

Differential Evolution Control Parameters Study for Self-Adaptive Triangular Brushstrokes

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This paper proposes a lossy image representation where a reference image is approximated by an evolved image, constituted of variable number of triangular brushstrokes. The parameters of each triangle brush are evolved using differential evolution, which self-adapts the triangles to the reference image, and also self-adapts some of the control parameters of the optimization algorithm, including the number of triangles. Experimental results show the viability of the proposed encoding and optimization results on a few sample reference images. The results of the self-adapting control parameters for crossover and mutation in differential evolution are also compared to results with keeping these parameters constant, like in a basic differential evolution algorithm. Statistical tests are furthermore included to confirm the improved performance with the self-adaptation of the control parameters over the fixed control parameters.

Povzetek: V članku je predlagana izgubna predstavitev slike, kjer je referenčna slika aproksimirana z evoluirano sliko, ki je sestavljena iz spremenljivega števila potez trikotniškega čopiča. Parametre vsake poteze čopiča optimiramo s pomočjo diferencialne evolucije, ki samoprilagaja trikotniške poteze na referenčno sliko in prav tako samoprilagaja nekatere krmilne parametre samega optimizacijskega algoritma, vključno s številom trikotnikov. Rezultati poizkusov kažejo primernost predlagane metode in rezultati optimizacije so prikazani za več izbranih referenčnih slik. Rezultati samoprilagodljivih krmilnih parametrov za diferencialno evolucijo so primerjani tudi z rezultati, kjer so ti parametri nespremenljivi, kot je to primer pri osnovnem algoritmu diferencialne evolucije. Dodatno so podani še statistični testi, ki nadalje potrjujejo izboljšanje kakovosti pristopa ob samoprilaganju krmilnih parametrov v primerjavi s pristopom z nespremenljivimi krmilnimi parametri.

1 Introduction

In this paper, evolvable lossy image representation utilizing an image compared to its evolved generated counterpart image, is proposed. The image is represented using a variable number of triangular brushstrokes [7], each consisting of triangle vertices coordinates and color parameters. These parameters for each triangle brush are evolved using differential evolution [13, 4], which self-adapts the control parameters, including the proposed self-adaptation for the number of triangles to be used. Experimental results show the viability of the proposed encoding and evolution convergence for lossy compression of sample images. Since this paper is an extended version of [8], new additional results are included, where the experiments results with fixed control parameters for differential evolution are included to check and demonstrate the self-adaptation mechanism influence on results. The results show clear superiority of the proposed approach with the self-adaptive control parameters over the approach where its control parameters are fixed.

The approach presented is built upon and compared

with [7], by addressing and also extending the original challenge. Namely, the challenge introduced in [7] uses triangles in trying to build an approximate model of an image [7]. The triangle is an efficient brush shape for this challenge, since it covers more pixels than a single point, and also allows overlaying and blending of colors over several regional surface pixels, which lines can not. Also, an arbitrary triangle shape is less constrained than any further point-approximated shape, and also other shapes can be built by combining several triangles. Instead of genetic programming in [7], in this paper differential evolution is used with a fixed size tree-like chromosome vector, which is cut-off self-adaptively to form codon and anti-codon parts of the chromosome. Also, our approach uses a modified challenge, where we can reconstruct the model for the reference image solely using the evolved model without using the reference image, whereas the [7] needs the reference image when drawing pixels to the canvas in deciding which pixels match the reference image for accepting them into the evolved canvas. Also, in this paper the triangle brushstroke encoding differs and is proposed especially designed for an efficient DE encoding.

In the following section, related work is presented, then the proposed approach is defined. In Section 4, the experimental results are reported. Section 5 concludes the paper with propositions for future work.

2 Related Work

In this section, related work on evolutionary computer vision, evolutionary art, image representation, and evolutionary optimization using differential evolution, are presented. These topics are used in the proposed method, defined in the next section.

2.1 Image-Based Modeling, Evolutionary Computer Vision, and Evolutionary Art

Image-based approaches to modeling include processing of images, e.g., two-dimensional, from which after segmentation certain features are extracted and used to represent a geometrical model [10]. For art drawings modeling, automatic evolutionary rendering has been applied [2, 12]. Heijer and Eiben evolved pop art two-dimensional scalable vector graphics (SVG) images [6] and defined genetic operators on SVG to evolve representational images using SVG, and also to evolve new images, different from source images, leading to new and surprising images for pop-art. Bergen and Ross [3] interactively evolved vector graphics images using genetic algorithm, where solid-coloured opaque or translucent geometric objects or mosaic tile effects with bitmap textures were utilized; they considered the art aspect of the evolved image and multiple possible outcomes due to evolution stochastics and concluded to investigate vector animation of the vectorized image.

In [14] animated artwork is evolved using an evolutionary algorithm. Then, Izadi et al. [7] evolved triangular brushstrokes challenge using genetic programming for two-dimensional images, using unguided and guided searches on a three or four branch genetic program, where roughly 5% similarity with reference images was obtained on average per pixel. In this paper, we build upon and compare our new approach with [7], by addressing and also extending this challenge. After extending the challenge, we optimize it using DE, which is described in the next section.

2.2 Evolutionary Optimization Using Differential Evolution

Differential evolution (DE) [13] is a floating-point encoding evolutionary algorithm for continuous global optimization. It has been modified and extended several times with various versions being proposed [5]. DE has also been applied to remote sensing image subpixel mapping [18], image thresholding [11], and for image-based modeling using evolutionary computer vision to reconstruct a spatial procedural tree model from a limited set of two dimensional

images [16, 15]. DE mechanisms were also compared to other algorithms in several studies [17]. Neri and Tirronen in their survey on DE [9] concluded that, compared to the other algorithms, a DE extension called jDE [4], is superior to the compared algorithms in terms of robustness and versatility over a diverse benchmark set used in the survey. Therefore, we choose to apply jDE in this approach.

