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Streamline Uniform Placement Algorithm With Dynamic Seed Points

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ABSTRACT Streamline generation is an important technique for vector field visualization. Streamline uniform placement algorithm can make streamline distribution evenly and express vector information better. An effective streamline placement method should effectively express the characteristics of vector field, make the streamline distribution uniform, and allow the streamline length to be as long as possible. In this paper, a dynamic seed placement algorithm based on critical points and grid points is proposed. The algorithm firstly finds and retains the key points to ensure the key information of vector field, and then introduces uniform grids to control the streamline density of vector fieldso as to guarantee that the streamlines are evenly distributed. The experimental results show that the proposed algorithm can display the characteristic information of vector field well, makes the streamline distribution uniform, and allows the length of streamline to be long. As a result, there are almost no short streamlines.

INDEX TERMS Vector field visualization, streamline uniform placement, seed point, critical point, key characteristics.

I. INTRODUCTION

The research of Line Integral Convolution (LIC) algorithm and streamline generation is inseparable, and the streamline is an important way to reasonably represent vector field visualization [1]. Stalling and Hege [2] proposed a fast convolution algorithm known as fast LIC. Sundquist [3] developed a fast convolution method known as Dynamic LIC, which uses two vector fields to visualize the dynamic electromagnetic field. Rezk-Salama [4] proposed a texture-based volume rendering method that can interactively display the visualization of a three-dimensional vector field. With the development of graphics hardware, many algorithms accelerated by GPU have been emerged e.g., the Image-based Flow Visualization algorithm proposed by Van Wijk [5], the Lagrangian-Eulerian Advection algorithm proposed by Jobard [6], and the Image Space Advection algorithm proposed by Laramee [7]. Huang *et al.* [8] proposed an image space continuity output algorithm to solve the surface flow field visualization problem. Primoz Skraba *et al.* [9] proposed a robust vector field visualization method designed to simplify the vector field feature points. After that, they further proposed the unsteady vector field simplification method [10]. Wang Quan et al. [11] proposed a visualization method for field strength driving. Shene *et al.* [12] proposed a three-dimensional streamline visualization method based on hierarchical clustering. Oeltze *et al.* [13] used multiple clustering methods for clustering. The LIC method is an important method in texture-based vector field visualization. The motion direction and trend of the flow field can be better displayed by streamline representation [14]. Streamline generation method is the basis of realizing the flow band, flow surface and streamline based-particle animation [15]. To a large extent, the visualization of the streamline depends on the choice of the initial point, and a reasonable initial point can retain the important characteristics of the flow field [16]. If the seed point is not properly selected, the important features of the flow field will be lost. There are many research methods on streamline placement, most of which focus on the selection of seed points, integration step size, sampling point position, and the number of iterations. For example, Schlemmer *et al.* [17] defined the regional density of a streamline. The placement of the streamline is controlled by taking the ratio of the number of streamline pixels of the area to the number of pixels of the area as a parameter.

Vector field visualization [18] can be expressed in various forms. The main forms can be divided into point, line, surface, particle, texture, vector field topology [19] and so on.

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Among them, the streamline form can better express the vector direction, and the streamline visualization effect depends largely on the selection of the initial seed points. Xu *et al.* [20] proposed a seed points selection and streamline generation algorithm based on information entropy. A streamline can be thought of as a trajectory of a particle that changes position with the vector in the vector field. The streamline generation starts from the seed point and searches for the position of the corresponding next point in both the forward and reverse directions, and iterates until it meets the termination condition and stops.

How to place the streamline reasonably is a very important research topic. Chen *et al.* [21] described a similarity measure between streamlines, and reduced the occlusion in three-dimensional space by controlling the generation of similar streamlines, and thus realized the visualization of specific flow fields. At present, there is no standard definition for the correct placement of the streamline. However, an effective streamline placement method should mainly take the following aspects into consideration: whether the vector field features are effectively expressed; whether the streamline distribution is sufficiently uniform; and how long the streamline lines are. If the streamline placement strategy can make the density of the streamline layout reasonable, the feature points are clearly expressed and the streamlines are mostly longer. Such a streamline placement method is a more reasonable and effective streamline placement strategy.

