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ORIGINAL RESEARCH

Cellular automata-based efficient method for the removal of high-density impulsive noise from digital images

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Abstract Cellular automata (CA) are simple dynamical systems used for solving simple as well as complex problems. It uses a discrete space, like the space used in spatial domain for image processing, to store the values of the input data. Then, the input data can be processed according to the transition rules, functions, or, programmes, for the required output. This research work presents an efficient algorithm based on two dimensional cellular automata (2D CA), with hybrid rules under null and periodic boundary conditions, for filtering high-density impulsive noise from corrupted digital images. The most important advantage of the proposed method is that, it can be applied on all types of digital images (binary, greyscale, or, true color). The paper is organized as follows: Sect. 1 gives a brief introduction towards the problem of noise in digital images with emphasis on its solution. Further, this section presents a brief review of existing standard noise filtering methods based on general image processing and CA techniques. Section 2 discusses the basic concept of CA with special emphasis on 2D CA and related concepts. Section 3 presents the proposed algorithm for the removal of high-density impulsive noise from corrupted digital images. Section 4 discusses, in detail, the experimental results using both mathematical and subjective analysis; and, the extensive experimentation reveals that the proposed 2D CA based algorithm yields better results than the standard noise filtering algorithms. And, then finally Sect. 5 presents the conclusions and future scope.

Keywords Cellular automata · Image processing · Noise filtering

1 Introduction

During the transmission of digital images through the networks or the manipulations of digital images on the computers, the intensity values of the digital images changes due to many problems like faulty memory locations or graphics fluctuations or bit errors in transmission [1]. And, anything that does not represent any useful information, particularly in case of digital images, is called a noise. Thus, digital images suffer from various kinds of noises, like, salt and pepper, Gaussian, speckle, etc. And, the different kinds of noises attacked the digital image will greatly reduce/degrade the quality of the digital image and therefore also cause damage to the information present in it [2]. Therefore, noise present in a digital image is an unwanted thing for the user and must be eliminated. Hence, noise filtering of digital images is highly focussed, especially in two fields, one is computer vision, and other is image processing. By definition, noise filtering of digital images is the task of removing different types of noises using the appropriate filter. However, removal of noise from digital images is a difficult and challenging task, because it creates blurring in the digital images if special care has not been taken.

There has been made a lot of efforts in designing an efficient filtering algorithm for digital images. One of the traditional/standard filtering algorithms is the average filter (AF) that comes under the category of linear techniques.

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However, during the process of noise removal, it also removes much incriminate information present in the digital image [2]. And, it has been proved that noise filtering based on linear filtering methodology are not effective [3]. The next traditional noise filtering algorithm that was proposed is known as the median filter (MF) that comes under the category of non-linear techniques. This filter is known for its removal of noise, especially salt and pepper noise, present in digital images effectively, while preserving the details of the image better as compared to the AF [2]. Due to effectiveness of MF for noise removal and its simplicity of implementation on computers, variants of the MF have been proposed such as weighted median filter (WMF) [4]. However, the WMF performs better as compared to the MF, but the MF and its variants operate uniformly across the entire grid of 2D image. And, thus processes both the pixels—noisy as well as noiseless pixels. In addition to this major drawback, the noise removal capabilities of such filters are effective only when the given digital image is corrupted with less noise, usually below 10%. Later, a new filter known as switching filter (SF) has been proposed, which combines the MF with an impulse detector [5, 6]. That is, this filter and its variants first check the pixel under examination and if the pixel is found noisy then only it is replaced by some value, otherwise its value is left unchanged.

However, non-linear filters, like linear filters, also perform well when the noise present in the digital image is less. Therefore, due to lack of adaptability of filters or designing of filters for a particular task/image, the variants of MF also cannot perform well when the noise present in the digital image is greater than 15%. But, here we also note theoretically that the non-linear filters perform better as compared to the linear filters. However, recently, CA based filters has emerged as an attractive and efficient tool [7–9].