The original DE has a main evolutionary loop where a population of vectors is computed within each generation. For one generation, counted as g , each vector \mathbf{x}_i , $\forall i \in \{1, \dots, NP\}$ in the current population of size NP , undergoes DE evolutionary operators, namely the mutation, crossover, and selection. Using these operators, a trial vector (offspring) is produced and the vector with the best fitness value is selected for the next generation. For each corresponding population vector, mutation creates a mutant vector $\mathbf{v}_{i,g+1}$ ('rand/1' [13]):

$$\mathbf{v}_{i,g+1} = \mathbf{x}_{r_1,g} + F(\mathbf{x}_{r_2,g} - \mathbf{x}_{r_3,g}), \quad (1)$$

where the indexes r_1 , r_2 , and r_3 are random and mutually different integers generated in from set $\{1, \dots, NP\}$, which are also different from i . F is an amplification factor of the difference vector, mostly within the interval $[0, 1]$. The term $\mathbf{x}_{r_2,g} - \mathbf{x}_{r_3,g}$ denotes a difference vector, which is named the amplified difference vector after multiplication with F . The mutant vector $\mathbf{v}_{i,g+1}$ is then used for recombination, where with the target vector $\mathbf{x}_{i,g}$ a trial vector $\mathbf{u}_{i,j,g+1}$ is created, e.g., using binary crossover:

$$\mathbf{u}_{i,j,g+1} = \begin{cases} v_{i,j,g+1}, & \text{if } rand(0, 1) \leq CR \\ & \text{or } j = j_{rand}, \\ x_{i,j,g} & \text{otherwise,} \end{cases} \quad (2)$$

where CR denotes the crossover rate, $\forall j \in \{1, \dots, D\}$ is a j -th search parameter of D -dimensional search space, $rand(0, 1) \in [0, 1]$ is a uniformly distributed random number, and j_{rand} is a uniform randomly chosen index of the search parameter, which is always exchanged to prevent cloning of target vectors. The original DE [13] keeps the control parameters fixed, such as $F = 0.5$ and $CR = 0.9$ throughout optimization.

However, the jDE algorithm, which is a modification of the original DE, self-adapts the F and CR control parameters to generate the vectors $\mathbf{v}_{i,g+1}$ and $\mathbf{u}_{i,g+1}$, corresponding values F_i and CR_i , $\forall i \in \{1, \dots, NP\}$ are updated prior to their use in the mutation and crossover mechanisms:

$$F_{i,g+1} = \begin{cases} F_1 + rand_1 \times F_u & \text{if } rand_2 < \tau_1, \\ F_{i,g} & \text{otherwise,} \end{cases} \quad (3)$$

$$CR_{i,g+1} = \begin{cases} rand_3 & \text{if } rand_4 < \tau_2, \\ CR_{i,g} & \text{otherwise,} \end{cases} \quad (4)$$

where $\{rand_1, \dots, rand_4\} \in [0, 1]$ are uniform random floating-point numbers and $\tau_1 = \tau_2 = 0.1$. Finally, the selection operator evaluates and compares the trial to current

vector and propagates the fittest:

$$\mathbf{x}_{i,g+1} = \begin{cases} \mathbf{u}_{i,g+1} & \text{if } f(\mathbf{u}_{i,g+1}) < f(\mathbf{x}_{i,g}), \\ \mathbf{x}_{i,g} & \text{otherwise.} \end{cases} \quad (5)$$

3 Differential Evolution for Self-Adaptive Triangular Brushstrokes

In this section, the encoding aspect, genotype-phenotype rendering, and evaluation mechanisms of the proposed approach are defined.

3.1 Encoding Aspect

We encode an individual compressed image into a DE vector as follows. A DE vector $\mathbf{x} = (x_1, x_2, \dots, x_{8T^{\max}}, F_i, CR_i, T_i^L, T_i^U)$ is composed of floating-point scalar values packed sequentially as $\{x_j : \forall j \in \{1, \dots, D + 4\}\}$, starting with a triangles-coding part of length $D = 8T^{\max}$, and the rest are the self-adaptive control parameters of the vector to be used during the DE. The self-adaptive control parameters part of the \mathbf{x} vector encodes and uses the scaling factor F and crossover rate CR as in the jDE [4]; then the $T_i^L, T_i^U \in \{1, \dots, T^{\max}\}$ control parameters follow.

The self-adaptive T_i^L and T_i^U control parameters determine index-wise triangles encoded in the vector \mathbf{x} to be used for rendering the evolved image, i.e., the portion of \mathbf{x} to render an image is $\{x_j : \forall j \in \{T_i^L, \dots, T_i^U\}\}$.

In this paper, we propose to have the whole vector represent a triangle set, organized similar to serializing a tree as a linear vector in visiting nodes by depth-first search. However, the leaf nodes are mostly exposed to being cut-off, whereas the root node is encoded in the middle of the vector and the near-root nodes are therefore more protected in being retained, since they are more anchored due to cut-offs mostly around the codon edges. After being included into a new trial vector, all nodes have an equal probability of having their triangle data changed.

In this way, the T_i^L and T_i^U allow us to render only a sub-portion of the triangles set, similarly to taking an inseparable portion of a GP tree traversal as in [7]. This gives us an arbitrary length render set, and keeps the crossover of anti-codon to help us find the number of triangles $T_i \in \{1, \dots, T^{\max}\}$, which is more suitable for image approximation:

$$T_i = \begin{cases} T_i^U - T_i^L + 1 & \text{if } T_i^L < T_i^U \\ (T^{\max} - T_i^L) + T_i^U & \text{otherwise.} \end{cases} \quad (6)$$

The T_i^L and T_i^U are updated similarly to the F_i control parameter:

$$T_{i,g+1}^L = \begin{cases} \lfloor \text{rand}_1^L \times T^{\max} \rfloor & \text{if } \text{rand}_2^L < \tau^L, \\ T_{i,g}^L & \text{otherwise,} \end{cases} \quad (7)$$

