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APPLICATION OF GREY-RELATIONAL ANALYSIS TO FIND THE MOST SUITABLE WATERMARKING SCHEME

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Abstract. *This study aimed to use the grey-relational analysis method to assess watermarking schemes that have been published in recent years. Watermarking technology has been widely used in multimedia copyright protection with good progress in development. However, each watermarking scheme has its advantages and disadvantages against various attacks, and the optimal resistance against all attacks has not been achieved. Therefore, this paper aimed to find the optimal watermarking scheme using grey-relational analysis. The experimental results showed that a relatively better watermarking scheme could be selected based on the various requirements of watermarking.*
Keywords: Grey-relational analysis, Optimal watermarking scheme, Discrete sequence, Larger-the-better, Smaller-the-better, Nominal-the-better

1. **Introduction.** In recent years, watermarking has been considered a viable and effective method in digital multimedia copyright protection. Watermarking in audio files and 2D or 3D images with good features [2-22] has been reported in numerous studies. For example, the hierarchy detector concept was proposed in [2] in order to increase the watermark withdrawing rate. Based on the human visual system (HVS), some studies have proposed a nonlinear self-masking model detector [3], with a watermark withdrawing

effect that is better than a linear correlation detector. Some studies have proposed multidimentional time-frequency analysis [4] that is suitable for watermarking audio, image and video signals. In terms of audio watermarking, some studies focused on studying the resistance to desynchronization attacks, such as time-scale modification (TSM) and random cropping. In [5], the researchers adopted an audio histogram shape for adding a multi-bit watermark so as to enhance resistance to TSM and random cropping attacks. In [6], the researchers adopted a synchronization pattern that is effective to synchronous attacks. In [7], Mansour and Tewfik adopted a time-scale invariant watermarking strategy. In [8,9], the researchers adopted a pitch-invariant TSM mode. In [10], Tachibana adopted multiple pseudo-random arrays to resist random cropping attacks. In terms of 2D images, Zheng et al. [11] used image segmentation to divide an image into several blocks, assigned a Gaussian distribution to each block, and used a mathematic model to add watermarks, resulting in significant improvements of resistance to rotation and scaling attacks. Akhaee et al. [12] adopted a maximum-likelihood decoder in combination with the optimum control of the watermarking intensity factor, so as to enhance resistance to rotation attacks. Wang et al. [13] chose the appropriate local characteristic region (LCR) to add a watermark and the Harris-Laplace detector to find watermarks, and found it has a significant effect in resistance to desynchronization attacks such as rotation. Boato et al. [14] adopted genetic algorithms (GA) to assess types of attack resistance before determining the watermark parameter intensity, in combination with a weighted peak signal-to-noise ratio (WPSNR) proposed in a human visual system (HVS), in order to improve the watermark withdrawing rate. Lin and Horng et al. [15,24] selected significant coefficients from wavelet coefficients with very strong resistance to attacks, such as JPEG compression, low-pass filtering and Gaussian noise. Lin and Horng et al. [23] inserted multiple copies of watermarks to improve the error rate. Lin et al. [25] proposed a wavelet-tree-based watermarking method using the distance vector of binary clusters to improve the robustness. Bi et al. [16] adopted multiband wavelet transformation to add watermarks to a number of middle-frequency subimages, with superior performance in resistance to JPEG compression, Gaussian noise and median filtering attacks. In terms of 3D images, in [17], a cluster tree was built from clusters of 3D points, then a watermark was imposed on the cluster tree to increase the watermark capacity and enhance the resisting attack intensity. In [18], the researchers applied 3D mesh spatial techniques in watermarking. In [19], the researchers adopted simple 3D meshes for watermarking. In [20], the researchers used progressive compression invariant points for watermarking, achieving better resistance to global attacks. In [21], the researchers applied 3D mesh nonspatial techniques in watermarking, with poorer resistance to local attacks. Zafeiriou et al. [22] applied 3D meshes in watermarking, with the number of watermarks based on mesh vertices, and found the results did not provide ideal resistance to local attacks. Lo et al. [26] found that higher-order statistics-based digital image watermark detectors could resist the impact of anti-Gaussian noise and anti-rotation. Lai et al. [27] stated that the digital image watermark scheme of the singular value decomposition (SVD) and micro-genetic algorithms could resist some impacts well. Zhang et al. [28] proposed a watermark scheme that could protect the data of a cloud computing system. Gu et al. [29] presented a new reversible watermarking algorithm with good effect. Although the watermarking schemes introduced above have very good resistance to a number of attacks, there is no single scheme that can resist all attacks. Therefore, an objective assessment and selection of methods is needed to find the optimal watermarking scheme. Usually, the grey-relational analysis method is used to analyze uncertain factors, and it can obtain good results. This paper also used grey-relational analysis to find the optimal watermarking scheme.