Cellular automata's are well-suited to the noise filtering tasks because they effectively adapt the local nature of the problem. For digital image noise filtering based on CA, Gonzalo and Herrmann proposed iterative automata using median rules [10]. Popovici and Popovici has proposed a local transition function, considering that current cell's state should be consistent with that of mostly cells in its neighbourhood [11]. Haiming et al., proposed an automata rule based on coordinate logic and erosion and dilation operations of mathematical morphology [12]. Selvapeter and Hordijk proposed a majority CA rule based on the Moore neighbourhood for noise filtering [13]. And, if there is no majority in the gray levels present in the Moore neighborhood, then there is a tie and this tie can be overcome using either deterministic or random manner. Songtao et al., proposed a novel de-noising algorithm based on CA to filter digital images corrupted with "Salt and Pepper" noise [14]. Their CA local transition functions or update rules are based on the Moore neighbourhood. They have tested and compared their approach with the existing MF using hamming distance.

Furthermore, Pourkashani and Kangarvari proposed a CA based technique which enhances the current widow based relevance criterion by adding neighborhood distance, as another relevance measure for data samples [15]. Their experiments showed that the good choice of CA rules can considerably reduce the convergence time of reaching the solution and thereby also increases robustness to the problems of noise. Thus, presenting a more accurate stream of learning. Rosin proposed a three-state CA for processing of intensity images [16]. The major problem in his work was that the increased number of intensity values results in the formation of huge number of possible rules. Later, Chihyu et al., proposed a method based on the concept of CA for removing "Salt and Pepper" noise in digital images, efficiently [17]. The paper discussed the concept of programming for developing an algorithm and named the software as CA Image De-noising toolkit. Matlab codes were used to develop a program for the removal of "Salt and Pepper" noise present in digital images. Jana et al., presents two new approaches to eliminate the noise from a noisy digital image [18]. In the first approach, difference values in the Moore neighborhood from the central pixel are calculated, then these values are sorted in ascending order and the centre pixel value is updated depending on the present pixel values using CA rule. In second approach, all pixel values in the Moore neighborhood including the central pixel are sorted in ascending order. Then the minimum and maximum values are eliminated from the sorted pixel values and the center pixel value is updated using CA rule. Sahin et al., proposed a method for salt and pepper noise filtering based on fuzzy cellular automata [3]. Nayak et al., presents two filters for removing salt and pepper noise from corrupted digital images based of 2D CA and the work showed that the proposed algorithm removes noise while preserves details in the image in expenses of supression of noise [19]. And, recently, Priego et al., presents a novel denoising technique based on spatio-temporal CA and presents several advantages over standard single frame denoising techniques [20].

However, we find that these filtering algorithms based on CA provides better results only when the images are corrupted by small amount of noises and therefore they are not ideal for filtering "Salt and Pepper" noises, especially when the noise percentage is very high. Therefore, new CA rules for filtering "Salt and pepper" noises are put forward. The major motivation is to efficiently utilize the simple, regular and modular structure of CA as the basic building blocks for software implementation of the image processing schemes.

2 Cellular automata

Cellular automata's (CA) are well known extensions of the traditional automata and are considered as very powerful models in computer sciences. They are used as discrete dynamical models in space and time. The basic theory of CA was given by the famous mathematician known as Neumann [21]. Later, Stephen Wolfram developed its theory [22]. The physical environment of the CA consists of a grid of cells as shown in the Fig. 1. Each cell in the grid can be assigned a finite value, depending upon the type of digital image used, like, for binary (0 and 1), for grayscale ($0–2^8$), and for true color images ($0–2^{24}$). And, the CA topology can be used in any one of the following dimensions 1D, 2D or 3D. In 2D CA grid of cells, the processing of cells is done based on its neighborhood (usually, including the cell under examination). The initial sate of the cell under consideration and the cells in its neighborhood are selected at time (t = 0). Then, the next state of the cell under examination is generated based on the CA rule, at time (t = 1). This process is continued till we reach the specified time (t = n).