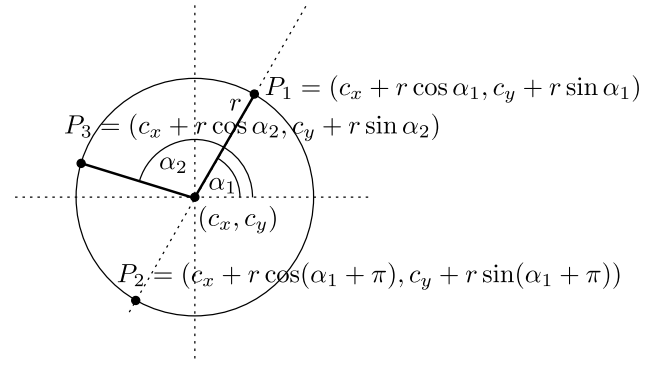


Figure 1: The triangle brush definition and the circumscribed circle.

$$T_{i,g+1}^U = \begin{cases} \lfloor \text{rand}_1^U \times T^{\max} \rfloor & \text{if } \text{rand}_2^U < \tau^U, \\ T_{i,g}^U & \text{otherwise,} \end{cases} \quad (8)$$

where $\tau^L = \tau^U = \tau_1 = 0.1$ of the jDE.

3.2 Genotype-Phenotype Rendering

A DE vector $\mathbf{x}_i, \forall i \in \{1, \dots, NP\}$ encoded using floating-point numbers $x_{i,j}, \forall j \in \{1, \dots, D + 4\}$ constituting a genotype is rendered into a phenotype image $\mathbf{z}_i = \{z_{i,x,y}\}$ of R_x width and R_y height in pixels, to be compared against a reference image \mathbf{z}^* as follows.

The triangle brushstrokes (Figure 1) are represented as $(c_x, c_y, r, \alpha_1, \alpha_2, b^Y, b^{Cb}, b^{Cr})$, where $c_x \in [0, \dots, R_x)$, $c_y \in [0, \dots, R_y)$, and $r \in [0, R_x/\sqrt{T^{\max}}]$ define the circumscribed circle center and radius for the triangle to be rendered; $\alpha_1 \in [1^\circ, 360^\circ)$ and $\alpha_2 \in [1^\circ, 180^\circ)$ define the vertices of this triangle on its circumscribed circle; and $b^Y \in [16, 236)$, $b^{Cb} \in [16, 241)$, and $b^{Cr} \in [16, 241)$ are the color components of the brush for the triangle contained pixels.

The triangles' vertices coordinates encoded by i -th DE vector construct T_i triangles, each triangle $\mathbf{T}_k = (c_{x,k}, c_{y,k}, r_k, \alpha_{1,k}, \alpha_{2,k}), \forall k \in \{1, \dots, T_i\}$ (\mathbf{T}_k being packed as $\mathbf{x}_i = \{x_{i,j}\}, j = 8k + m, m \in \{1, \dots, 8\}$), defining the vertices of a triangle $P_{1,k}, P_{2,k}$, and $P_{3,k}$:

$$P_{1,k} = \lfloor (c_{x,k} + r_k \cos \alpha_{1,k}, c_{y,k} + r_k \sin \alpha_{1,k}) \rfloor, \quad (9)$$

$$P_{2,k} = \lfloor (c_{x,k} + r_k \cos(\alpha_{1,k} + \pi), c_{y,k} + r_k \sin(\alpha_{1,k} + \pi)) \rfloor, \quad (10)$$

$$P_{3,k} = \lfloor (c_{x,k} + r_k \cos \alpha_{2,k}, c_{y,k} + r_k \sin \alpha_{2,k}) \rfloor. \quad (11)$$

The brush color $\mathbf{b}_k^{YCbCr} = (b_k^Y, b_k^{Cb}, b_k^{Cr})$ is first transformed into RGB color model as $\mathbf{b}_k^{RGB} = (b_k^R, b_k^G, b_k^B)$ ($b_k^R, b_k^G, b_k^B \in [0, 255]$), where:

$$b_k^R = \lfloor 1.164(b_k^Y - 16) + 1.596(b_k^{Cr} - 128) \rfloor \quad (12)$$

$$b_k^G = \lfloor 1.164(b_k^Y - 16) - 0.813(b_k^{Cr} - 128) - 0.391(b_k^{Cb} - 128) \rfloor \quad (13)$$

$$b_k^B = \lfloor 1.164(b_k^Y - 16) + 2.018(b_k^{Cb} - 128) \rfloor \quad (14)$$

For each triangle T_k , a solid color is rendered without antialiasing over the triangle brush area rasterizing [1] with a transparency factor of $1/T_i$:

$$\mathbf{b}_k = \left\lfloor \frac{255}{T_i} \mathbf{b}_k^{\text{RGB}} \right\rfloor. \quad (15)$$

This is analogous to blending the triangle as a part-transparent layer within the evolved image $\mathbf{Z}_i = \sum_k \mathbf{z}_{k,x,y}$ and computes R, G, and B color layers for the pixels of the i -th individual:

$$\begin{aligned} \mathbf{z}_{k,x,y} &= \sum_{\mathbf{T}_k \text{ over } (x,y)} \mathbf{b}_{k,x,y} \\ &= \sum_{\mathbf{T}_k \text{ over } (x,y)} \left\lfloor \frac{255}{T_i} \mathbf{b}_{k,x,y}^{\text{RGB}} \right\rfloor, \end{aligned} \quad (16)$$

where $\mathbf{T}_k \text{ over } (x, y)$ denotes each triangle being rendered over the pixel (x, y) such that $\mathbf{b}_{k,x,y}$ contains the rendered pixels of a brushstroke. Triangles defined possibly over the edges of image canvas are drawn by clipping away pixels outside of the canvas area.

The initialization of a genotype is such that the $c_x, c_y, \alpha_1, \alpha_2, b^Y, b^{Cb}, b^{Cr}, T_i^L$, and T_i^U are initialized uniform randomly to integer values within their respective definition intervals, while r is kept as a floating-point. All parameters are however evolved as floating-point scalar values in DE.

