Reversing Global and Local Geometrical Distortions in Image Watermarking

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Abstract. A new method improving watermark robustness against both global and local geometrical distortions is presented in this article. The proposed approach is based on a self-reference concept and exploits special autocorrelation features of a spatial template. The template allows identifying both the transformation parameters and translation coordinates. Distortions are estimated and reversed on a level as global as possible to maximize watermark recovery effectiveness and minimize a time needed for that purpose. Experimental results showed that an inserted watermark could be successfully read even after Stirmark attack.

1 Introduction

In the course of a few last years intensive research has been done in the field of digital watermarking. Many algorithms, methods, techniques and fully functional systems hiding information in images have been elaborated. Several industrial solutions have also been developed. Nevertheless, an important problem concerning most current watermarking methods is their vulnerability to geometrical distortions. Such distortions as translation, scaling, rotation, shearing, projection and random bending do not remove the watermark but desynchronize its detection and make automatic decoding impossible. Although many systems are more or less robust against global affine geometrical transformations, it appears that utilized algorithms are often insecure. Local and nonlinear distortions are even more difficult to resist.

The state of the art methods for detecting watermarks after geometrical distortions can be divided into the following groups:

- methods operating in transformation invariant domain,
- methods using exhaustive search for an *a priori* known template,
- methods exploiting permanent image features,
- methods inserting some easy to find features,
- methods exploiting the self-reference of a template,
- other methods (self similarity, fractals).

The methods operating in transformation invariant domain often exploit the properties of Fourier-Mellin transform (FMT) [1][2]. Other methods, like embedding a circular watermark in Fourier transform domain [3], are to some degree similar to FMT. An important property of the discrete Fourier transform (DFT) is that its magnitude is invariant to translations in the spatial domain. Spatial shifts affect only the phase representation of an image, thus a watermark inserted into a magnitude spectrum is robust against cropping. If we represent a DFT magnitude spectrum as a log-polar map, both rotation and scaling are converted to a translation that can be estimated by cross-correlation with the template. Similarly, a log-log map converts aspect ratio changes to a translation. However, the effect of more general geometrical transformations cannot be reversed. Another important disadvantage of those methods is their poor robustness against JPEG compression and other non-geometrical attacks, because of the use of magnitude components, which are less robust and have more visual impact than phase components.

A completely different strategy was presented by Hartung et al. [4]. Hartung proposes an exhaustive search for an *a priori* known template. The decoder examines each combination of scaling, translation or rotation for every small block (e.g. 16x16 pixels). The authors suggest that only a small percentage of all search positions have to be tested. However, this approach, although functioning, is in general very time consuming.

Some researchers present methods exploiting permanent image features. Alghoniemy and Tewfik [5] propose to compute two indicators to estimate scaling and rotation parameters. The "Edges Standard Deviation Ratio" gives an estimation of the scaling factor. The rotation angle is approximated by the "Average Edges Angles Difference". These indicators are computed from wavelet maxima locations.

A more sophisticated approach based on image features was proposed by Bas et al. [6]. Firstly, feature points of the image are extracted and a Delaunay tessellation on the set of points is performed. Then the mark is embedded inside each triangle of the tessellation using a classical additive scheme. The detection is done using correlation properties on the different triangles. The presented technique permits automatic resynchronization of the watermark after both local and slight global (rotations, scaling) geometrical transformations. An important advantage of that method is that the orientation of the signature is carried by the content of the image itself. Celik *et al* showed another example of using certain features of the image itself as a watermark's synchronization points [7]. Johnson *et al* proposed a different approach related to the concept of permanent image features [8]. A small set of "salient" image points is saved as an identification mark of the image. The coordinates of those points are used as a key to recover an original size and appearance of geometrically distorted images.