An image is considered as a 2D function f_i (x_i, y_j), for i = 1 to n and j = 1 to n, where (x_i, y_j) denotes the cell location in the 2D CA grid and f_i represents the corresponding intensity values. This 2D function is known as a digital image when both the quantities f_i and (x_i, y_j) becomes finite. As we know that a digital image is represented on a 2D grid, so here we use the 2D grid structure of CA. In the 2D CA grid, all the cells are connected to its neighboring cells as shown in Fig. 1. And, the structure of the neighborhoods mainly includes Neumann neighborhood and Moore neighborhood as shown in the Fig. 2. The Von Neumann neighborhood of a 2D CA grid is a diamond shaped neighborhood surrounding the cell (x_i, y_j) with ($1 \leq$ radius $< n$). And, the Moore neighborhood in a 2D CA grid is a square shaped neighborhood surrounding the cell (x_i, y_j) with ($1 \leq$ radius $< n$).

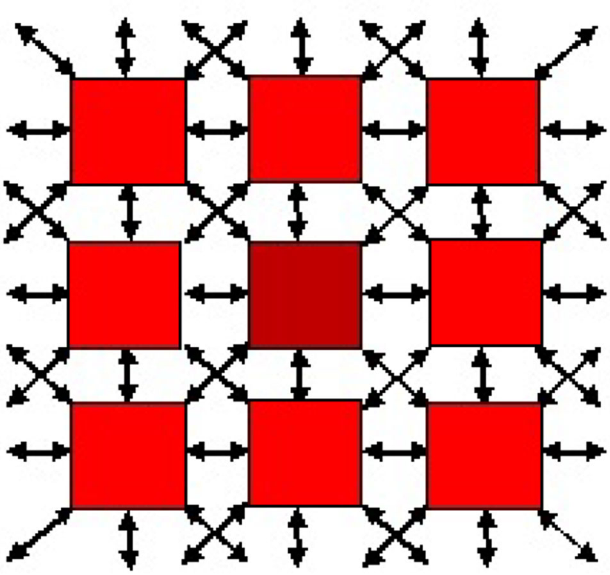

Fig. 1 Physical environment of CA. **a** Von-Neumann neighborhood, **b** Moore neighborhood

The existing 2D CA theory and their specific rule convention's are directly meant for only binary images [7–9, 21]. So, there is an urgent need for giving a new rule convention that will work irrespective of the input data used. In the proposed 2D CA 25 neighbourhood model, the next state of the cell under examination is calculate by its current state and/or its 24 neighbouring cells as shown in the Table 1. Here, 2D CA mathematics is applied with the help of rules and the rule is applied to all the cells recursively. And, a 2D CA rule can be any simple program that generates the next state of the cell under examination.

The central box, indicated by the number 0 and cell location (i, j), represents the cell under examination. And, the 24 cells in its vicinity are known as its neighbouring cells. Each neighboring cell is represented by an integer value that denotes the rule number. That is, if the next state of the cell depends only upon its right neighbour, then it is known as rule number 2, denoted by R2. Similarly, if the next state of the cell depends only upon its top-left neighbour, then it is called as rule number 16, denoted by R16. Similarly, rules numbers can be developed for all other cells in the neighborhood. In general, if the cell under examination depends only upon one of its neighboring cells then the rules are called as primary rules. Otherwise, rules are called as secondary rules and the rule number for such rules are calculated by the arithmetic sum of the values in the dependent boxes.

3 Proposed technique for noise filtering

The most important aspect of CA is the problem of applying rules, because there are different types of rules available in CA for processing the input data. In this research work, we use 2D CA rules and a 2D CA rule is a simple code of logical gates which is applied recursively on the input data. Further, different rules can be applied to different cells in a single iteration, known as hybrid rules. The proposed noise filtering method uses the primary rules and the majority rule of the above described 2D CA model.

First, the central pixel within the Moore neighborhood of the corrupted digital image is tested for impulse. And, if the pixel under consideration is found as a noisy pixel, it is replaced, otherwise remains unchanged. Suppose, the pixel is identified as corrupted, then each time the primary rules within (r = 1) are checked for the impulse and the corrupted pixel is then replaced by the rule which is not