3.3 Evaluation

Evaluation of the phenotype image \mathbf{Z}_i to be compared against a reference image \mathbf{Z}^* is as follows. A reference image \mathbf{Z}^* is represented as RGB-encoded colored pixels integer values in layers $\mathbf{Z}^* = \{(z_{x,y}^R, z_{x,y}^G, z_{x,y}^B)\}$.

To obtain a difference assessment value, the following comparison metric is used for comparing an evolved image $\mathbf{Z} = \mathbf{Z}_i$ to \mathbf{Z}^* :

$$f(\mathbf{Z}) = 100 \times \left(\frac{\sum_{y=0}^{R_y-1} \sum_{x=0}^{R_x-1} |z_{x,y}^{*R} - z_{x,y}^R|}{255 \times R_x R_y} + \frac{\sum_{y=0}^{R_y-1} \sum_{x=0}^{R_x-1} |z_{x,y}^{*G} - z_{x,y}^G|}{255 \times R_x R_y} + \frac{\sum_{y=0}^{R_y-1} \sum_{x=0}^{R_x-1} |z_{x,y}^{*B} - z_{x,y}^B|}{255 \times R_x R_y} \right). \quad (17)$$

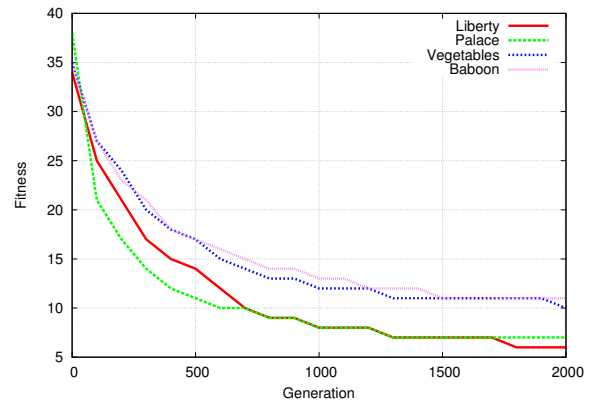


Figure 2: Fitness convergence, for best runs of each test image.

4 Experiments

The following experiments assess the viability of the approach on different control parameters, each with several independent runs. The parameter sets are as follows: the DE population size $NP = \{25, 50, 100\}$ and $T_{\max} = \{10, 20, \dots, 150\}$, thereby for each run $RNi = \{0, 1, \dots, 51\}$ this counts for total of 45 parameter sets, i.e., 2340 independent runs. The NP and T_{\max} are fixed during one run. The maximum number of function evaluations (MAXFES) used is same as with [7], MAXFES is 10^5 . For image rendering, basic GDI+ is used.

4.1 Obtained Results

The obtained fitness values at the MAXFES termination of 10^5 , over different parameters of T_{\max} and NP , are seen in Tables 1 and 2. The best values obtained overall for an image are marked in bold underlined text font. The fitness convergence graphs for these best runs are seen in Figure 2, where after the initialization, the fitness is roughly below 40 (i.e., 40% similarity with reference), then drops below 15 for all test images and even further to slightly above 6 for two of them.

The convergent obtained results depend on the MAXFES used being same as with [7], but also NP and T_{\max} , as reported below. From Tables 1 and 2, we choose to report further evolved images up to MAXFES of 10^6 with all images. The best approximated images after MAXFES of 10^6 are shown in the Figure 3 which shows the evolution of the four images. In each line of Figure 3, the best fitting vectors upto MAXFES of 10^6 in generations $g = \{0, 100, 200, 400, 700, 1200, 2000\}$, and the final generation, are shown, then the rightmost the corresponding reference image. Figure 4 shows for each test image, dynamics of the number of triangle brushes in current best vector during generations, displaying varying convergent best T_i values across images.

Our approach searches for a representative image model and the values obtained such as 6.77, can roughly be compared to the 4.83 of [7]. Such representation of the problem

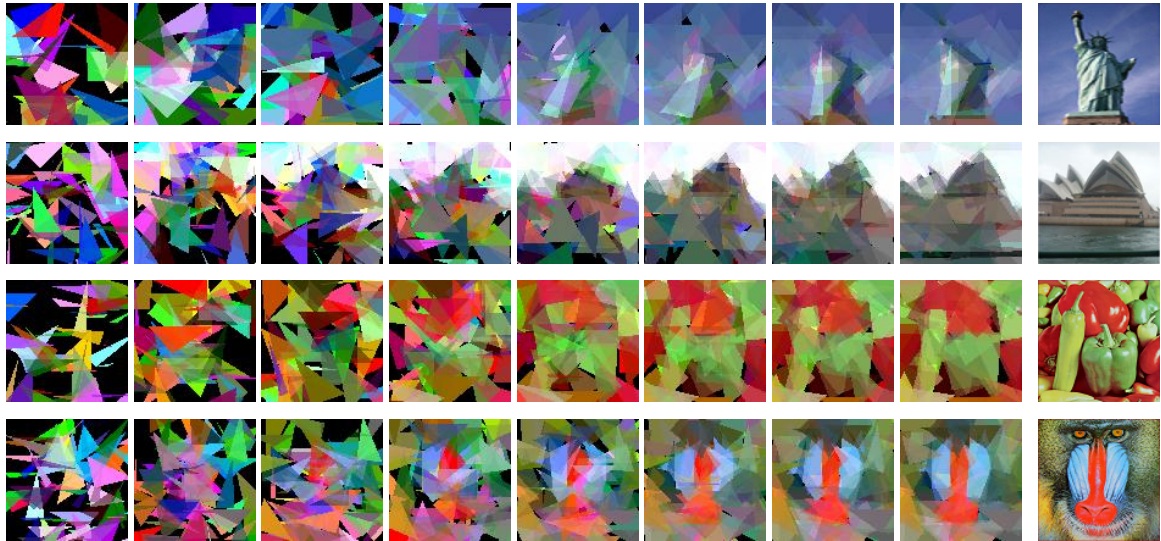


Figure 3: The evolved and the reference images (self-adaptive F and CR).

also makes our NP parameter have higher value, since we have no guided search and the problem is therefore more general. Also, our approach does not use a dynamically re-allocatable morphable variable-size tree structure as in genetic programming encoding, in spite it rather uses a fixed size vector and limits its brushstrokes set by two simple bounds, making the approach faster for execution.