The remainder of this paper is organized as follows: Section 2 introduces the theory of grey-relational analysis; Section 3 discusses the grey-relational analysis in watermarking audio files; Section 4 describes the grey-relational analysis in watermarking 2D images; Section 5 presents the grey-relational analysis in watermarking 3D images; the concluding remarks are given in the last section.

2. The Theory of Grey-Relational Analysis.

Grey-relational analysis [1] is mainly used to conduct a relational analysis of the uncertainty of a system model and the incompleteness of information. It can generate discrete sequences for the correlation analysis of such sequences with processing uncertainty, multi-variable input and discrete data. Therefore, grey-relational analysis is a measurement method to discuss the consistency of an uncertain discrete sequence and its target. In a given group for grey-relational analysis, all the sequences should comply with the comparability conditions of normalization, S-calling and polarization.

2.1. Grey-relational generation.

First, generate the measurement space factor from the original sequence factor in a process known as grey-relational generation. This can be divided into three types: larger-the-better, smaller-the-better and nominal-the-better by characteristics.

- Larger-the-better grey-relational generation: the maximum of the sequence factors is the ideal factor.

$$X_i(p) = \left(X_i^{(0)}(p) - \min\ X_i^{(0)}(p)\right) / \left(\max\ X_i^{(0)}(p) - \min\ X_i^{(0)}(p)\right) \tag{1}$$

Example 2.1. *Take the SNR column in Table 1 for example,* $\min\ X_i^{(0)}(p) = 29.5dB$, $\max\ X_i^{(0)}(p) = 40dB$. *As to [7,10], there is no available data and the worst data (*$29.5dB$*) will be given, hence, after being calculated by Equation (1), the SNR for Tachibana et al. [6] in Table 2 is:*

$$X_i(p) = (35.0 - 29.5)/(40 - 29.5) = 0.524$$

- Smaller-the-better grey-relational generation: the minimum of the sequence factors is the ideal factor.

$$X_i(p) = \left(\max\ X_i^{(0)}(p) - X_i^{(0)}(p)\right) / \left(\max\ X_i^{(0)}(p) - \min\ X_i^{(0)}(p)\right) \tag{2}$$

Example 2.2. *Take the BER%/Rotation column in Table 5 for example. Based on the different rotation degrees, the BER% is hard to compare for all methods listed in Table 5. Set the rotation degree to 1°, then each BER% is normalized to 1°. For example, the BER%/Rotation of [11] is 12.5%/45° originally. After normalization, it becomes 0.28%/1°. The rest are then normalized to 2.02%/1°, 2.23%/1°, 33%/1°, 30.2%/1° and 30.4%/1°, respectively. Hence,* $\min X_i^{(0)}(p) = 0.28\%/1°$, $\max X_i^{(0)}(p) = 33\%/1°$. *As calculated by Equation (2), the BER%/Rotation for Akhaee et al. [12] in Table 6 is:*

$$X_i(p) = (33 - 2.02)/(33 - 0.28) = 0.95$$

- Nominal-the-better grey-relational generation: the one in line with the target value of the sequence factors is the ideal factor.

$$X_i(p) = 1 - \left|X_i^{(0)}(p) - OD\right| / \max\ \left[\max\ X_i^{(0)}(p) - OD; OD - \min\ X_i^{(0)}(p)\right] \tag{3}$$

where OD is the target value; $X_i(p)$ is the data after grey-relational generation; $\max\ X_i^{(0)}(p)$ is the maximum value of the original sequence factor; $\min\ X_i^{(0)}(p)$ is the minimum value of the original sequence. The signal to noise ratio (SNR) is used as a metric to measure the signal to the noise. Usually, the ratio used is the larger the better.