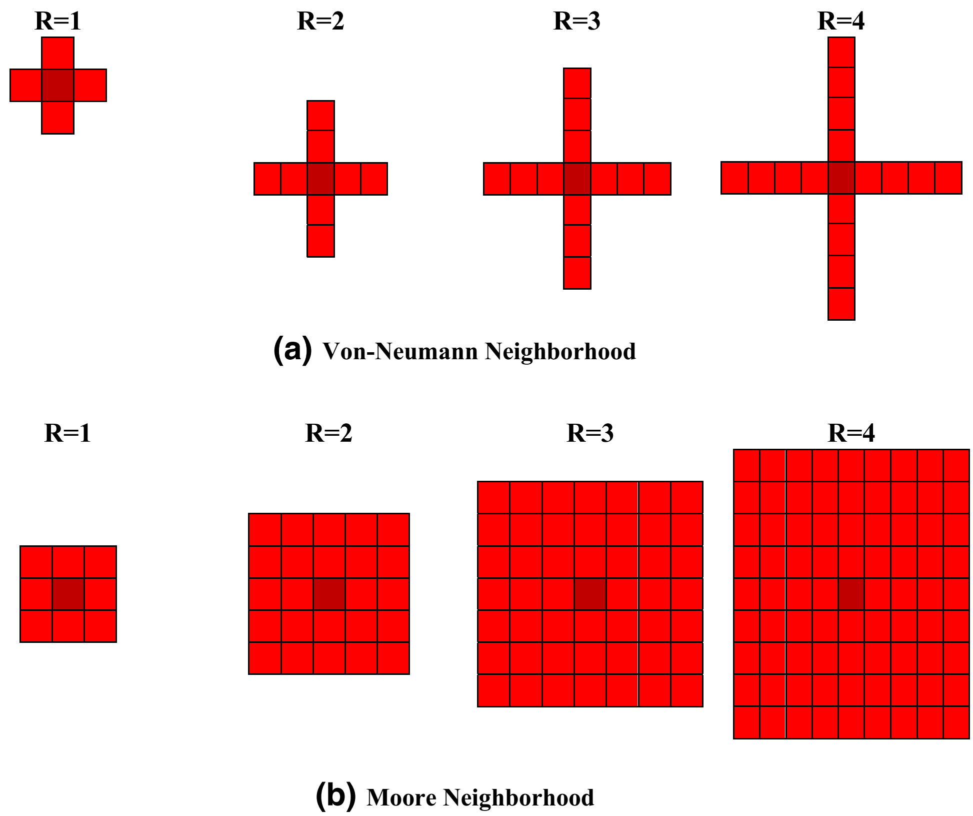

Fig. 2 Structure of the neighbourhoods

Table 1 2DCA rule convention

65,536	32,768	16,384	8192	4096
131,072	16	8	4	2048
262,144	32	1 (i, j)	2	1024
524,288	64	128	256	512
1,048,576	2,097,152	4,194,304	8,388,608	16,777,216

corrupted by noise. In case, all the primary rules within (r = 1) are corrupted by noise, then it is replaced by the majority rule of the 2D CA, within (r = 2). At higher noises, the method is applied fewer times on the input digital image, so the convergence is achieved efficiently.

The steps of the proposed algorithm are as follows:

1. Read the image *I*, affected by noise or without noise.
2. Select the Moore neighbourhood with $r = 2$ and the central pixel $S_{i,j}$ (t) of the neighborhood is the pixel which is testing for impulse.
3. If $S_{i,j}$ (t) is a noisy pixel and if any of the primary rules within r = 1 is not affected by noise, then $S_{i,j}$ $(t + 1)$ is replaced by that primary rule, otherwise, go to step (5).
4. Otherwise, $S_{i,j}$ $(t + 1) = S_{i,j}$ (t);
5. $S_{i,j}$ $(t + 1)$ is replaced by the majority rule within r = 2.
6. Repeat steps (2)–(4) for all of the pixels in the input image *I*.