Another group of methods concerning the synchronization problem insert some easy-to-find features to the image. Gruhl and Bender suggested a scheme in which a predefined reference pattern (for example multiple cross shapes) is embedded into a host image using any of the high bit-rate coding techniques (for example by LSB plane manipulation) [9]. Estimation of the geometric transformation of the image is achieved by comparing the original shape, size, and orientation of the reference pattern to that found in the transformed image. The drawback of this scheme is its low robustness towards compression and noise. Kostopoulos, Skodras and Christodoulakis also propose to embed a reference pattern consisting of cross-shaped figures [10]. The method uses a predefined set of attacked cross-shaped patterns in order to approximate a possible attack. However, usability of the proposed scheme is limited to detection of the predefined geometrical attacks only.

The same group includes methods inserting “peaks” in Fourier transform domain. Pereira and Pun propose to embed the template consisted of a random arrangement of peaks in the Fourier domain [11]. Then a point-matching algorithm between the peaks extracted from an image and the reference template points estimates the geometric transformation. Another method based on a calibration signal in the Fourier domain has been patented by Digimarc Corporation [12]. Unfortunately, template peaks can be easily removed by an attacker. In addition, such an operation can improve the quality of the attacked image [13].

The methods exploiting the self-reference of a template have very promising results. Kutter suggested embedding four shifted copies of the same template [14]. Deguillaume et al. propose to insert many neighboring copies of a relatively small template [15]. A similar approach was presented by Honsinger and Rabbani [16] where a watermark itself is copied. Multiple copies of the same pattern produce local peaks in an autocorrelation function spectrum. These peaks undergo the same transformations as the image, so estimating the transform matrix is possible. The self-reference concept is useful to recover from global geometrical distortions, and with some enhancements, it can help in a local distortions case [17]. However, multiple copies of the same small pattern create a possibility of an autocorrelation attack [18].

Other methods exploit fractal properties and self-similarity of the image [19]. First results were promising (robustness to basic geometric transformations), but that concept still needs further research.

Most of the approaches described above assume that geometrical changes introduced into an image have global, affine character. Local or nonlinear distortions cannot be detected with those methods mainly because such distortions do not affect globally transform domains (Fourier, autocorrelation) and the size of modified regions is often smaller then the templates’ size. Unfortunately, small nonlinear distortions, which efficiently destroy watermarks, do not result in a sufficient perceptible image quality loss, so the watermarking systems that fail to resist such attacks, cannot be considered robust and secure.

It is noteworthy, that some watermarking algorithms do not need perfect decoder synchronization and can resist some very small geometrical distortions [20][21]. This property can reduce the template search space and enhance the watermark resistance to approximation errors. To achieve such synchronization tolerance, a watermark can be embedded in mid- or low-frequencies, so its autocorrelation is not as narrow as for a high-frequency watermark.

This work presents a method based on the self-reference concept, allowing estimation and recovering from local or nonlinear geometrical transformations. The watermark is decoded after reversing geometrical distortions.

2 Geometrical Distortions

Nonlinear geometrical distortions can be introduced in the printing/scanning process (it especially depends on scanner quality) or with adequate software. The Stirmark benchmarking tool applies some almost unnoticeable geometric distortions: combination of stretching, rotating, cropping, shifting, and bending by small random amounts. Additionally, slight random displacements, both low and high frequency, are applied to each pixel [22].

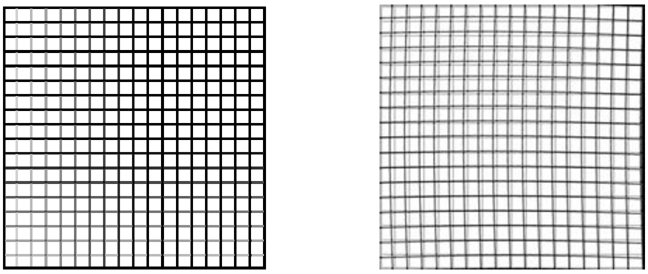


Fig. 1. A regular grid (*left*) and a grid subjected to Stirmark attack – small local distortions are visible (*right*)

The Stirmark attack, although nonlinear on the global level, can be considered as a composition of affine transforms concerning small local regions of the image. The size of those regions is not constant, because the frequency of attack displacements varies randomly. The approach proposed herein is based on that observation.