Example 2.3. *For example, in Table 1, suppose an SNR value of [8] is chosen as the target value, then* $OD = 32.4dB$, $\min X_i^{(0)}(p) = 29.5dB$, $\max X_i^{(0)}(p) = 40dB$. *As calculated by Equation (3), the SNR value of Tachibana et al. [6] in Table 2 becomes:*

$$X_i(p) = 1 - |35.0 - 32.4| / \max\ [40 - 32.4; 32.4 - 29.5] = 0.66$$

The algorithms for larger-the-better, smaller-the-better and nominal-the-better are listed in the following.

Algorithm 2.1.1
Algorithm grey-relational generation for larger-the-better (....)
{
Step 1: if the metrics are quite different, run data normalization first.
Step 2: find the maximum of the raw data or normalized data.
Step 3: find the minimum of the raw data or normalized data.
Step 4: if the raw data is not available then it is replaced with the object that is farthest from the ideal value, and it is represented by the minimum.
Step 5: calculate the grey-relation generation as stated in Equation (1).
}

FIGURE 1. Algorithm grey-relational generation for larger-the-better

Algorithm 2.1.2
Algorithm grey-relational generation for smaller-the-better (....)
{
Step 1: if the metrics are quite different, run data normalization first.
Step 2: find the maximum of the raw data or normalized data.
Step 3: find the minimum of the raw data or normalized data.
Step 4: if the raw data is not available then it is replaced with the object that is farthest from the ideal value, and it is represented by the maximum.
Step 5: calculate the grey-relation generation as stated in Equation (2).
}

FIGURE 2. Algorithm grey-relational generation for smaller-the-better

Algorithm 2.1.3
Algorithm grey-relational generation for nominal-the-better (....)
{
Step 1: if the metrics are quite different, run data normalization first.
Step 2: determine the target value.
Step 3: find the maximum of the raw data or normalized data.
Step 4: find the minimum of the raw data or normalized data.
Step 5: if the raw data is not available, it is replaced with the object that is farthest from the ideal value, and if $\max X_i^{(0)}(p) - OD > OD - \min X_i^{(0)}(p)$, then it is represented by $\max X_i^{(0)}(p)$; otherwise, it is represented by $\min X_i^{(0)}(p)$.
Step 6: calculate the grey-relation generation as stated in Equation (3).
}

FIGURE 3. Algorithm grey-relational generation for nominal-the-better

2.2. **Grey-relational degree.** The grey-relational degree is used to measure the correlation between the measurement space factor and target sequence after a grey-relational generation of the discrete sequence. The grey-relational degree can be divided into two types of localized grey-relational degree and globalized grey-relational degree. This paper used the localized grey-relational degree in analysis.

Suppose that

$X_o(p)$: the target sequence, $o = 1, 2, \ldots, m$;

$X_i(p)$: the comparison sequences.

Assume each comparison sequence has m data and $i = 1, 2, \ldots, m$. Also assume there are n comparison sequences, where $p = 1, 2, \ldots, n$. The grey-relational coefficient is defined as

$$\gamma\left(X_o(p), X_i(p)\right) = (\Delta\text{min} + \zeta \times \Delta\text{max})/(\Delta oi(p) + \zeta \times \Delta\text{max}) \tag{4}$$

where

$\Delta\,\text{min}$: the absolute value of the minimum difference of the comparison sequence and the target sequence;

$\Delta\,\text{max}$: the absolute value of the maximum difference of the comparison sequence and the target sequence;

$\Delta oi(p) = |X_o(p) - X_i(p)|$: the absolute value of the target sequence and the comparison sequence;

ζ: identification coefficient, [0, 1].

Finally, the average value of the grey-relational coefficient for n comparison sequences is obtained as below:

$$\gamma(X_i) = (1/n)\Sigma\gamma\big(X_o(p), X_i(p)\big) \tag{5}$$

Example 2.4. *Taking the SNR column in Table 2 for example, let* $X_o(p) = \{1, 1, 1, 1, 1, 1\}$*, as it is the largest value based on the larger-the-better grey-relational generation.* $X_i(p) = \{0,\ 0.524,\ 0,\ 0.276,\ 0,\ 1\}$*, and* $\zeta = 0.5$*, then* $\Delta\,\text{min} = |X_o(p) - X_6(p)| = 1 - 1 = 0$*,* $\Delta\,\text{max} = |X_o(p) - X_1(p)| = 1 - 0 = 1$*,* $\Delta o2(p) = |X_o(p) - X_2(p)| = 0.476$*. Using Equation (4), the SNR of Tachibana et al. [6] in Table 3 is:*

$$\gamma\left(X_o(p), X_2(p)\right) = (0 + 0.5 \times 1)/(0.476 + 0.5 \times 1) = 0.54.$$