The effect of streamline visualization [22] mainly depends on the selection of the initial points, and its purpose is to make the streamline layout look reasonable. Regarding the research on rational layout, Turk and Banks [23] proposed an image-guided method which uses the energy function to sample the flow field and merges the streamlines that are close to each other based on calculation. Zhan and Robert [24] proposed a uniformly distributed streamline placement algorithm that takes into account the priority order of topological seed points and guarantees the length of the streamlines as much as possible. Verma [25] proposed a flow-guided method which uses different initial point layout strategies for different flow patterns, and adjusts the streamline position and length appropriately. Abdelkrim Mebraki *et al.* [26] proposed the farthest seed point algorithm. Olufemi *et al.* [27] proposed a dual streamline placement algorithm, which simplified the parameters by means of a dual flow field, highlighting the flow field topology and easily extending to a three-dimensional surface. Lu *et al.* [28] proposed a streamline extraction algorithm based on iterative nearest neighbors and K-means clustering, aiming at solving the occlusion and clutter of three-dimensional flow field visualization.

In this paper, a dynamic seed point placement algorithm for vector field streamline generation based on critical point and mesh is proposed. Fig. 1 shows the flow chart of the algorithm, which will be introduced in detail in Sec.3. Compared with other methods, the streamline generated by this method is evenly distributed and long, almost no short streamline, and the efficiency is faster. In addition, the generated streamlines can display the characteristic information of vector field very well.

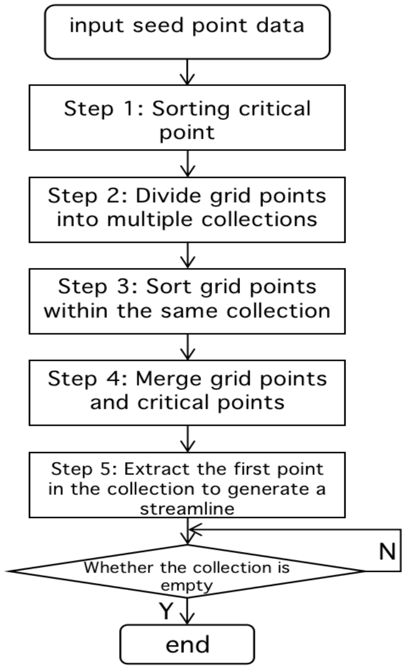


FIGURE 1. Use bilinear interpolation to determine whether there is a critical point.

II. SEARCH AND CLASSIFICATION OF CRITICAL POINTS

Critical points are very important information used to represent the characteristics of vector fields, and cannot be ignored in the visualization of vector fields. A critical point is the key point in the vector field, which is generally the point where the vector value is zero. In this paper, both key point and critical point mean the same. This paper mainly focuses on the two-dimensional vector field data which consists of rectangular grid points. The specific location of the key points can be obtained by interpolation.

A. FINDING THE CRITICAL POINTS

Based on the assumption of local linearity, we can use a variety of schemes to detect the critical points in vector field. The two-dimensional vector field raw data points are usually represented by a unit rectangular grid. We use bilinear interpolation to detect the critical points of the vector field. The interpolation calculation is shown in Figure 2.

The calculation of the critical point in the grid point using the bilinear interpolation algorithm is shown in equation (1).

$$\begin{cases} (1-x)(1-y)\,u1+(1-x)\,yu4+x\,(1-y)\,u2+xyu3=0 \\ (1-x)(1-y)\,v1+(1-x)\,yv4+x\,(1-y)\,v2+xyv3=0 \end{cases} \tag{1}$$

When solving the above equation, if there is a zero in the data grid, then we can calculate the critical point position.

In the actual calculation process, we do not need to calculate each grid. When the vector component values of four

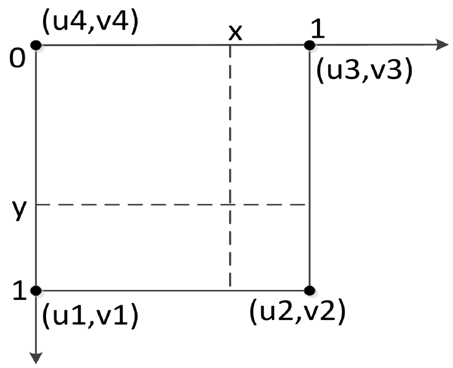


FIGURE 2. Use bilinear interpolation to determine whether there is a critical point.

points of a grid are both greater than 0 or less than 0, there is no criticality in this grid.