4 Experimental results and discussions

At low noise level (1–30%), the proposed algorithm is applied only once to the given noisy image as shown in Fig. 3. Figure 3a is the original Lena image corrupted by 25% of "Salt and Pepper" noise and Fig. 3b shows the noise reduced image after applying the proposed algorithm for noise filtering. So, here it is also proved visually that the proposed algorithm works better as compared to the linear and non-linear filters. However, at high noise levels (i.e; $> 30\%$), the proposed algorithm is recursively applied to the given noisy digital image as soon as the noise is eliminated, efficiently. And, the different patterns of noise cleaning process in different iterations for Lena image corrupted by 50 and 70% of "Salt and Pepper" noise are shown in Figs. 4 and 5. The Fig. 4a is the original Lena image corrupted by 50% of noise and the Fig. 4b, c shows the two iterations required for said noise filtering. Similarly, Fig. 5a is the original Lena image corrupted by 70% of noise and the Fig. 5b–d shows the three iterations required for said noise filtering.

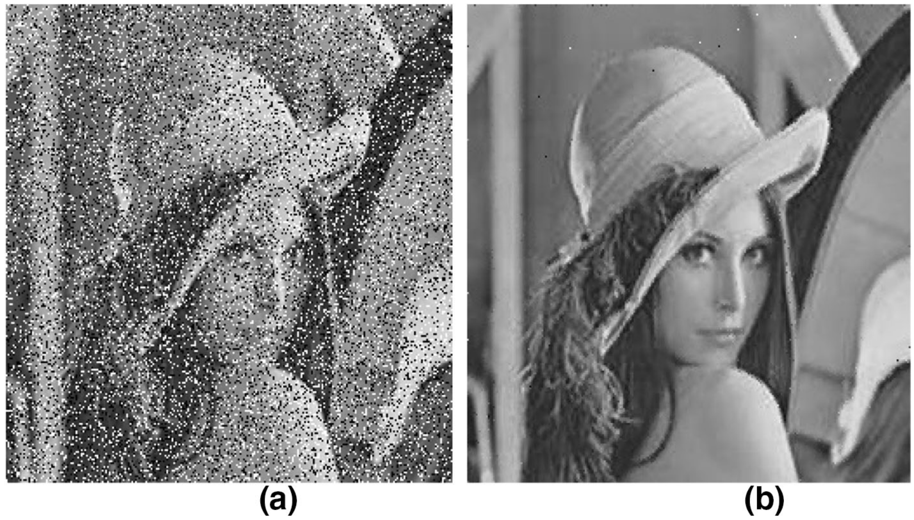

Fig. 3 Noise filtering using primary rules for Lena corrupted by 25% of noise; **a** Lena corrupted by 25% of "Salt and Pepper" noise; **b** image obtained after applying proposed method

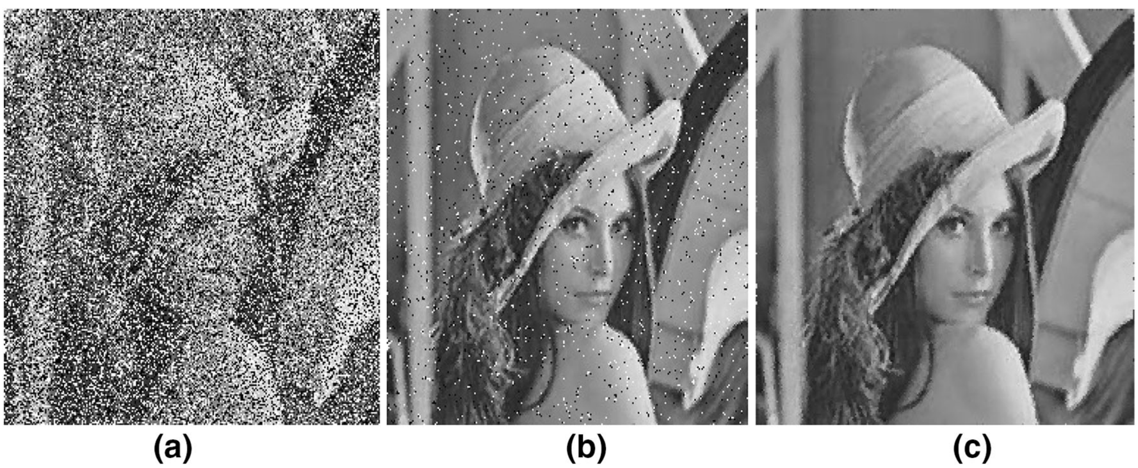

Fig. 4 Operations of noise cleaning in different iterations using primary rules for Lena corrupted by 50% of noise: **a** Lena, corrupted by 50% of "Salt and Pepper" noise; **b**, **c** are obtained after time (t = 1 and 2)