Then using Equation (5), the average value $\gamma(X_2)$ *of Tachibana et al. [6] in Table 4 is:*

$$\gamma(X_2) = (1/3)(0.54 + 0.33 + 0.33) = 0.40 = 40\%.$$

The algorithm for the grey-relational degree is listed in Figure 4.

According to the discrete sequences obtained under various attacks with the addition of different watermarking schemes, compare the measurement space factor after the grey-relational generation with the target sequence to obtain the average value of the grey-relational coefficient. Such an average value is the grey-relational degree between various watermarking schemes and the ideal scheme. The scheme with the largest grey-relational degree against the ideal scheme is the optimal choice. The following sections discuss the grey-relational analysis of watermarking schemes in sound files, 2D images and 3D images.

3. **Grey-Relational Analysis of Watermarking Schemes for Audio Files.** In recent years, watermarking schemes for audio files have been categorized into two types: (1) hosting-interference non-rejecting methods, and (2) hosting-interference rejecting methods. The first type simply adds false noise sequences and the second type is similar to the QIM (quantization index modulation) method. For both methods, the problems to be solved are attacks of desynchronizing distortion and the arbitrary cutting of TSM (time-scale modulation). From articles published in recent years, this paper selected six

Algorithm 2.2.1

Algorithm grey-relational degree (....)

{

Step 1: generate the comparison sequence according to larger-the-better, smaller-the-better or nominal-the-better.

Step 2: generate the target sequence from the comparison sequence, where each element of the target sequence is set to the largest no matter what kind of comparison sequence was generated in Step 1.

Step 3: according to the grey-relation generation data sheet, calculate the absolute difference between every comparison sequence and the corresponding target sequence, $\Delta oi(p)$.

Step 4: from Step 2, find the maximal absolute difference, Δmax.

Step 5: from Step 2, find the minimal absolute difference, Δmin.

Step 6: determine ζ, (here $\zeta = 0.5$), it is used to select the grey-relational degree of average distribution. If $1 > \zeta > 0.5$, then the grey-relational degree moves toward the maximum value; if $0.5 > \zeta > 0$, then the grey-relational degree moves toward the minimum value.

Step 7: calculate the grey-relational coefficient using Equation (4). If each data row of anycolumn in the grey-relational generation table is the same (such as the uniform affine transforms column and the element reordering column in Table 10), and the grey-relational degree is not compared, the corresponding grey-relational coefficient table (such as the uniform affine transforms column and element reordering column in Table 11) will not be included in the comparison.

Step 8: according to the grey-relational coefficient in Step 7, calculate the grey-relational degree using Equation (5).

}

FIGURE 4. Algorithm grey-relational degree

for grey-relational analysis in order to find the method with the highest grey-relational degree, that is, the relatively best watermarking scheme for audio files.

This paper applied the larger-the-better scheme to find the grey-relational generation for each attribute listed in Table 1. The results are shown in Table 2. According to the Figure 1 algorithm, take the SNR column in Table 1 for example:

Step 1: data normalization is unnecessary for the SNR column.

Step 2: max $X_i^{(0)}(p) = 40$dB.

Step 3: min $X_i^{(0)}(p) = 29.5$dB.

Step 4: the SNR of [7] and that of [10] is represented by 29.5dB (as min $X_i^{(0)}(p) = 29.5$dB), respectively.

Step 5: calculate the grey-relation generation using Equation (1). The SNR of [6] in Table 2 is then:

$$X_i(p) = (35.0 - 29.5)/(40 - 29.5) = 0.524.$$

Others can be calculated similarly.

Note that the Watermarking capacity column listed in Table 1 has to be normalized, and all are normalized to the number of bits per second. Hence, after normalization, the watermarking capacity column becomes {2.3/s, 2.13/s, 2.13/s, 4.26/s, 4.26/s, 3/s}.

According to Step 1∼Step 7 in the Figure 4 algorithm, take the SNR column in Table 2 for example:

Step 1: $X_i(p) = \{0, 0.524, 0, 0.276, 0, 1\}$.

