sub-bands at first level are set to zero (i.e. discard HL_1, LH_1 and HH_1) as they do not affect image details. Additionally, only a small number of non-zero values are present in these sub-bands. In contrast, high-frequency sub-bands in the second level (HL_2, LH_2 and HH_2) cannot be discarded, as this would significantly affect image quality. For this reason, high-frequency values in this region are quantized. The quantization $\boldsymbol{Q}$ depends on the maximum value in each sub-band as follows:

$$Q = Quality * H_{\max} \tag{1}$$

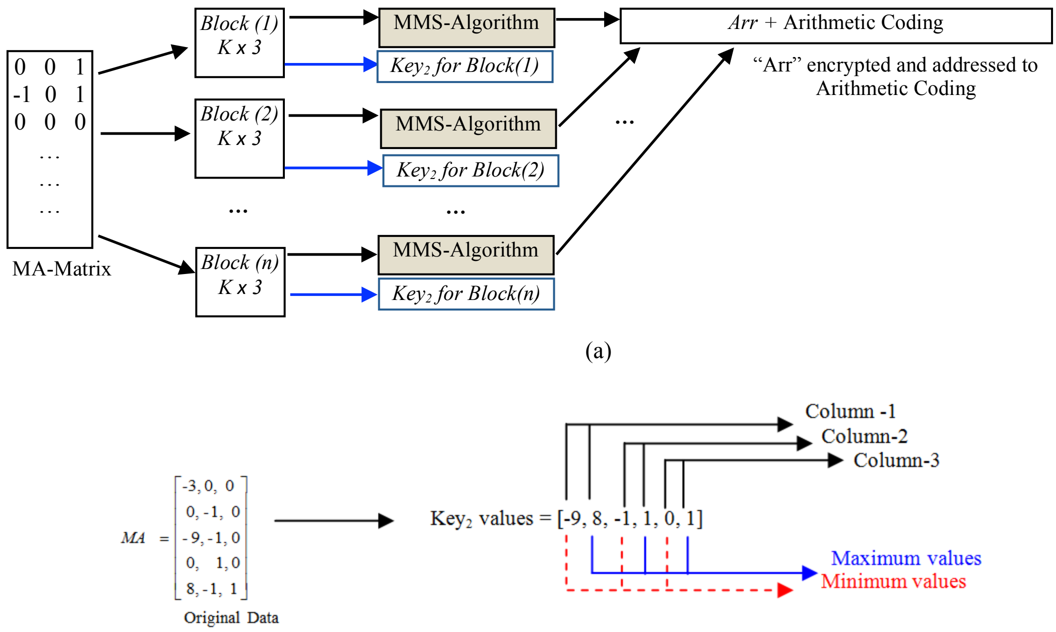
where the matrix $\boldsymbol{H}$ refers to the high-frequency coefficients in HL_2, LH_2 and HH_2, the factor Quality is used to increase/decrease $\boldsymbol{H}$. Thus, image details are reduced in case Quality >=0.01. The limit range for this factor is less than or equal to 0.9 for the 3D data used in this paper.

3. MINIMIZE-MATRIX-SIZE ALGORITHM (ENCRYPTION)

The purpose of this algorithm is to reduce the size of the MA-Matrix. This process depends on a key value and three adjacent coefficients to calculate and store the sum in a new array. The MMS algorithm consists of two parts: first, the MA-Matrix is partitioned into non-overlapping blocks (Kx3) of coefficients, where K refers to number of rows in a block as shown in Fig. 3(a). Second, each block is encrypted by a *Key1* value. Additionally, new key values are generated for each block called *Key2*. Each key from each block is organized as minimum and maximum value for each column as shown in Fig. 3(b). Each row and column *(r,c)* of the MA matrix is coded as follows:

$$Arr_{(r,c)} = Key1_{(r,c)} * MA_{(r,c)} + Key1_{(r,c)} * MA_{(r,c)} + Key1_{(r,c)} * MA_{(r,c)} \tag{2}$$

The *Arr* contains stream of encrypted values. Thereafter, *Arr* is compressed by using arithmetic coding to produce stream of bits. The *key1* values are used in the Minimize-Matrix-Size Algorithm generated randomly, these key values are between {0…1} (for example; *Key1*= {0.128, 0.65, 0.8519}).



(b)

Figure 3. (a) MA-Matrix divided into blocks and each block encrypted by MMS-Algorithm, (b) Key_2 Values generated from a block, as an example block size =5.