Firstly, the performance evaluation of the proposed filter's are performed on the grey scale test image of Lena as visual comparison with AF, MF, WMF and SF. When 20% of "Salt and Pepper" noise is added to original Lena image as shown in the Fig. 6, then, the de-noising effects of the proposed filter and the standard or existing filters are shown in Fig. 6b–f. It is clearly seen in the Fig. 6 that AF, MF, WMF and SF leaves many dots or unwanted things in the resulting images. Whereas, the proposed 2D CA based filter removes the noise effectively and preserving the details in the digital image very well. Thus, the filtering effect of the proposed filters is better than those of the standard filters. All the filters (standard as well as proposed), are applied only once to the noisy digital image.

In order to evaluate the performance of the standard filters and proposed 2DCA based filters objectively, MSE and PSNR between filtered digital image and the original digital image are used and are defined as follows [3, 6]:

$$\mathrm{PSNR} = 10\log_{10}\left(\frac{b * b}{MSE}\right).$$

where,

$$\mathrm{MSE} = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{j=1}^{M}[a(i-j) - b(i,j)]2}{M * N},$$

and, b = 255.

In Table 2, performance evaluation of the standard filters and proposed 2DCA based filters are presented using MSE. Similarly, in Table 3, performance evaluation of standard filters and proposed 2DCA based filters are presented using PSNR. From these two tables it can be seen that the proposed filters have the lowest MSE and highest PSNR than standard filters at low as well as high noise levels, which implies proposed filters based on 2DCA are comparatively the best filters. Furthermore, we have tested MF and SF with 3 × 3 and 5 × 5 windows and the results