Step 2: $X_0(p) = \{1, 1, 1, 1, 1, 1\}$.

Step 3: $\Delta o_i(p) = \{1, 0.476, 1, 0.724, 1, 0\}$.

Step 4: $\Delta\max = 1$.

Table 1. Relevant data of the original six articles for audio files

Algorithms	SNR	Watermarking capacity	Resistance to TSM attack
Mansour et al. [7]	not available	2.3 bits/1s	about ±8%
Tachibana et al. [6]	35.0dB	64 bits/30s	about ±4%
Tachibana et al. [10]	not available	64 bits/30s	about ±8%
Li et al. [8]	32.4dB	64 bits/15s	about ±7%
Li et al. [9]	29.5dB	64 bits/15s	about ±10%
Xiang et al. [5]	> 40dB	60 bits/20s	about ±20%

Table 2. Grey-relational generation of the six articles for audio files

Algorithms	SNR	Watermarking capacity	Resistance to TSM attack
Mansour et al. [7]	0	0.079	0.25
Tachibana et al. [6]	0.524	0	0
Tachibana et al. [10]	0	0	0.25
Li et al. [8]	0.276	1	0.187
Li et al. [9]	0	1	0.375
Xiang et al. [5]	1	0.41	1

Step 5: $\Delta\text{min} = 0$.
Step 6: $\zeta = 0.5$.
Step 7: Using Equation (4), the SNR of [6] in Table 3 is:

$$\gamma\left(X_0(p), X_2(p)\right) = (0 + 0.5 \times 1)/(0.476 + 0.5 \times 1) = 0.54.$$

Others can be calculated similarly.

According to Step 8 in Figure 4, take Tachibana et al. [6] in Table 3 for example:

Step 8: Using Equation (5), Tachibana et al. [6] in Table 4 can be obtained as:

$$\gamma(X_2) = (1/3)(0.54 + 0.33 + 0.33) = 0.40 = 40\%$$

The grey-relational degree shown in Table 4 indicates that the method proposed in article [5] was the best, although the watermarking capacity of [5] was worse than those of [8,9], respectively.

4. Grey-Relational Analysis of Water Marking Schemes for 2D Images.

Methods of watermarking the digital content of 2D images, such as DCT, DFT, DWT, as well

Table 3. The grey-relational coefficient of six articles for audio files

Algorithms	SNR	Watermarking capacity	Resistance to TSM attack
Mansour et al. [7]	0.33	0.35	0.4
Tachibana et al. [6]	0.54	0.33	0.33
Tachibana et al. [10]	0.33	0.33	0.4
Li et al. [8]	0.41	1	0.38
Li et al. [9]	0.33	1	0.44
Xiang et al. [5]	1	0.46	1

TABLE 4. Grey-relational degrees of methods proposed in six articles for audio files

Algorithms	Grey-relational degree
Mansour et al. [7]	36%
Tachibana et al. [6]	40%
Tachibana et al. [10]	35%
Li et al. [8]	59.7%
Li et al. [9]	59%
Xiang et al. [5]	82%

as various types of modification methods [11-16] have been widely published in the literature. However, image quality and resistance to attacks can still not be achieved at the same quality, as almost all methods will perform differently with resistance to different attacks. This paper analyzed six typical methods [11-16] as follows:

The grey-relational generation for PSNR was based on the larger-the-better scheme, but those of the rest were based on the smaller-the-better scheme. The grey-relational generation for the six articles shown in Table 5 is shown in Table 6. According to the Figure 2 algorithm, take the BER%/Rotation column in Table 5 for example:

Step 1: normalize the BER% to per degree, $X_i^{(0)}(p) = \{0.28\%/1°,\ 2.02\%/1°,\ 2.23\%/1°,\ 33\%/1°,\ 30.2\%/1°,\ 30.4\%/1°\}$.
Step 2: max $X_i^{(0)}(p) = 33\%/1°$.
Step 3: min $X_i^{(0)}(p) = 0.28\%/1°$.
Step 4: all data are available.
Step 5: using Equation (2), the BER%/Rotation of [12] in Table 6 is:

$$X_i(p) = (33 - 2.02)/(33 - 0.28) = 0.95$$

Others can be calculated similarly.