Geometrical transformations, such as scaling, rotation, shearing or any combination of them, can be represented as an affine transform:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = A \cdot \begin{bmatrix} x \\ y \end{bmatrix} + T, \quad A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}, \quad T = \begin{bmatrix} t_x \\ t_y \end{bmatrix} \qquad (1)$$

The expression (1) maps each point of the original image from Cartesian coordinates *(x, y)* to new coordinates *(x', y')* in the transformed image, where *a, b, c, d* are the components of the transformation matrix *A* and t_x, t_y are the components of the translation vector *T*. Equation 1 does not describe all possible image distortions, e.g. perspective or trapezium-like transformations. However, we can use it for local regions of the image to approximate global, generally non-linear distortion.

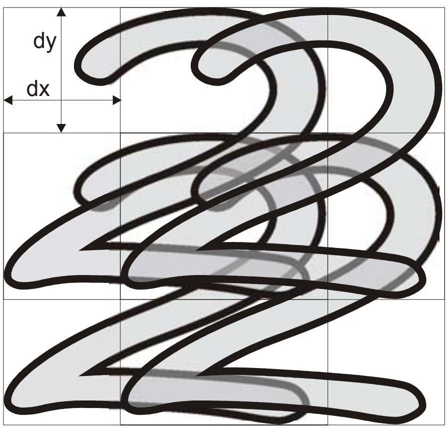
The estimation of affine transformation parameters is decomposed into two parts. The *A* matrix components are calculated with the use of a self-referencing template and its autocorrelation. Subsequently the image is transformed to restore the original image position. Then the translation is estimated by calculating the cross-correlation matrix of a distorted watermarked image and a key-dependant, *a priori* known template.

3 Self-referencing Template Embedding

As stated before, the proposed method is based on the self-reference concept. A specially designed template is used to recover from geometrical distortions. Generally, there were two approaches to the self-referencing template design presented in the previous work. Kutter proposed embedding four shifted copies of the same template in the spatial domain [14]. A schematic view of that idea is depicted on

Fig. 2. In ideal conditions, the template autocorrelation function has 9 peaks with the strongest one in the center. The four peaks on the axes are two times weaker, and four peaks on the diagonals are four times weaker then the center one. Such autocorrelation function properties enable both identifying parameters of the geometrical transformation (the *A* matrix) and finding translation of the attacked image (the *T* vector). Another advantage of the Kutter's approach is its relatively good resistance to autocorrelation attack, because only four copies of the template are embedded into the image. On the other hand the scheme makes it difficult to recover from local or non-linear geometrical distortions. In that case the *dx* and *dy* shifts should be small, in order to detect geometrical transformations on local level, but too small shifts can cause unacceptable approximation errors. A different problem is overlapping of the shifted copies, which can – depending on an implementation - increase visible artifacts (when overlapping template pixels) or lower robustness to non-geometrical distortions (when not overlapping pixels, but embedding watermark in very high frequencies).

Another idea assumes inserting into the image multiple adjoining copies of the same pattern (Fig. 3)[15][16]. The corresponding autocorrelation function spectrum has some very useful features. First of all there are many peaks placed in the corners of a regular grid and each peak has the maximum autocorrelation value 1 (in ideal conditions). That fact makes it possible to successfully recover even from local and non-linear geometrical distortions. Unfortunately, the regular template grid cannot be used to identify translation. To obey that drawback another template can be used, or a watermark can be embedded in translation invariant domain. However, the first solution enhances visible artifacts and the second usually reduces watermark robustness against non-geometrical attacks, i.e. JPEG compression.