For comparison purposes and since this paper is an extended version of [8], following additional comparison is included. The algorithm is run again with fixed control parameters $F = 0.5$ and $CR = 0.9$ in DE, all other settings are kept same as with the proposed above approach.

Further, the results in Tables 1 and 2 are statistically tested using t-test with $\alpha = 0.001$, against the null hypothesis, that the results obtained with fixed control parameters $F = 0.5$ and $CR = 0.9$ in DE, do not statistically differ. The symbol \dagger with the values in bold text font signifies that the self-adaptive F and CR parameters approach results are significantly better and the symbol \ddagger with values in italicized text font signifies that the fixed parameters approach results are significantly better. Comparing the statistics on the varied NP and T_{max} settings, DE with changing F and CR is 164 times better, 13 times worse, and 3 times with no significant performance difference, compared to the DE with $F = 0.5$, $CR = 0.9$.

The Figure 5, the best DE run with $F = 0.5$, $CR = 0.9$, nonetheless still shows self-adaptation of the T_i parameter – this is an additional indicator that the performance difference lines in the changing of the F and CR control parameters, which, compared to fixed values, improve the approach performance if they are self-adaptive.

Visually, the performance difference is observed from the rendered images in Figure 6, showing superiority of the proposed approach with self-adaptive control parameters over the approach using fixed control parameters. The Figure 7 shows fitness convergence of the best evaluated vector of the best DE run with $F = 0.5$, $CR = 0.9$, this

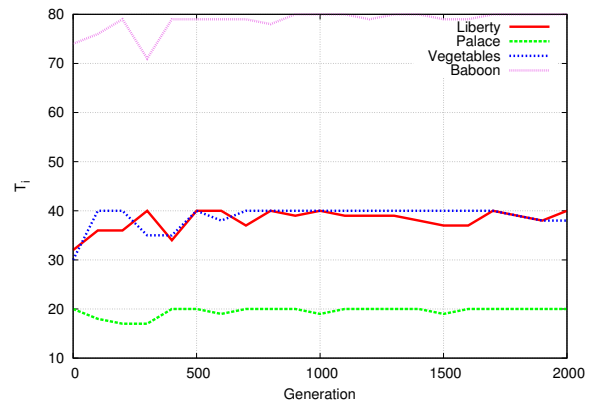


Figure 4: Number of brushstrokes in best vector, for best runs of each test image, self-adaptive F and CR parameters.

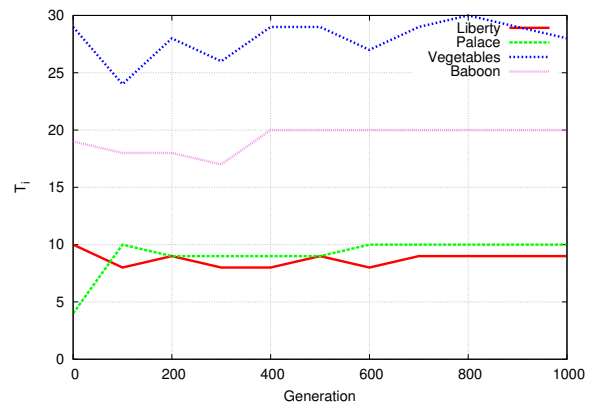


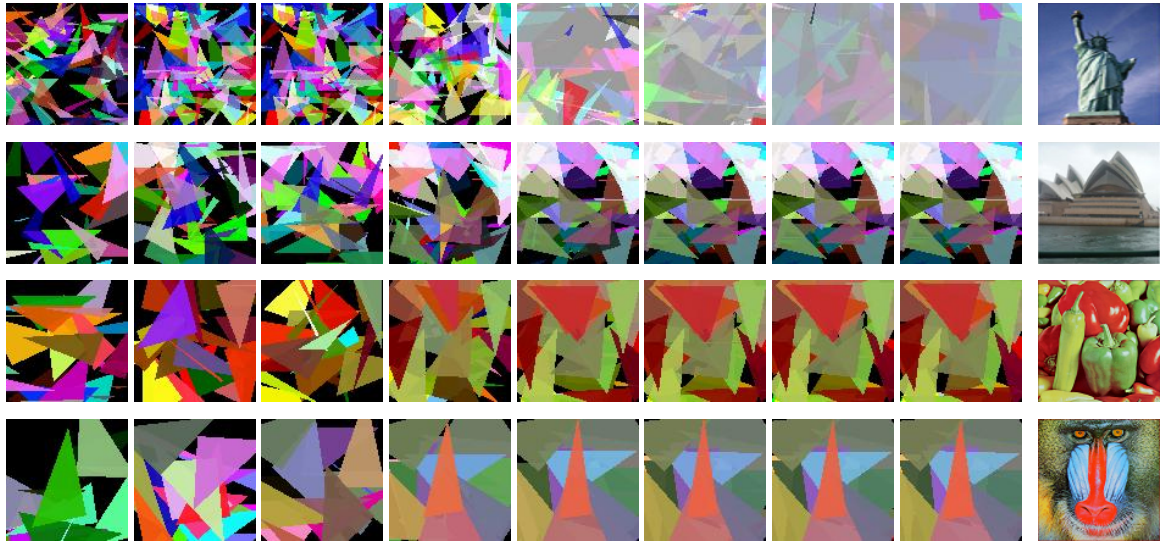
Figure 5: Number of brushstrokes in best vector, for best runs of each test image, $F = 0.5$, $CR = 0.9$.