TABLE 5. Relevant data of the original six articles for 2D images

Algorithms	PSNR	BER%/ Rotation	BER%(JPEG, QF=30)	BER%/ Scaling
Zheng et al. [11]	42.089dB	12.5%/45°	50%	12.5%/1.2
Akhaee et al. [12]	42dB	4.03%/2°	0%	0%/1.2
Wang et al. [13]	42dB	67%/30°	67%	83%/1.4
Boato et al. [14]	40.6dB	74%/2.25°	48%	65%/0.25
Lin et al. [15]	44.25dB	68%/2.25°	13%	14%/0.25
Bi et al. [16]	42dB	60.94%/2°	0%	not available

According to Step 1∼Step 7 in the Figure 4 algorithm, take the PSNR column in Table 6 for example:

Step 1: $X_i(p) = \{0.41,\ 0.39,\ 0.39,\ 0,\ 1,\ 0.39\}$.
Step 2: $X_o(p) = \{1,\ 1,\ 1,\ 1,\ 1,\ 1\}$.
Step 3: $\Delta o_i(p) = \{0.59,\ 0.61,\ 0.61,\ 1,\ 0,\ 0.61\}$.
Step 4: $\Delta\max = 1$.
Step 5: $\Delta\min = 0$.
Step 6: $\zeta = 0.5$.
Step 7: using Equation (4), the PSNR of [11] in Table 7 is:

$$\gamma\left(X_o(p), X_1(p)\right) = (0 + 0.5 \times 1)/(0.59 + 0.5 \times 1) = 0.46$$

Table 6. The grey-relational generation of six articles for 2D images

Algorithms	PSNR	BER%/ Rotation	BER%(JPEG, QF=30)	BER%/ Scaling
Zheng et al. [11]	0.41	1	0.26	0.71
Akhaee et al. [12]	0.39	0.95	1	1
Wang et al. [13]	0.39	0.93	0	0
Boato et al. [14]	0	0	0.28	0.60
Lin et al. [15]	1	0.093	0.81	0.92
Bi et al. [16]	0.39	0.086	1	0

Others can be calculated similarly.
For the rest of the columns of Table 6, all target sequences are set to {1, 1, 1, 1, 1, 1}.

According to Step 8 in the Figure 4 algorithm, take Zheng et al. [11] in Table 7 for example:

Step 8: using Equation (5), Zheng et al. [11] in Table 8 is:

$$\gamma(X_1) = (1/4)(0.46 + 1 + 0.40 + 0.63) = 0.62 = 62\%$$

Table 7. The grey-relational coefficients of six articles for 2D images

Algorithms	PSNR	BER%/ Rotation	BER%(JPEG, QF=30)	BER%/ Scaling
Zheng et al. [11]	0.46	1	0.40	0.63
Akhaee et al. [12]	0.45	0.91	1	1
Wang et al. [13]	0.45	0.88	0.33	0.33
Boato et al. [14]	0.33	0.33	0.41	0.56
Lin et al. [15]	1	0.36	0.73	0.86
Bi et al. [16]	0.45	0.35	1	0.33

Table 8. Grey-relational degrees of methods proposed in six articles for 2D images

Algorithms	Grey-relational degree
Zheng et al. [11]	62%
Akhaee et al. [12]	84%
Wang et al. [13]	49%
Boato et al. [14]	41%
Lin et al. [15]	74%
Bi et al. [16]	53%

Like before, the grey-relational degree as shown in Table 8 shows that the method proposed in article [12] was the best one although the PSNR and BER%/Rotation were not the best out of all the methods.

5. **Grey-Relational Analysis of Watermarking Schemes for 3D Images.** Objects in 3D images often appear in CAD products, therefore, in recent years, watermarking schemes for 3D images have been introduced, such as the adoption of grids of various shapes and modifications [17-22]. Grey-relational analysis was conducted for the six articles to find the optimal method as below.