In addition, to quickly calculate the critical point, we need to detect the direction consistency of two vectors, and we can achieve thisby cross product of the four point vectors in the grid. Whether there is a critical point in the grid or not can be judged by comparing whether the vectors cross product is smaller than a given sum threshold.

B. CRITICAL POINTS CLASSIFITION

After critical points obtained by the above method, according to the critical point theory [29], we can classify the obtained critical points. Different types of critical points use different drawing methods when streamline drawing. Suppose there is a critical point (x_0, y_0) in a grid, and a flow vector (u, v), there is a Jacobian matrix J_0, as shown in equation (2):

$$J_0 = \left.\frac{\partial (u, v)}{\partial (x, y)}\right|_{x=x_0, y=y_0} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix}_{(x_0, y_0)} \tag{2}$$

Let the two eigenvalues of the Jacobian matrix J_0 be $\lambda_1 = R_1 + iI_1$ and $\lambda_2 = R_2 + iI_2$, then the critical points can be divided into the following cases according to the calculated values of R_1, I_1, R_2, I_2. We divide the critical points into six cases as shown in Fig. 3.

For the case of critical points classification in the vector field as shown in Fig. 3, different critical points need to be treated differently when generating seed points and drawing streamlines. The specific processing method is described in the next section.

III. DYNAMIC SEED POINTS PLACEMENT METHOD BASED ON CRITICAL POINTS AND GRID POINTS

A. STREAMLINE UNIFORM PLACEMENT ALGORITHM

The seed points have an important impact on the streamline layouts, especially when the vector field contains the feature points. If the seed points are not properly selected, then it is very likely that the feature points will not be expressed. There are many algorithms for streamlines placement, and the followings are the commonly used streamlines placement methods.

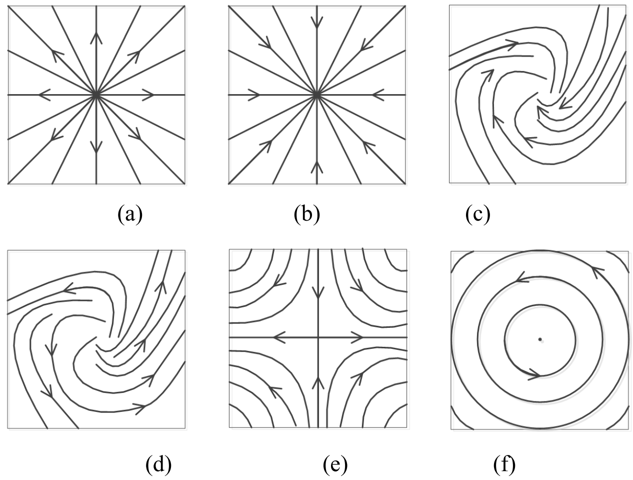


FIGURE 3. Classification of critical points: (a) repelling node, (b) attracting nodes, (c) attracting focus, (d) repelling focus, (e) saddle point, and (f) center point.

1) RANDOM SEED POINTS PLACEMENT

This algorithm mainly sets the number of seed points and randomly generates their position to draw the corresponding streamlines. The algorithm has high efficiency and is relatively simple, but it cannot guarantee the uniform distribution of streamlines. The streamlines generated by this method are likely to have very dense streamlines in one area, and no streamlines in the other area. The key feature points of the flow field cannot be accurately expressed.

2) EVENLY DISTRIBUTED SEED POINTS PLACEMENT [24]

This algorithm mainly sets reasonable grid sampling points according to the values of the flow field to obtain evenly distributed seed points and draw corresponding streamlines. Since the seed points are evenly distributed, the resulting streamlines are also relatively uniform. However, this situation may not be able to express key feature points of the flow field, and there are some problems with the density and length of the streamlines.

3) IMAGE GUIDED PLACEMENT [23]

This algorithm was proposed by Turk and Banks in 1996. It uses the energy function to modify the position and length of the streamlines in the vector field to obtain a uniform distribution of streamlines placement effects.

4) REGIONAL STREAMLINE UNIFORM DISTRIBUTION [30]

This algorithm is proposed by Jobard and Lefer in 1997. When a streamline is generated, a series of seed points are generated on both sides and stored as candidate seed points in the seed point set. Then a seed point is selected from the set to generate the next streamline and remove it from the container. When the point set is empty, the algorithm will stop. The algorithm could guarantee the streamlines spacing, but it cannot guarantee the length of the streamlines.