Table 1: Obtained fitness over T_{\max} and NP : test instances Liberty and Palace

| NP | T_{\max} | Liberty | | | | Palace | | | |
|------|------------|-------------|-------|-----------------------------|--------|------------|-------|-----------------------------|--------|
| | | Best | Worst | Average | STD | Best | Worst | Average | STD |
| 25 | 10 | 8.29 | 11.99 | 9.93096 [†] | 0.8233 | 8.69 | 13.69 | 10.1362 [†] | 0.9655 |
| 25 | 20 | 8.03 | 13.14 | 10.0935 [†] | 1.0845 | 7.83 | 11.5 | 9.12173 [†] | 0.8092 |
| 25 | 30 | 8.41 | 13.74 | 10.0525 [†] | 1.1712 | 7.52 | 11.1 | 8.97942 [†] | 0.7992 |
| 25 | 40 | 8.13 | 12.81 | 10.4408 [†] | 1.1416 | 7.34 | 11.36 | 8.91788 [†] | 0.8922 |
| 25 | 50 | 8.49 | 13.37 | 10.6767 [†] | 1.1768 | 7.65 | 12.53 | 8.87442 [†] | 0.9788 |
| 25 | 60 | 7.95 | 14.65 | 10.9858 [†] | 1.4284 | 7.9 | 11.88 | 8.99673 [†] | 0.8761 |
| 25 | 70 | 8.28 | 14.21 | 11.4075 [†] | 1.3630 | 7.79 | 13.17 | 9.50327 [†] | 1.0482 |
| 25 | 80 | 8.72 | 15.89 | 11.7554 [†] | 1.6330 | 7.97 | 12.34 | 9.43558 [†] | 0.9765 |
| 25 | 90 | 8.84 | 16.24 | 12.1342 [†] | 1.6608 | 8.41 | 13.54 | 9.82 [†] | 1.2756 |
| 25 | 100 | 9.01 | 16.74 | 12.4798 [†] | 1.7521 | 8.62 | 12.96 | 9.83635 [†] | 0.8869 |
| 25 | 110 | 8.07 | 16.78 | 12.7412 [†] | 1.7849 | 9.01 | 14.42 | 10.4119 [†] | 1.2468 |
| 25 | 120 | 9.67 | 16.14 | 12.8467 [†] | 1.7359 | 8.93 | 15.13 | 10.3858 [†] | 1.3149 |
| 25 | 130 | 10.16 | 17.96 | 13.2692 [†] | 1.7193 | 9.02 | 14.2 | 10.2858 [†] | 1.0292 |
| 25 | 140 | 9.29 | 17.99 | 13.7029 [†] | 1.7886 | 8.29 | 13.51 | 10.7779 [†] | 1.0299 |
| 25 | 150 | 10.82 | 18.56 | 14.0373 [†] | 1.6573 | 9.89 | 14.91 | 11.1206 [†] | 1.0586 |
| 50 | 10 | 7.51 | 9.69 | 8.45077 [†] | 0.4198 | 7.43 | 11.84 | 8.68058 [†] | 0.8825 |
| 50 | 20 | 6.78 | 8.99 | 7.80173 [†] | 0.4987 | 7.1 | 11.39 | 8.79173 [†] | 0.9592 |
| 50 | 30 | 6.89 | 9.17 | 7.81788 [†] | 0.5119 | 7.53 | 12.58 | 9.75654 [†] | 1.1186 |
| 50 | 40 | 6.77 | 9.87 | 8.0375 [†] | 0.6578 | 8.27 | 12.24 | 10.0575 [†] | 0.9537 |
| 50 | 50 | 7.08 | 10.61 | 8.39923 [†] | 0.7056 | 7.97 | 13.14 | 10.3338 [†] | 1.1009 |
| 50 | 60 | 7.15 | 10.4 | 8.67115 [†] | 0.7472 | 8.59 | 12.49 | 10.7817 [†] | 1.0754 |
| 50 | 70 | 7.46 | 10.9 | 9.1025 [†] | 0.8666 | 7.58 | 12.8 | 10.7744 [†] | 1.1086 |
| 50 | 80 | 7.6 | 11.4 | 9.47981 [†] | 0.8689 | 9.15 | 13.11 | 11.3802 [†] | 1.0178 |
| 50 | 90 | 8.05 | 12.65 | 9.67346 [†] | 0.9115 | 9.97 | 13.41 | 11.5227 [†] | 0.9315 |
| 50 | 100 | 8.75 | 11.75 | 10.0152 [†] | 0.7824 | 8.55 | 13.62 | 11.4356 [†] | 0.9923 |
| 50 | 110 | 8.93 | 13.63 | 10.6356 [†] | 0.9682 | 9.32 | 13.77 | 12.0712 [†] | 0.9579 |
| 50 | 120 | 9.22 | 13.01 | 10.7502 [†] | 0.9840 | 9.77 | 14.21 | 12.429 [†] | 0.8972 |
| 50 | 130 | 9.42 | 12.59 | 11.0527 [†] | 0.7707 | 11.37 | 14.07 | 12.7387 [†] | 0.6134 |
| 50 | 140 | 9.99 | 13.39 | 11.5719 [†] | 0.7815 | 9.69 | 15.5 | 12.9317 [†] | 0.9708 |
| 50 | 150 | 10.2 | 14.56 | 12.2633 [†] | 1.0702 | 9.58 | 15.36 | 12.8092 [†] | 1.1717 |
| 100 | 10 | 7.1 | 9.12 | 7.98596 [†] | 0.4241 | 7.91 | 13.88 | 10.9573 [†] | 1.8019 |
| 100 | 20 | 6.85 | 9.77 | 7.83962 [†] | 0.5360 | 8.86 | 14.59 | 12.1117 [†] | 1.2862 |
| 100 | 30 | 7.15 | 11.8 | 8.49077 [†] | 1.1563 | 9.59 | 16.15 | 12.9098 [†] | 1.0589 |
| 100 | 40 | 7.22 | 13 | 8.86327 [†] | 1.1092 | 9.65 | 14.97 | 13.2477 [†] | 1.1543 |
| 100 | 50 | 7.41 | 12.75 | 9.34846 [†] | 1.3939 | 11.01 | 15.52 | 13.8606 [†] | 0.9750 |
| 100 | 60 | 8.06 | 12.97 | 9.77731 [†] | 1.1539 | 11.5 | 16.14 | 14.1856 [†] | 1.1234 |
| 100 | 70 | 8.67 | 13.28 | 10.1954 [†] | 1.3722 | 10.77 | 16.32 | 14.3629 [†] | 1.1713 |
| 100 | 80 | 8.73 | 14.48 | 11.0929 [†] | 1.4093 | 10.98 | 17.06 | 14.9348 [†] | 1.1679 |
| 100 | 90 | 9.04 | 14.92 | 11.3594 [†] | 1.3483 | 11.1 | 16.8 | 15.104 [†] | 1.2586 |
| 100 | 100 | 9.4 | 16.13 | 11.6604 [†] | 1.4952 | 10.8 | 17.62 | 15.36 | 1.2330 |
| 100 | 110 | 10.17 | 15.68 | 12.3365 [†] | 1.5685 | 13.01 | 17.86 | <i>16.0202</i> [‡] | 0.9744 |
| 100 | 120 | 10.26 | 15.45 | 12.3358 [†] | 1.5076 | 11.07 | 17.99 | <i>15.6113</i> [‡] | 1.6455 |
| 100 | 130 | 10.22 | 16.19 | 13.2212 [†] | 1.6108 | 12.33 | 18.37 | <i>16.4085</i> [‡] | 1.3168 |
| 100 | 140 | 11.42 | 16.65 | 13.7808 [†] | 1.5502 | 11.64 | 18.35 | <i>16.1229</i> [‡] | 1.4990 |
| 100 | 150 | 11.35 | 18.68 | 14.6113 [†] | 1.9726 | 10.11 | 18.34 | <i>16.2929</i> [‡] | 2.0056 |