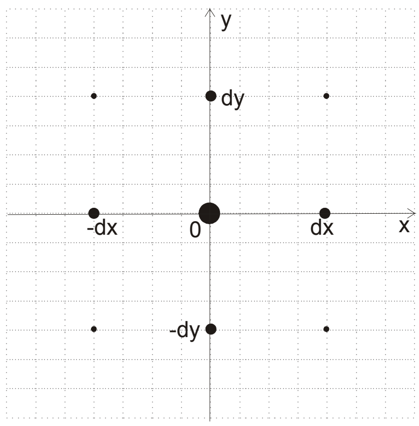


Fig. 2. A schematic view of the "shifted-copies" template design [14] and the corresponding autocorrelation function graph

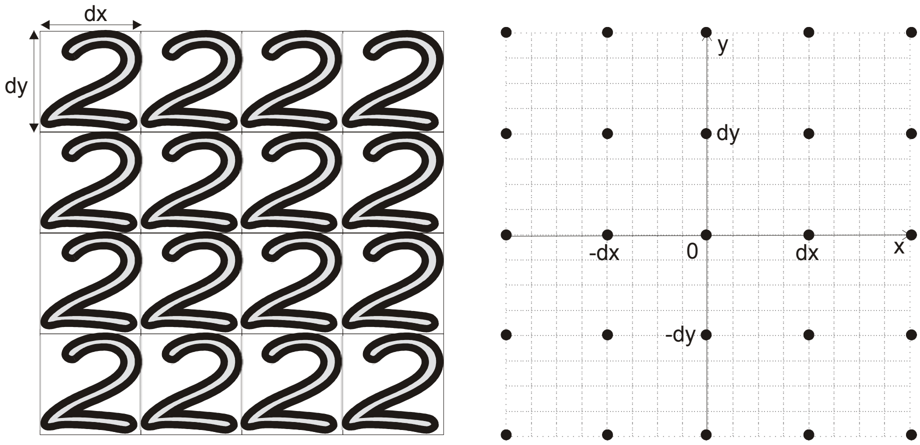


Fig. 3. A schematic view of the "multiple-copies" template design [15][16] and the corresponding autocorrelation function graph

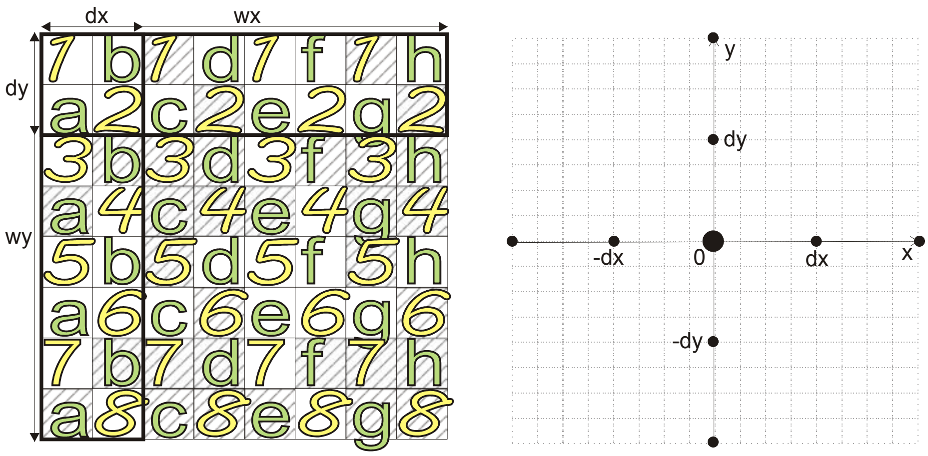


Fig. 4. A schematic view of the proposed template design and the corresponding autocorrelation function graph

The template proposed herein consists of two parts, which produce periodical peaks on the axes of the autocorrelation function graph (Fig. 4). Each part forms a narrow rectangle, which is copied along its shorter side. The longer side is as long as possible (lengths w*x, wy*), taking into account performance constraints and the expected image size. The shorter sides of the rectangles are relatively small (lengths *dx* and *dy*). The vertical rectangle is copied horizontally, so the copies form strong peaks on the OX coordinate axis, whereas the horizontal one is copied in the vertical direction, which forms peaks on OY. Additionally, every second copy of the template has a negated value of each pixel. This feature lowers visible artifacts, because it reduces the risk that an observer would notice a regular pattern on the watermarked image. The parts of the template do not overlap, but they have separate locations shown as digits and letters on Fig. 4. They jointly fill the whole image surface.