5) FLOW FIELD GUIDED PLACEMENT [25]

This algorithm is proposed by Verma in 2000. The main idea is to select the seed points to generate the streamlines near the key points of the vector field, and to randomly place the seed points to generate the streamlines for the rest area. The algorithm can display the flow field features well, but cannot control the streamlines density and guarantee the length of the streamlines.

6) THE FARTHEST DISTANCE SEED POINTS PLACEMENT [26]

This algorithm is proposed by Abdelkrim Mebraki *et al.*. The algorithm selects the center point of the largest blank area of the vector field region as a seed point each time when a new streamline is generated. For the largest blank area, the Delaunay triangulation is used to determine the maximum empty loop detection. The continuity of the method to generate streamlines is good, but some special parts will lack the key feature information of the vector field.

7) TOPOLOGY-DRIVEN PLACEMENT [31]

The algorithm is proposed by Zhang Wenyao and Deng Jianquan in 2009. The main idea of the algorithm is to find the key points, draw the flow field topology structure, divide the flow field into several regions according to the topology structure, and traverse these regions. When traversing a region of vector field, the gravity center of the region is used as a seed point of streamline to generate and draw the streamline. Then it traverses the two sub-regions divided by the generated streamlines to get the seed points and draw the streamlines. Repeat above process until the sub-area streamline density reaches the set number of streamlines. The algorithm can reflect the flow field characteristics and run faster. However, sometimes the connection of two topological points in the topology is not necessarily the actual streamline. At this time, the generated topology will affect the generation of streamlines. In addition, when the sub-area becomes smaller, the streamline is very short.

In the streamline representation of the vector field, it is important to place the seed points in streamline generation. In order to ensure that the feature points of the vector field can be accurately expressed, we propose a dynamic seed points placement method based on both critical points and grids in combination with the idea of topology-driven.

B. DYNAMIC SEED POINTS PLACEMENT ALGORITHM BASED ON CRITICAL POINTS AND GRID POINTS

Due to the importance of the critical point in the flow field, it must be expressed completely and correctly. Based on this feature, we need to find the key points of the vector field as the initial seed point for streamlines generation. After finding the critical point, we do not connect the critical point to form a topology to divide the region, but retain the critical point in the vector field. In order to control the streamlines density and make the streamlines evenly distributed, we introduce a grid to control the streamlines and use the grid points as seed points. Our idea is firstly to use the key points as seed points and generate streamlines from near to far according to the distance of these seed points from the center of the vector field. In order to ensure the length of the streamline, we do not limit the length of the streamline. We call these streamlines as critical streamlines, and the grid points through which the critical streamlines pass (setting threshold to judge, such as streamlines passing within 6 pixels of the grid points, counting them as grid points) are no longer seed points. We call these streamlines as critical streamlines, and the grid points through which the critical streamlines pass (setting threshold to judge, such as streamlines passing within 6 pixels of the grid points, counting them as grid points) are no longer seed points. After generating the critical streamlines, we traverse all the grid points and classify them based on their distance to the critical points. According to the distance, the kind of grid points that belong to the critical points is also generated as seed points from near to far and is drawn.

We propose a dynamic seed point vector field streamline generation algorithm based on critical point and grid. The algorithm combines the idea of uniformly distributed seed point algorithm and topologically driven algorithm, and uses key points and grid points as seed points for generating streamlines (the critical point is also called key point). Since the key points are the expression of important features of the flow field, those key points must be fully utilized when the streamlines are generated. The algorithm first looks for the key points in two-dimensional vector field and uses these points as seed points. The streamlines generated by these seed points are called critical streamlines. After the key streamlines are all drawn, although the vector field features have not been fully expressed, the key features of the vector field will not be ignored. If a 2D vector field has no key seed points, then we use the center point as the only key point. In order to ensure uniform distribution of streamlines, we use a uniform grid to dynamically generate seed points, which are called grid seed points. It should be noted that all seed points here refer to a specific grid point, rather than a specific location in the grid calculated by interpolation, in order to avoid the vector value of seed points being 0. The specific process of the algorithm can be described in Table 1.

It should be noted that in order to guarantee the length of the streamlines, our termination condition does not limit the number of steps. In addition, the grid seed points that are particularly close to the streamline can be removed only after the complete streamline is generated. The relationship from the near to the far in the above steps can also be changed from far to near, but it does not change suddenly, which can easily lead to the generation of short streamlines.

