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Advanced evolutionary image filtering

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Abstract
This paper aims to use cellular automata (CA) with a transition function of conditionally matching rules (CMR) designed by the evolution strategy (ES) for the removal of noises of different types and intensities from digital images. The proposed method improves the original concept of CMR by modifying the right side of the rule, extending it from a single value to a selection of functions. Furthermore, various ES setups were explored, resulting in high-quality filters for each noise model. Comparing these filters to the existing methods shows great improvement from the original approach and the ability to evolutionarily design filters that are placed among the top methods quality-wise.

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1. Introduction

Image noise filtering [1] is an important pre-step of image processing. Digital images can be damaged during their creation, transfer, or storage, and many types of noises might affect them. For the purposes of this paper, the most common noise models are considered: salt and pepper, impulse burst, and random noise (sometimes referred to as shot noise). Pixels damaged by salt and pepper noise are either white or black (255 or 0), while for random noise it can be any value from {0...255}. Impulse burst damage appears as multiple random sequences of damaged pixels in the image. All of these model noises are demonstrated in Figure 1.

Restoring the lost original information usually boils down to noise detection and its filtration, where only detected damaged pixels are corrected. The conventional approach to the problem is the use of Median Filters (MF) [2], which apply one function, the median, on all pixels with filtering windows of size 3x3 or 5x5. The downside of this widely used approach is weak edge preservation leading to blurry images. Advanced conventional methods that extend and improve the MF are IDBMF (Improved Decision-Based Median Filter) [3] and EMF (Extended Median Filter) [4].

Using cellular automata (CA) [5] for image noise removal is getting more attention in recent years. The standard setup is to use 2D CA on 8-bit greyscale digital images where the cells correspond to the pixels with 256 possible states, and either Moore (3x3) or von Neumann neighborhood (von Moore without diagonal neighboring cells). One of the methods that yields high-quality results for both salt and pepper and impulse burst noise is from [6]. Recently, another approach [7] proposed a novel method where the transition function for CA consists of conditionally matching rules (CMR) that are evolutionarily designed.

The goal of this paper is to further improve the method from [7] and explore its potential for different types of noises and intensities by modifying the CMR concept and evolution-running parameters.

2. Proposed method

Modified conditionally matching rules

Our proposed method follows up on the evolutionary designed CMR CA filters by expanding the right side of the CMR. The modified CMR consists of 5 conditions evaluated for each cell in the neighborhood (von Neumann neighborhood with indexing, as shown in Figure 2), followed by a function ($func$) returning the next state value for the central cell. CMR is applied if all conditions are satisfied. The transition function contains several CMRs that are evaluated sequentially until the first match. In case no CMR is matched, the state value of the central cell remains unchanged. An example of such a transition function can be found in Figure 3 and Table 1.

A list of considered possible functions that can be assigned to $func$ are median, mean, Gaussian filter, bilateral filter, minimum, maximum, major value, minor value, half of minimum and maximum, a state value of one of the neighboring cells (N, W, E, S), and evolved constant value. Having a large number of options is not ideal as it greatly increases the search space, thus experiments were done on combinations of the listed functions to find an optimal selection. Two sets of functions were reached where one consists of 8 possible functions and the other of only 4. The sets are: median, minimum, maximum, evolved constant value, N, W, E, S; and median, evolved constant function, N, S.

Fitness function

To evaluate the quality of the designed CA filter, a PSNR (peak signal-to-noise ratio) value was chosen as it is commonly used to compare different image filters. Firstly, the mean squared error (MSE) is calculated:

$$MSE = \frac{1}{m \cdot n} * \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} (C(i,j) - R(i,j))^2,$$

where m x n are the height and width of the image C and R, and C represents the corrupted image, while R is the reference image and $0 \leq i \leq m$ and $0 \leq j \leq n$ are the indexes to the pixels in the images. Then, the PSNR value is acquired:

$$PSNR = 20 \cdot \log_{10}(MAX_I) - 10 \cdot log_{10}(MSE),$$

for $MAX_I = 255$ as the maximum value, a pixel can hold. The PSNR value after several steps of applying the CA filter is then used as a fitness function. The higher the value of PSNR, the better quality of the restored image.

Evolution strategy

The CMR transition function can be encoded into an array of integers representing a chromosome of an individual in the evolution scheme. Evolution strategy (ES) [8] is used to design a suitable CMR transition function for CA. In this paper, the 'comma' strategy is used in a configuration (4, 8)-ES. The initial population is randomly generated, evaluated by the fitness function, and sorted from the best to the last with an index i from 1 to 4. Two offspring are generated from each individual by mutating them. The mutation is done by changing i randomly selected integers in the individual's chromosome to random value from interval {0...255}. This way the higher quality individuals are mutated less than lower quality individuals. Offspring are then evaluated as well and 4 best offspring are selected for the population in the next generation. Additionally, the ES utilizes the elitism approach, which means that the best solution so far is stored and returned to the population in each generation.

3. Experimental results

Over 5000 experiments were done in order to find the best combination of parameters controlling both the ES and CA resulting in high-quality filters. Among the examined parameters were: noise type, noise intensity, number of steps of CA, number of CMRs, number of possible functions. Experiments were evaluated on a dataset of 25 images[1] on all considered noise types. Even though the experiments ran for only 2500 generations, it was shown that the most significant improvements happened before the 500th generation (see Figure 4).

For each noise type, salt and pepper, impulse burst, and random noise, two results with the best average PSNR were selected. Moreover, an experiment with the best average PSNR on all considered noises was found. These best experiments were compared for each noise type with both the conventional methods and methods using CA, [6] and [7], in Figure 5. From each of the best experiments, a highest-quality-yielding filter was chosen and used for practical visual comparison (example in Figure 6). All the filters are also available in readable table representations (salt and pepper filter in Table 1).

4. Conclusions

Modification of the original concept of CMR represents the most important factor leading to the great improvement of the original method from [7]. The proposed method is capable of developing high-quality image noise filters for all the considered noise models.

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[1] Public dataset of the University of Berkeley, available here: `https://www2.eecs.berkeley.edu/Research/Projects/CS/vision/bsds/BSDS300/html/dataset/images/gray/test-026-050.html`

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