The initial template (before copying) is a spread spectrum sequence with zero mean, distributed on all frequencies and taking into account contrast sensitivity of the Human Visual System. It is constructed in discrete cosine transform (DCT) domain in order to achieve better robustness against JPEG compression. The embedding process is defined as adding the template values to image pixels' values in specified color space (i.e. luminance).

The proposed scheme has some advantages comparing to the two described above. In ideal conditions the autocorrelation function is defined as:

$$R(x,y)=\begin{cases}1, & (x,y)=(0,0)\\ \frac{1}{2}\cdot(-1)^{|n|}, & (x,y)=(n\cdot dx,0)\vee(x,y)=(0,n\cdot dy), n\neq 0\\ 0, & (x,y)\neq(n\cdot dx,n\cdot dy)\end{cases} \quad (2)$$

where dx and dy are the parameters of the template and n is an integer. Such properties allow the decoder to estimate both the geometrical transformation matrix A and the translation vector T. Regularly repeated autocorrelation peaks are used to determine geometrical distortions with good accuracy (approximation and rounding errors are minimized). Thanks to small dx and dy intervals it is possible to identify transformations on local level. Artifacts caused by a regularly repeated pattern are reduced, which improves a subjective image quality perception.

4 Recovering from Geometrical Deformations

The objective of that operation is to identify geometrical transformations performed on the watermarked image. At the initial stage it is necessary to minimize autocorrelation properties of the given image itself, and leave only the predicted template information. We use the second derivative of the image as the template prediction, using Laplace filters with various kernels (Fig. 5) to approximate the second derivative.

$$\begin{pmatrix}0 & -1 & 0\\ -1 & 4 & -1\\ 0 & -1 & 0\end{pmatrix}\quad\begin{pmatrix}-1 & 0 & -1\\ 0 & 4 & 0\\ -1 & 0 & -1\end{pmatrix}\quad\begin{pmatrix}0 & 0 & -1 & 0 & 0\\ 0 & 0 & -1 & 0 & 0\\ -1 & -1 & 8 & -1 & -1\\ 0 & 0 & -1 & 0 & 0\\ 0 & 0 & -1 & 0 & 0\end{pmatrix}$$

Fig. 5. Laplace filter kernels used to predict the hidden template

For each template prediction thus obtained, the following procedure is executed. We choose a fragment of the image and compute its autocorrelation function. At first we try to identify geometrical distortions on the global level (i.e. the image was simply scaled), so initially the chosen fragment covers the whole image.

Having computed the autocorrelation function values, all the local extreme peaks are found. Then we choose the two angles for which the sum of autocorrelation peaks is the biggest. Extremes with other angles are filtered out as a noise. For the chosen angles, all the extremes are compared to find the period in the sequence of their distances from the (0, 0) point. That step is carried out with computing for each pair of peaks' distances the equivalent of the greatest common divisor in real numbers domain, defined as:

$$RealGCD(a, b) = max\{d: a \bmod d < \varepsilon \;\&\; b \bmod d < \varepsilon\} \quad \textbf{(3)}$$

where ε is a tolerance. A modified version of Euclidean algorithm is used to calculate the extremes' distances period. The best fitting period for each angle is converted to a point in Cartesian coordinates. As a result of the presented sequence of operations, we obtain the coordinates of two points and a corresponding summary autocorrelation value. The two points represent the original template points *(0, dx)* and *(dy, 0)* after performing geometrical transformation. If the results of the self-referencing template detection for the chosen image block are satisfactory (summary autocorrelation value exceeds a given threshold), we can reverse geometrical distortions. Firstly an inverse transformation matrix is computed according to the formula:

$$A^{-1} = \begin{bmatrix} 0 & d_x \\ d_y & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 & x_2 \\ y_1 & y_2 \end{bmatrix}^{-1} \quad \textbf{(4)}$$

where d_x, d_y are initial template's shorter side lengths and (x_1, y_1), (x_2, y_2) are the coordinates of periodical peaks found before. Then the image block is transformed with A^{-1} matrix to recover its original position. The transformed block is saved to be used in the next step of the algorithm – the translation finding.