In Fig. 4, the red points are the critical points or grid points as alternate seed points, and the green points have been generated or streamlined according to the rules. Green critical points or grid points can no longer be used as seed points. In Fig. 4 (a), the critical point is first found in the vector field, and then it is used as the seed point to generate the critical streamline. In Fig. 4 (b), the grid points are used as seed

TABLE 1. Dynamic seed points streamlines placement algorithm based on critical points and grid points.

Input: input raw vector data, critical seed points, grid seed points
Output: streamlines with uniform distribution

Step1: The critical points of the vector field are calculated by the method described in Section 2. According to the distance from the critical point to the center of the vector field, the critical points are sorted near to far. The set of ordered critical points is $X_{\text{key}} = \{x_1, x_2, \cdots, x_m\}$.

Step2: The grid points are classified according to the distance of the grid seed points from the critical points. Grid seed points are divided into the following subsets: $x1\_P, x2\_P, x3\_P, \cdots$ (The subset of grid points clustered around the critical point xi is xi_P, but each grid seed point subset does not contain a corresponding critical point xi).

Step3: The elements in the grid points subsets $x1\_P, x2\_P, x3\_P, \cdots$ are ordered according to the distance from the corresponding critical point from near to far. The sorted grid seed point sets are $X_{\text{key}\_x1\_P}, X_{\text{key}\_x2\_P}, X_{\text{key}\_x3\_P}$.

Step4: The set of critical points X_{key} and the set of grid points $X_{\text{key}\_x1\_P}, X_{\text{key}\_x2\_P}, X_{\text{key}\_x3\_P}, \cdots$ are combined to obtain a complete set of seed points $X_{seed} = \{x_1, x_2, \cdots, x_m, X_{\text{key}_{x1\_A}}, X_{\text{key}_{x2\_B}}, X_{\text{key}_{x3\_C}}, \cdots\}$. Simply, we record the seed point set as $X_{seed} = \{x_{seed\_0}, x_{seed\_1}, \cdots, x_{seed\_n}\}$.

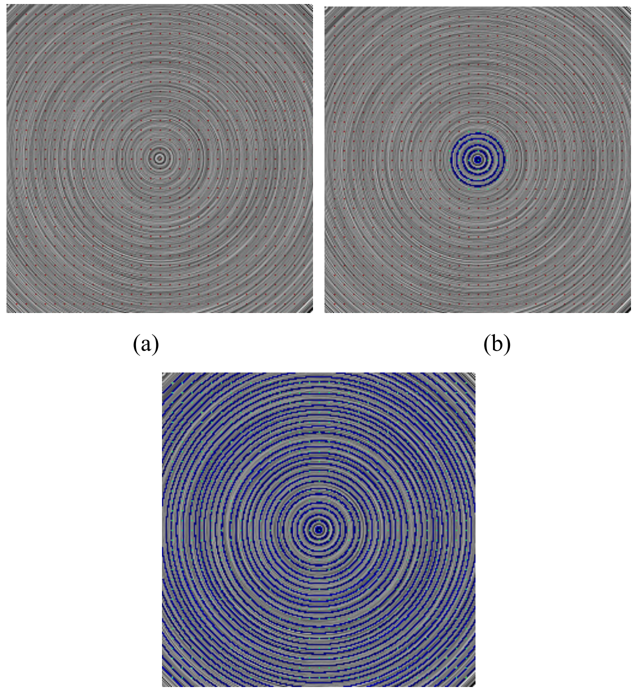
Step5: The streamline is generated starting from the seed point subset x_{seed_0}. After the current streamline generation is completed, the seed point of the current streamline generation and the seed points the streamline passed are eliminated from the set X_{seed}.

Step6: If the set X_{seed} is empty, it means that there is no seed point and the algorithm ends. Otherwise, loop **Step5, Step6**.

points, and streamlines are generated from near to far according to the distance between the grid points and the critical points. When a streamline is generated, grid points passing through or near the streamline are deleted. Fig. 4 (c) is the final result of the dynamic seed point streamline generation algorithm based on critical points and grid points.

It is worth noting that for different critical points, the classification processing is required in the streamline generation process. Different processing methods are adopted for different critical points to ensure that the streamlines passing through the critical point can be completely generated and drawn.