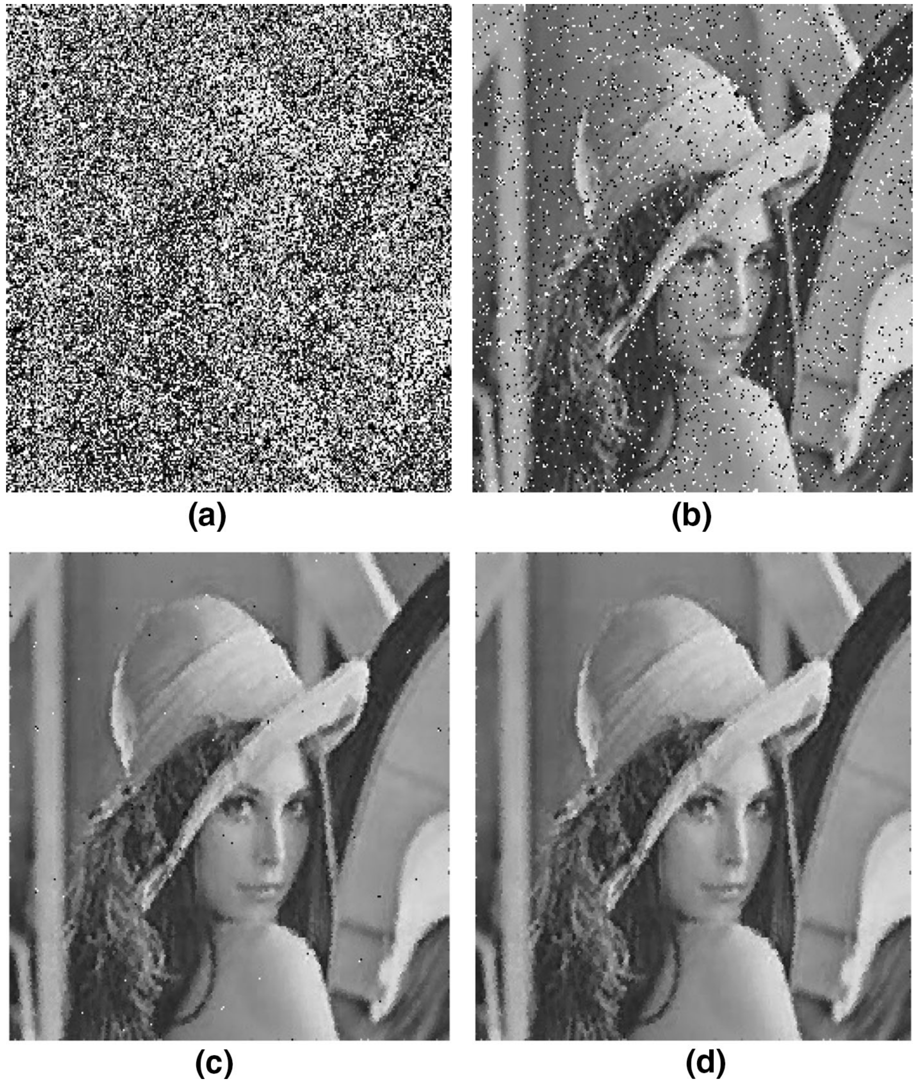

Fig. 5 Operations of noise cleaning in different iterations using primary rules for Lena corrupted by 70% of noise: **a** Lena, corrupted by 70% of "Salt and Pepper" noise; **b**–**d** are obtained time (t = 1, 2 and 3)

shows that 3 × 3 MF performs better as compared to the 5 × 5 MF whereas, 5 × 5 SF performs better as compared to the 3 × 3 SF.

In addition to mathematical experiments, visual experiments are also analysed in this study. The evaluating results obtained through MSE and PSNR as show in Tables 2 and 3 are consistent with the subjective evaluation. Hence, the mathematical evaluation based on MSE and PSNR and subjective evaluation based on visual comparisons of filtered digital images reveals that the proposed filters based on our proposed 2D CA model have the best restoration performance among all the compared filters.

5 Conclusions and future work

We have presented an efficient digital image noise filtering algorithm, that can be applied to all types of digital images (binary, greyscale, or, RGB), based on our proposed 2D CA theory. The major advantage of the proposed method is that the pixel under examination is first checked for impulse and then only it is replaced, otherwise it is left unchanged; which significantly reduces the computing efforts. Next, we discussed the performance of the proposed method with the exiting standard techniques of noise filtering methods visually as well as objectively. And, the results reveal that the performance of the proposed method is better visually as well as objectively than the standard filtering techniques such as AF, MF, WMF and SF.