In the case of global affine deformations, most of the found extreme peaks are strong, regular and located on two straight lines. In such a situation, we do not need to acquire more information to restore the original image position. However, when distortions are local or nonlinear we do not obtain peaks satisfying the above requirements. If that happens, we divide the image into 5 blocks (each four times smaller than the divided block – see Fig. 6 (left)) and repeat recursively the template detection process for each block. The presented division scheme is a compromise between the accuracy of the sliding correlator and the effectiveness of the algorithm. It is also influenced by partial autocorrelation properties of the template. Thanks to the template properties, autocorrelation peaks should be relatively strong on each decomposition level until the block size is comparable with the initial template size.

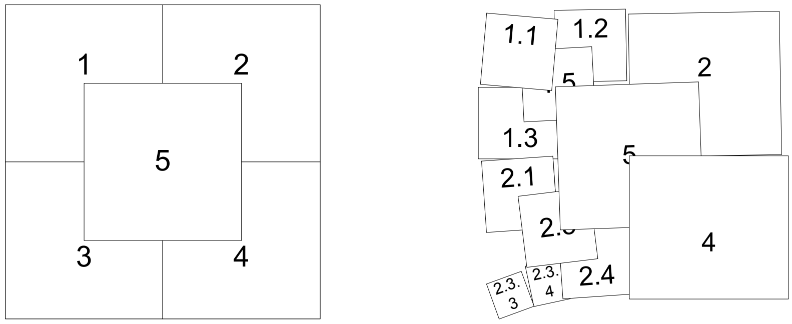


Fig. 6. Template division schema (*left*) and a schematic view of template recovering from some example local distortions (*right*)

In other words, we terminate the recursion either when we find the two extreme peaks fulfilling some requirements (they have to be placed periodically on two straight lines, with the total autocorrelation exceeding a given threshold) or if the block size is too small. The result is a list of transformed image fragments. The effects of the geometrical transformations that were performed on the watermarked image are reversed in the obtained image fragments; however, in general the fragments are not yet placed in the original positions. Some watermarking algorithms assume translation invariance, but usually synchronization of a decoder in respect of translation allows achieving better robustness against non-geometrical distortions (i.e. JPEG compression, filtering, etc.). Such watermarking schemes as spread-spectrum wavelet or DCT watermarking require synchronizing a decoder, so both geometrical distortions and translation effects should be reversed.

5 Restoring the Original Image Placement

As stated before, the self-referencing template can be used to identify translation of the attacked image comparing to the original watermarked image. This is possible, because the function that correlates the predicted template (retrieved from the previous step of the algorithm) with the *a priori* known template produces, in ideal case, an output similar to the autocorrelation of that template (Fig. 4 (right)). The output has a strong central peak and many other peaks (two times weaker) on the two straights parallel to the axes OX and OY, and crossing in the central peak. The coordinates of the main peak follow the translation of the processed image in relation to the watermarked image.

In order to reverse the translation, for each image fragment coming from the previous step of the algorithm, a cross-correlation between the predicted template and the *a priori* known template is computed to find the maximum correlation peak. That peak validity is verified using information from the secondary peaks, which should be present on the straight lines as described above. The coordinates of the resulting peak are used to estimate the translation vector coefficients t_x and t_y. The image fragment is now shifted according to t_x and t_y, to restore its original position. Finally, all the restored image blocks are painted on the destination image. Blocks with higher correlation are painted on top of worse fitting blocks so that the resulting image is as close to the original undistorted image as possible (Fig. 6 (right)).

Blocks that were too heavily distorted are not recovered and sometimes can form "black holes" (Fig. 7). However, watermark information still can be read because of the watermark's itself robustness against non-geometrical artifacts [23].