Table 2: Obtained fitness over T_{\max} and NP: test instances Vegetables and Baboon

| NP | T_{\max} | Vegetables | | | | Baboon | | | |
|-----|------------|--------------|-------|-----------------------------|--------|--------------|-------|-----------------------------|--------|
| | | Best | Worst | Average | STD | Best | Worst | Average | STD |
| 25 | 10 | 14.13 | 17.21 | 15.7269 [†] | 0.7148 | 15.02 | 18.59 | <i>16.38</i> [‡] | 0.7128 |
| 25 | 20 | 12.56 | 18.03 | 14.5658 [†] | 0.9850 | 13.44 | 17.12 | 15.3815 [†] | 0.8129 |
| 25 | 30 | 12.33 | 15.98 | 13.9215 [†] | 0.8475 | 12.99 | 19.03 | 15.0204 [†] | 1.1150 |
| 25 | 40 | 11.62 | 16.21 | 13.674 [†] | 1.0436 | 11.99 | 16.85 | 14.4342 [†] | 1.0135 |
| 25 | 50 | 12.16 | 17.08 | 13.88 [†] | 1.0726 | 11.39 | 17.62 | 14.4573 [†] | 1.2299 |
| 25 | 60 | 11.64 | 17.88 | 13.6438 [†] | 1.2155 | 11.74 | 17.51 | 14.8038 [†] | 1.2229 |
| 25 | 70 | 11.29 | 17.15 | 13.9056 [†] | 1.3790 | 11.88 | 17.9 | 14.6267 [†] | 1.3495 |
| 25 | 80 | 11.61 | 16.6 | 14.0871 [†] | 1.3881 | 12.11 | 17.13 | 14.3606 [†] | 1.2815 |
| 25 | 90 | 11.63 | 17.96 | 14.1062 [†] | 1.4428 | 11.93 | 19.41 | 14.6644 [†] | 1.5269 |
| 25 | 100 | 11.34 | 17 | 14.4533 [†] | 1.4694 | 11.7 | 18.77 | 14.7642 [†] | 1.7438 |
| 25 | 110 | 11.74 | 19.66 | 14.6085 [†] | 1.7664 | 12.02 | 19.11 | 15.0046 [†] | 1.7605 |
| 25 | 120 | 12.26 | 17.91 | 14.7737 [†] | 1.5726 | 12.2 | 18.5 | 15.6467 [†] | 1.6086 |
| 25 | 130 | 12.1 | 19.75 | 14.6338 [†] | 1.9283 | 13.01 | 19.5 | 15.4254 [†] | 1.5505 |
| 25 | 140 | 11.94 | 19.01 | 14.7635 [†] | 1.6282 | 12.64 | 19.37 | 15.8235 [†] | 1.8458 |
| 25 | 150 | 12.82 | 18.7 | 14.6487 [†] | 1.3015 | 13.13 | 20.17 | 15.7952 [†] | 1.6923 |
| 50 | 10 | 13.03 | 15 | 14.0723 [†] | 0.4674 | 13.86 | 16.52 | <i>14.9192</i> [‡] | 0.5494 |
| 50 | 20 | 11.66 | 13.26 | 12.4644 [†] | 0.3184 | 11.8 | 14.54 | 13.271 [†] | 0.5569 |
| 50 | 30 | 11.12 | 13.59 | 12.2425 [†] | 0.6528 | 11.59 | 13.62 | 12.5506 [†] | 0.5732 |
| 50 | 40 | 10.94 | 14.1 | 12.1848 [†] | 0.6656 | 11.1 | 13.84 | 12.3137 [†] | 0.6090 |
| 50 | 50 | 11.04 | 13.92 | 12.2946 [†] | 0.7609 | 11.34 | 14.36 | 12.4075 [†] | 0.6304 |
| 50 | 60 | 11.29 | 15.86 | 12.5506 [†] | 0.9222 | 11.25 | 14.1 | 12.3662 [†] | 0.6161 |
| 50 | 70 | 11.18 | 15.21 | 12.6104 [†] | 0.8682 | 11.54 | 14.57 | 12.5437 [†] | 0.6510 |
| 50 | 80 | 11.32 | 15.26 | 12.8619 [†] | 0.7658 | 11.07 | 15.56 | 12.9473 [†] | 0.8087 |
| 50 | 90 | 11.84 | 15.28 | 13.0077 [†] | 0.8038 | 11.32 | 16.2 | 12.857 [†] | 1.0291 |
| 50 | 100 | 11.72 | 15.8 | 13.5058 [†] | 0.9565 | 11.85 | 15.72 | 13.2658 [†] | 0.7972 |
| 50 | 110 | 12.02 | 15.92 | 13.5204 [†] | 0.8750 | 11.98 | 15.56 | 13.4275 [†] | 0.7805 |
| 50 | 120 | 11.9 | 16.87 | 13.829 [†] | 1.1151 | 12.43 | 15.66 | 13.5106 [†] | 0.7265 |
| 50 | 130 | 12.51 | 15.97 | 14.094 [†] | 0.8855 | 12.64 | 16.32 | 14.085 [†] | 0.8259 |
| 50 | 140 | 12.16 | 17.07 | 14.8198 [†] | 1.2154 | 12.54 | 16.31 | 14.15 [†] | 0.8865 |
| 50 | 150 | 13.11 | 17.98 | 14.9838 [†] | 1.2072 | 13.08 | 18 | 14.8765 [†] | 1.0178 |
| 100 | 10 | 12.56 | 16.19 | 13.9815 [†] | 0.8083 | 13.49 | 16.19 | <i>14.5367</i> [‡] | 0.5672 |
| 100 | 20 | 11.84 | 16.45 | 13.4704 [†] | 1.0483 | 12.02 | 15.87 | <i>13.8244</i> [‡] | 0.8747 |
| 100 | 30 | 11.83 | 17.64 | 13.9133 [†] | 1.3335 | 12 | 15.76 | <i>13.7206</i> [‡] | 0.9727 |
| 100 | 40 | 12.01 | 17.95 | 14.6354 [†] | 1.3660 | 11.63 | 17.01 | <i>13.6467</i> [‡] | 1.3582 |
| 100 | 50 | 11.87 | 17.35 | 14.9156 [†] | 1.4272 | 11.99 | 17.48 | <i>14.1658</i> [‡] | 1.5554 |
| 100 | 60 | 12.32 | 18 | 15.21 [†] | 1.5119 | 12.12 | 17.46 | <i>14.5021</i> [‡] | 1.4517 |
| 100 | 70 | 12.13 | 18.05 | 15.6513 [†] | 1.2457 | 12.12 | 17.16 | 14.3881 [†] | 1.3782 |
| 100 | 80 | 12.9 | 18.86 | 16.2008 [†] | 1.4121 | 12.13 | 17.56 | 14.8656 [†] | 1.4214 |
| 100 | 90 | 12.32 | 20.04 | 16.3233 [†] | 1.7789 | 12.25 | 18.66 | 15.2558 [†] | 1.5144 |
| 100 | 100 | 12.98 | 20.55 | 16.7275 [†] | 1.7119 | 13.09 | 18.42 | 15.5398 [†] | 1.5064 |
| 100 | 110 | 13.76 | 20.18 | 17.2896 [†] | 1.5242 | 13 | 19.62 | 15.84 [†] | 1.6164 |
| 100 | 120 | 13.12 | 20.62 | 17.626 [†] | 1.5807 | 13.34 | 19.58 | 16.4725 [†] | 1.5223 |
| 100 | 130 | 13.52 | 20.12 | 17.9052 | 1.3516 | 13.84 | 19.6 | 16.9367 [†] | 1.7362 |
| 100 | 140 | 14.08 | 20.52 | 18.216 [†] | 1.6975 | 14.3 | 21 | 17.4387 [†] | 1.7372 |
| 100 | 150 | 14.97 | 21.19 | 19.1221 | 1.2128 | 14.75 | 21.13 | 17.9488 [†] | 1.6872 |