4. TRANSFORMED MATRIX (T-MATRIX)

The DC-Column contains the DC values of DCT partitioned into 64-arrays. Each array is transformed by one-dimensional DCT, thereafter the quantization process is applied to each array as per Eq. (3) and then stored in a matrix called Transformed-Matrix (T-Matrix).

$$Q_n = Q_{(n-1)} + 1 \tag{3}$$

where $64 \geq n \geq 1$. The values in T-Matrix are de-correlated yielding good compression ratio. Each row of T-Matrix consists of low and high frequency coefficients. After scanning column-by-column, the T-Matrix is transformed into one-dimensional array which is then subject to Arithmetic Coding [8]. Fig. 4 illustrates the process.

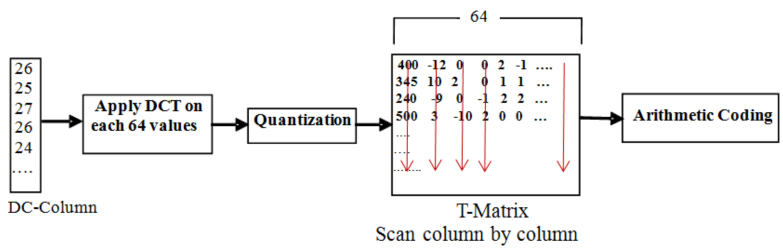


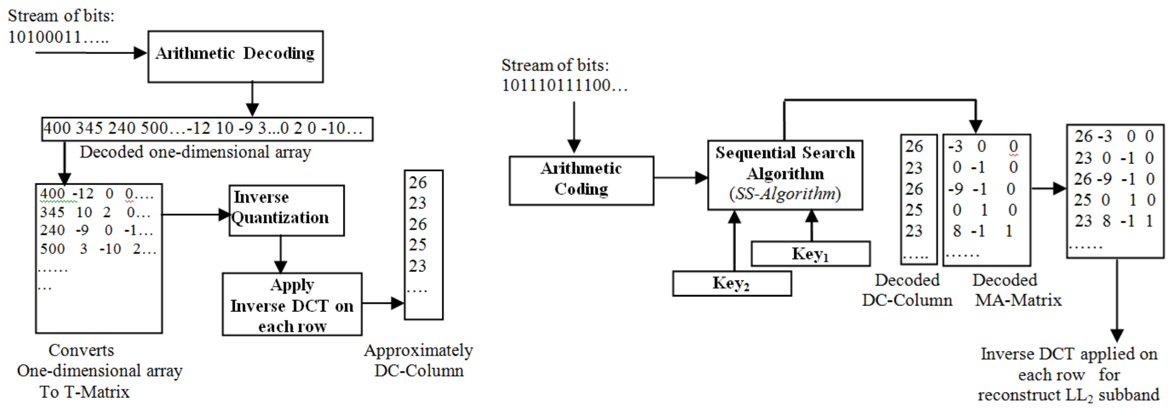
Figure 4. T-Matrix technique

5. ELIMINATE ZEROS AND STORE DATA (EZSD)

The EZSD algorithm is designed to increase compression ratio for high frequency sub-bands, and it is applied to each sub-band independently. It eliminates block of zeros, saving blocks of nonzero data in an array. The algorithm starts to partition the high-frequency sub-bands into non-overlapping 8x8 blocks, and then searches for nonzero blocks (i.e. search for at least one nonzero data inside a block). If the block contains any data, this block will be stored in the array called Reduced-Array; also the coordinates for the nonzero block are stored in new array called Positions. If the block contains just zeros, this block will be ignored, and the algorithm continues to search for other nonzero blocks. The final obtained Reduced Array is subject to Arithmetic Coding.

6. DECOMPRESSION BY SEQUENTIAL SEARCH (SS-ALGORITHM)

The decompression-decryption algorithm consists of four steps. First, arithmetic decoding is used to recover the one-dimensional-array containing the original data in the T-Matrix, illustrated in Fig. 5(a). Second, the novel SS-Algorithm is applied for decoding the MA-Matrix. This novel algorithm depends on the coded ***Arr***, Key_1 and Key_2 as illustrated in Fig. 5(b). The encrypted array is partitioned into sub-arrays of size K. Each sub-array is subject to SS-Algorithm to recover the block of data in the MA-Matrix.



(a) (b)

Figure5. **(a)** Decoding the DC-Column; **(b)** Decoding the MA-Matrix through the SS-Algorithm

The SS-Algorithm using three pointers, these pointers refer to original data in specific blocks of the MA-Matrix. The initial values of these pointers are set to minimum in the space search (Key2). These three pointers are called S1, S2 and S3 and are incremented by one in a gearwheel (e.g. similar to a clock, where S1, S2 and S3 represent hour, minutes and seconds respectively). At each iteration the SS-Algorithm computes the sum Eq. (4) and compares the error in Eq. (5) with zero. If true, the estimated values are S1, S2 and S3 corresponding to the original values in the MA-Matrix. In case of $E \neq 0$, the algorithm will continue to search for the original values in the block.