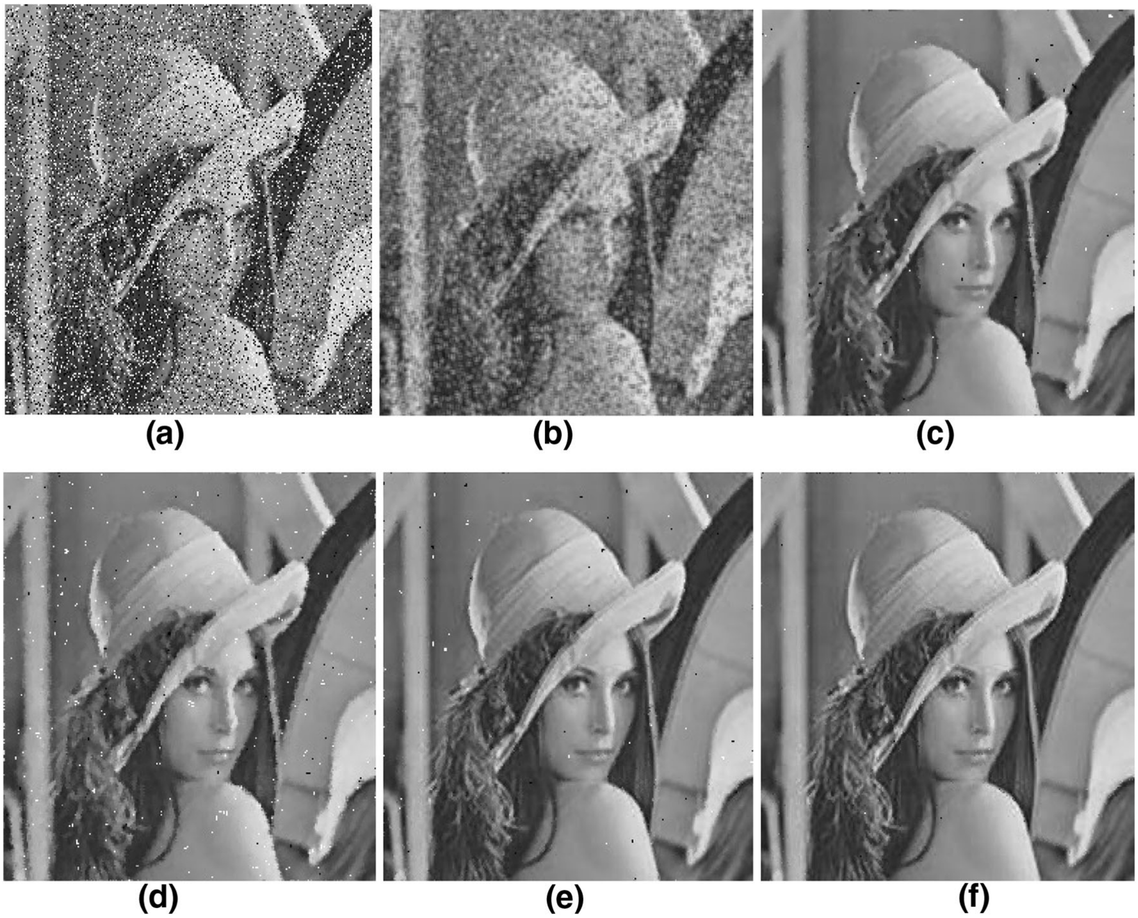

Fig. 6 Visual comparison of restored images using different methods for Lena corrupted by 20% of noise: **a** Lena, corrupted by 20% of "Salt and Pepper" noise; **b–e** image obtained after applying standard filters such as AF, MF, WMF, and SF; **f** image obtained after applying proposed method

Table 2 MSE results at different noise ratios of various filters for 'Lena'

Method	Noise						
	1%	5%	10%	15%	20%	25%	30%
AF 3 × 3	19.06	41.79	60.61	74.95	84.30	91.77	97.64
MF 3 × 3	08.32	13.86	21.10	27.35	34.12	40.93	47.17
MF 5 × 5	17.50	22.33	28.36	34.81	40.90	46.41	52.74
WMF 3 × 3	08.22	13.69	20.37	27.00	33.97	40.49	47.00
SF 3 × 3	03.24	08.17	14.40	20.50	24.48	32.76	38.40
SF 5 × 5	03.15	07.57	13.37	19.66	25.83	32.22	37.57
Proposed, V_N	01.15	05.96	12.23	18.50	24.88	31.41	37.46
Proposed, M_N	01.13	05.98	12.44	18.57	24.91	31.13	37.12

In the presented work, it has been shown that 2D CA is a very important tool for solving image processing problems using simple and efficient logic. For future works, a stopping condition may be developed that will find the exact number of iterations required for filtering a digital image corrupted by high density of impulsive noise, without, blurring the image, leaving unwanted things in the digital image, or damage the information present in the digital image, especially at edges where noise is very sensitive. Moreover, to improve performance even further, different

Table 3 PSNR results at different noise ratios of various filters for 'Lena'

Method	Noise						
	1%	5%	10%	15%	20%	25%	30%
AF 3 × 3	35.34	31.93	30.31	29.39	28.88	28.51	28.24
MF 3 × 3	38.94	36.72	34.89	33.77	32.81	32.02	31.40
MF 5 × 5	35.71	34.65	33.61	32.72	32.02	31.47	30.91
WMF 3 × 3	38.99	36.77	35.05	33.82	32.83	32.06	31.42
SF 3 × 3	43.04	39.00	36.55	35.02	33.91	32.98	32.29
SF 5 × 5	43.16	39.35	36.88	35.20	34.02	33.06	32.39
Proposed, V_N	47.57	40.37	37.26	35.47	34.18	33.17	32.40
Proposed, M_N	47.61	40.37	37.19	35.45	34.17	33.21	32.44

rules could be applied to different pixels (hybrid rules), different modifications could be applied to standard 2D CA approaches, and also at different time steps, depending upon the local conditions of the image.

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