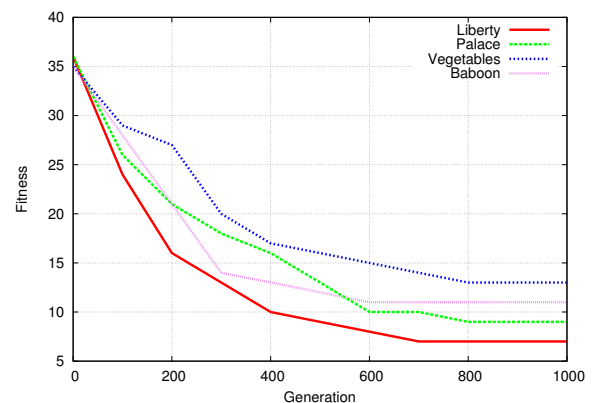
Figure 6: The evolved and the reference images, $F = 0.5$, $CR = 0.9$.

time with $NP = 100$ and therefore maximum generation number of 1000. The attained values tend to converge towards T_{\max} , but results are worse since the different T_{\max} , seen from Figures 4 and 5.

5 Conclusion

This paper presents an evolvable lossy image representation, approximating an image by comparing it to its evolved generated counterpart image. The image is represented using a variable number of triangular brushstrokes, each consisting of a triangle position and color parameters. These parameters for each triangle brush are evolved using differential evolution, which self-adapts the control parameters for mutation and crossover. Also, the proposed DE extension splits the DE vector in the codon and anticodon parts, where the triangles material is used only from the codon part, adjusting the genetic tree center and its borders, together with the number of triangle brushstrokes to be rendered. Experimental results show the viability of the proposed encoding and evolution convergence for the lossy representation of reference images, where fitness is displayed dependent on the population size, maximal number of function evaluations allowed, maximal number of triangles used in image representation, and different input reference images. While analyzing the NP and T^{\max} , moreover in this paper, we have shown that the self-adaptive jDE control parameters handling mechanism is preferable to the fixed control parameters mechanism from the original DE.

Future work can include increasing MAXFES, addressing different encoding aspects, evolutionary operators, control-parameters update, Euclidean distance for colors comparison, and more case studies on input images with different properties.

Figure 7: Fitness convergence, for best runs of each test image, $F = 0.5$, $CR = 0.9$.

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