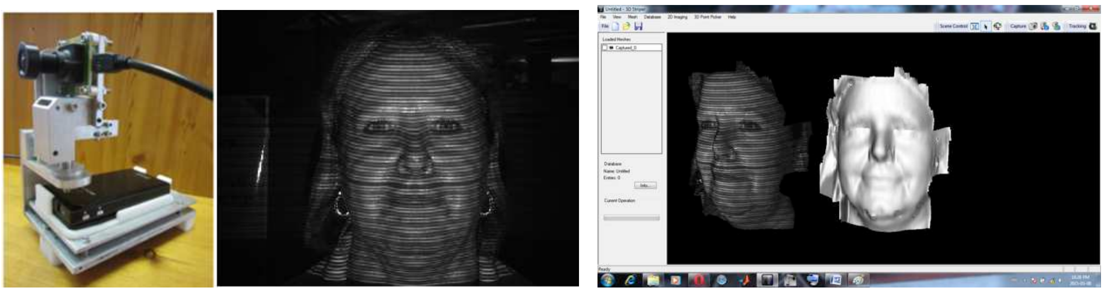
$$Sum = \sum_{i=1}^{3} S(i) \times Key_1(i) \tag{4}$$

$$E = |Arr - Sum| \tag{5}$$

At the third step, the decompression algorithm combines the DC-Column with MA-Matrix, and then using inverse DCT generates the LL2 sub-band. Next, the inverse EZSD recovers the high frequency sub-bands (LH2, HL2 and HH2); this algorithm recovers the locations and places the nonzero data in their exact locations in the recovered high-frequency matrix. Finally, the fourth step uses both inverse DWT and inverse DCT to decode 3D surface data recomposing all decompressed sub-bands.

7. EXPERIMENTAL RESULTS

The experimental results described here were implemented in MATLAB R2013a and Visual C++ 2008 running on an AMD Quad-Core microprocessor. We apply the compression and decompression algorithms to 2D images obtained from the GMPR scanner [13,14]; these images contain structured light patterns allowing 3D surface data to be generated from those patterns (Fig 6). The principle of operation of GMPR 3D surface scanning is to project patterns of light onto the target surface whose image is recorded by a camera. The shape of the captured pattern is combined with the spatial relationship between the light source and the camera, to determine the 3D position of the surface along the pattern. A surface can be scanned from a single 2D image and processed into 3D surface in a few milliseconds [15].



(a) (b)

Figure 6. **(a)** The 3D scanner captures a 2D image containing structured light**; (b)** 3D surface reconstruction from the 2D image using GMPR software

FACE1 FACE2 WALL

Figure 7. 2D images used in this research (dimension: 1392 x 1040 pixels, size: 1.38 MB)

In this research we use 3 images depicted in Fig 7; these will be subject to compression followed by 2D to 3D reconstruction. The justification for introducing 3D reconstruction is that we can make use of a new set of metrics in terms of error measures and perceived quality of the 3D visualization to assess the quality of the compression and decompression algorithms. The rationale is that high quality image compression is required, otherwise the resulting 3D structure from the decompressed image will contain apparent dissimilarities and artefacts when compared to the 3D structure obtained from the original (uncompressed) data. We report on these differences through standard measures of RMSE-root mean square error as shown in Table 1. Additionally Fig. 8 shows visualization of 3D reconstruction compared with original (uncompressed) images.

Table 1. Compression-encryption applied to 2D images followed by 2D to 3D reconstruction

Image Name	Quality	Compressed Size (KB)	2D RMSE	3D RMSE
FACE1	0.01	49.6	5.19	2.0
	0.05	24.4	5.67	1.01
FACE2	0.01	47.8	4.42	4.23
	0.05	23.7	5.2	3.88
WALL	0.01	23.0	2.1	0.3
	0.05	11.63	2.66	1.4