Table 9. Relevant data of the original six articles for 3D images

Algorithms	Uniform affine transforms	Local attack	Global attack	Remeshing or retriangulation	Element reordering
Agarwal et al. [17]	100%	100%	67%	100%	100%
Cayre et al. [18]	100%	50%	33%	25%	100%
Cho et al. [19]	100%	25%	100%	100%	100%
Alface et al. [20]	100%	75%	100%	100%	100%
Uccheddu et al. [21]	100%	25%	100%	25%	100%
Zafelrou et al. [22]	100%	25%	100%	100%	100%

This paper also used the larger-the-better scheme to find the grey-relational generation for each attribute listed in Table 9. The results are shown in Table 10. According to the Figure 1 algorithm, take the local attack column in Table 9 for example:

Step 1: no data normalization.
Step 2: $\max X_i^{(0)}(p) = 100\%$.
Step 3: $\min X_i^{(0)}(p) = 25\%$.
Step 4: all raw data are available in every case.
Step 5: calculate the grey-relation generation using Equation (1), e.g., the local attack of [18] in Table 10 is:

$$X_i(p) = (50 - 25)/(100 - 25) = 0.33$$

Others can be computed similarly.

Like before, following Step 1 to Step 7, for the local attack column in Table 10, the snapshots of the algorithm listed in Figure 4 are shown in the following:

Step 1: $X_i(p) = \{1,\ 0.33,\ 0,\ 0.67,\ 0,\ 0\}$
Step 2: $X_0(p) = \{1,\ 1,\ 1,\ 1,\ 1,\ 1\}$.
Step 3: $\Delta oi(p) = \{0,\ 0.67,\ 1,\ 0.33,\ 1,\ 1\}$.
Step 4: $\Delta \max = 1$.
Step 5: $\Delta \min = 0$.
Step 6: $\zeta = 0.5$.
Step 7: using Equation (4), the local attack of [18] in Table 11 is:

$$\gamma(X_0(p), X_2(p)) = (0 + 0.5 \times 1)/(0.67 + 0.5 \times 1) = 0.43$$

According to Step 7 in the Figure 4 algorithm, the uniform affine transforms column and the element reordering column in Table 11 were not included in the comparison.

According to Step 8 in the Figure 4 algorithm, using Equation (5), the average value of grey-relational coefficient of [18] in Table 11 can be computed by

$$\gamma(X_2) = (1/3)(0.43 + 0.33 + 0.33) = 0.36 = 36\%.$$

The result is shown in Table 12. All other results were obtained similarly.

In Table 9, for the method described in [20], the local attack was not the best of all methods but the Grey relation from Table 12 showed that article [20] was the best method, as it had the largest grey-relational degree.

6. **Conclusions.** This paper proposed grey-relational analysis for supporting a watermarking scheme that does not have the best effect in all attacks. By using grey-relational analysis for the watermarking schemes in audio files, 2D images and 3D images, based on the grey-level degree, a relatively better watermarking scheme for each medium was be

TABLE 10. The grey-relational generation of six articles for 3D images

Algorithms	Uniform affine transforms	Local attack	Global attack	Remeshing or retraingulation	Element reordering
Agarwal et al. [17]	1	1	0.5	1	1
Cayre et al. [18]	1	0.33	0	0	1
Cho et al. [19]	1	0	1	1	1
Alface et al. [20]	1	0.67	1	1	1
Uccheddu et al. [21]	1	0	1	0	1
Zafelrou et al. [22]	1	0	1	1	1

TABLE 11. Grey-relational coefficient of 6 articles for 3D images

Algorithms	Uniform affine transforms	Local attack	Global attack	Remeshing or retraingulation	Element reordering
Agarwal et al. [17]	*	1	0.50	1	*
Cayre et al. [18]	*	0.43	0.33	0.33	*
Cho et al. [19]	*	0.33	1	1	*
Alface et al. [20]	*	0.60	1	1	*
Uccheddu et al. [21]	*	0.33	1	0.33	*
Zafelrou et al. [22]	*	0.33	1	1	*

*not included in comparison

TABLE 12. Grey-relational degrees of methods as proposed in six articles for 3D images

Algorithms	Grey-relational degree
Agarwal et al. [17]	83%
Cayre et al. [18]	36%
Cho et al. [19]	77%
Alface et al. [20]	87%
Uccheddu et al. [21]	55%
Zafelrou et al. [22]	77%

found. The results can serve as a reference to future studies. The weight of the identification coefficient $\zeta[0, 1]$ can be adjusted according to the needs of selectors. In this paper, it was assumed that all metrics had the same importance and used the same value for each sequence. In the future, grey-relational analysis may also be used to study the selection of factor strengths in watermarking schemes or the selection of watermarked regions.

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