Fig. 7. An original watermarked image "lena.jpg" (*left*), an image attacked with Stirmark (*middle*), and a recovered image (*right*) – 64-bit watermark was decoded correctly

6 Experimental Results

The performance of the proposed scheme was tested with Stirmark 3.1. The standard test images were watermarked with 72 bits of information, without any error correction. The description of the used watermarking algorithm [23] is not the aim of this article. We will only mention that it is a private, key-dependant, spread-spectrum scheme, optimized for JPEG compression robustness. The watermark is embedded in DCT domain and its decoding routine does not need the original image (blind algorithm). Beside an "information carrier" part of the watermark, the synchronization template was embedded into the images, according to the algorithm described herein. Throughout the evaluation, the template parameters were set to:

dx = 32, dy = 32, - the shorter side of the template rectangle,
wx = 1024, wy = 1024 - the longer side of the template rectangle.

The PSNR of the watermarked image was kept not less than 38 dB. The detection was done without the presence of the original image. The test case was marked as successful, if at least 64 bits of hidden information were decoded correctly.

The results in **Table 1** show the effectiveness of the proposed scheme. The synchronization template proved its ability to recover from geometrical distortions in almost all cases. Only the cases of 90 degree rotation and 50% scaling were usually not detected correctly. However, that limitation could be easily overcome, at a cost of time efficiency, by performing template search for pre-transformed image versions: rescaled 200%, rotated 90, 180, 270 degrees.

Table 1. Stirmark 3.1 benchmark results

Image modifications class	*Average response*
Signal enhancement	**1.00**
Gaussian	1.00
Median	1.00
Sharpening	1.00
FMLR	1.00
Compression	**0.94**
JPEG	0.89
GIF	1.00
Scaling	**0.86**
Without JPEG 90	0.89
With JPEG 90	0.83
Cropping	**0.96**
Without JPEG 90	1.00
With JPEG 90	0.93
Shearing	**1.00**
Rotation	**0.92**
Auto-crop	0.93
Without JPEG 90	0.92
With JPEG 90	0.94
Auto-scale	0.92
Without JPEG 90	0.92
With JPEG 90	0.92
Other geometric trans.	**1.00**
Col & line removal	1.00
Flip	1.00
Random Geometric Dist.	**1.00**
Overall Performance	**0.96**

Both the synchronization template and the "information hiding" watermark are resistant to non-geometrical distortions. In the experiment, the watermark (in fact its "information" part) was robust against JPEG compression up to quality factor equal 10. Relative robustness of different watermark parts can be adjusted in the embedding process, with respect that they both influence the image quality.

For all images, it was possible to decode the watermark even after the "Stirmark" attack [22]. The results show that the proposed scheme is applicable and efficient to recover from both global and local or non-linear geometrical distortions. The overall performance at the level of 0.96 is very high.

7 Discussion and conclusions

The watermarking system is as insecure as its weakest part. Here, although the template is created with a secret key, its autocorrelation could be read without the knowledge of the key. It creates a possibility for an attack, aiming to remove synchronization template from the watermarked image [13]. Especially, an autocorrelation attack is threatening [18]. The proposed scheme to some degree lowers the risk of a successful autocorrelation attack, because the template is constructed from two distinct parts, which correlate independently. The naive implementation of the autocorrelation attack would introduce too big artifacts to accept the results. To provide against more sophisticated attacks, taking into account the specific template design, it is possible to introduce a different, key-dependant method of merging the parts of the template.

Another threat is an attack that introduces some strong peaks into the autocorrelation function of the watermarked image. This could mislead the decoder. The remedy for such an attack is possible but it would heavily influence the computational performance of the detection process – the watermark detector would have to try some combinations of the autocorrelation function peaks other than the strongest ones.

The approach introduces a few novel elements on various stages of template embedding and detection. The template design makes it possible to obtain a high autocorrelation response for different block sizes. This feature is used during detection, which is held on a level as global as it is possible. The same template is used to estimate translation parameters. The use of one template in those two operations allows to achieve better robustness with smaller decrease of image quality at the same time. Experimental results showed that the described approach survives local geometrical attacks, which only a few watermarking systems can resist today.

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