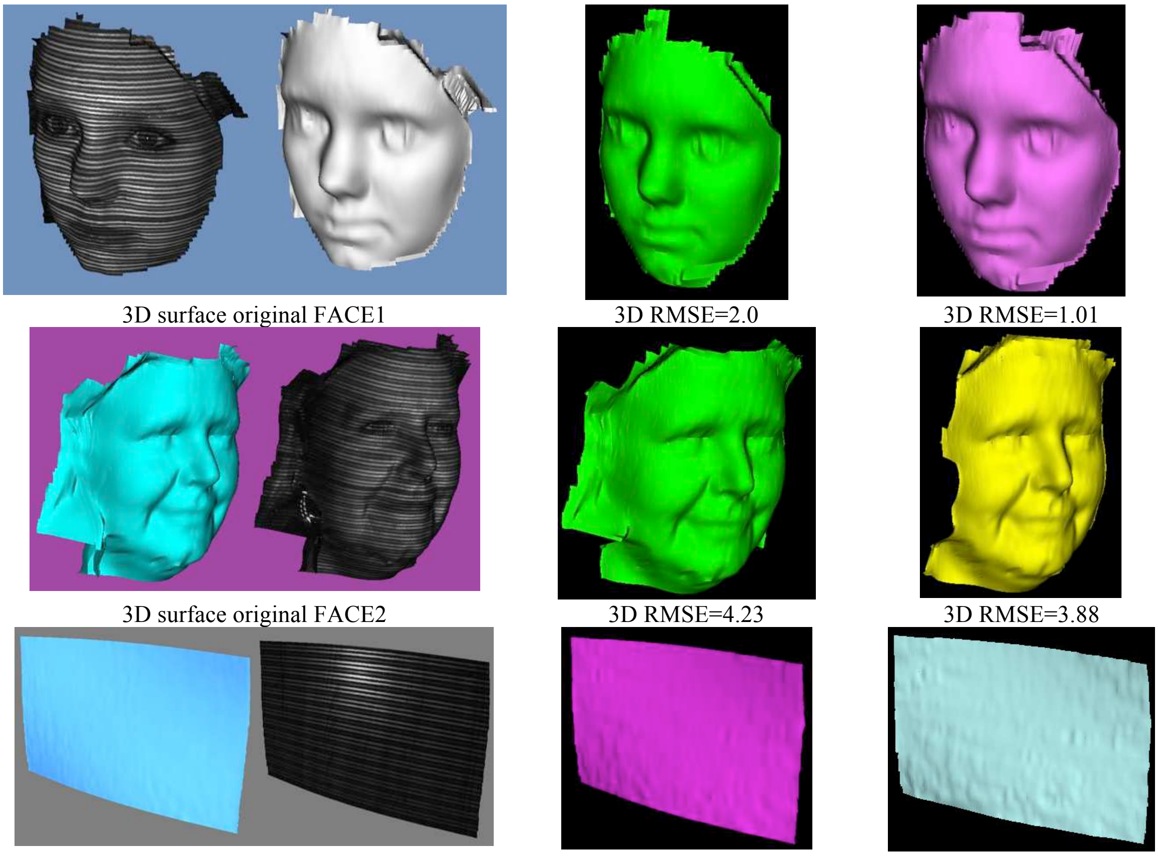


Figure 8. Comparison of 3D surface reconstruction using the original (uncompressed) images on the left, with compressed images on the right with RMSE measures.

8. CONCLUSIONS

This research has presented and demonstrated a novel method for 2D image compression and encryption. The quality of the method is illustrated through 2D to 3D reconstruction, 2D and 3D RMSE and the perceived quality of the visualization. The method is based on DWT and DCT in connection with the MMS algorithm. The results show that the proposed approach is capable of accurate 3D reconstructing with high compression ratios. The algorithm's advantages are highlighted as follows.

1. Using two transformations results in an increased number of high-frequency coefficients, leading to higher compression ratios.
2. The properties of the Daubechies wavelets are useful to obtain higher compression ratios; this is because high frequencies from the first level can be ignored without loss of accuracy.
3. The Minimize-Matrix-Size-Algorithm is used to partition the MA-Matrix into blocks and each row in each block are converted to a single value by Key_1. Additionally, it generates Key_2 for each block to increase the encryption level, thus Key_1 and Key_2 are both used in decryption step.
4. The SS-Algorithm (Decryption algorithm) represents the core of the decompression-decryption algorithm, which recovers the MA-Matrix by using encrypted data with Key_1 while Key_2 is used to specify the space search for each block in the recovered MA-Matrix.
5. The EZSD algorithm used in this research removes block of zeros; at the same time it converts a high-frequency sub-band to an array containing few nonzero data, this process increases the compression ratio.

The approach disadvantages are summarized as follows. The overall complexity of the approach leads to increased execution time for both compression-encryption and decompression-decryption; the SS-Algorithm iterative method is particularly complex. Future work includes tackling the complexity of the method and developing alternative approaches to encoding and decoding the key management methods.

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