As shown in Fig. 3, for the case where the critical point is a repelling node, an attraction node or a saddle point, the vector field streamline generation is mainly considered to maintain one of the two key streamlines. The direction of the streamline depends mainly on the vector direction of the four vertices of the mesh. Because only the key point as a seed point can get one streamline at most. In these three cases, it is necessary to ensure that two key streamlines are generated, so that a better streamline distribution effect can be obtained. At this point, you need to use the four vertices of the grid where the key points are located as seed points. Other streamlines are obtained according to the general streamline generation rules.



(a) (b) (c)

FIGURE 4. Dynamic seed points streamline generation algorithm based on critical points and grid points.

For the case where the key point is the center point, we use the key point as the seed point to draw directly without generating the key streamline. Other streamlines are obtained according to the general streamline generation rules. For the center point, the key streamline is a solid circle.

For the case of node repelling, node attracting, focus repelling, focus attracting, and saddle point, if the key point is exactly a grid point, then the seed point is offset by one unit from the grid point.

If the key point is somewhere in the grid, then the seed point is one of the grid points, and the seed point is $P_{\text{seed}} = (\lfloor x_s \rfloor, \lfloor y_s \rfloor)$, where $\lfloor x_s \rfloor, \lfloor y_s \rfloor$ is the lower limit of (x_s, y_s) and (x_s, y_s) is the coordinate value of the key point. Since the vector value of the key point is 0, the key point is directly selected as the seed point, and the generation of the stream line cannot be started.

C. STREAMLINE GENERATION STEPS

In the dynamic seed point streamline generation algorithm, the critical point and the grid point are first sorted according to the rule and used as a seed point set. Then, while generating the streamline, the seed points close to the generated streamline are removed from the point set. The even distribution generation process of streamlines is shown in Figure 5.

Fig. 5 shows the process in which streamlines are generated in sequence. The red points are the seed points, and the blue points indicate that the streamlines have been generated with seed points and the streamlines pass through the points during the streamlines generation process. These blue points are no

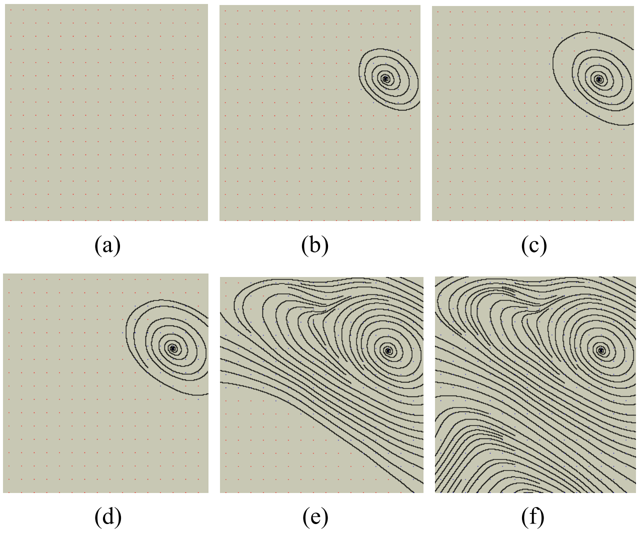


FIGURE 5. Streamlines even distribution generation process.

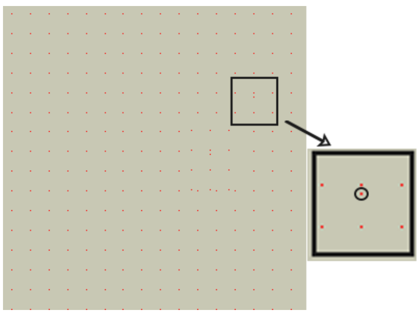


FIGURE 6. An enlarged view of the Fig.4 (a).

longer used as seed points. When all the red points turn blue, it means that the streamlines are evenly distributed and the generation is completed.

It can be seen from Fig. 6 that the point in the black circle is a key point. When the key point is used as a seed point, the first streamline is generated (Fig. 5(b)). The grid points which are passed by the generated streamline turn blue. This indicates that these blue points are no longer used as seed points, as shown in Fig. 5(c). Next, the grid point which is closest to the key point is used as the seed point to generate the next streamline, and the seed points passed by the streamline become blue when the streamline is generated. This process is repeated until all streamlines are generated.

The grid spacing of the red points in Fig. 5 is 19 unit pixels. Here we consider the grid points near the 8-pixel units of streamlines as the points streamlines passed. When the distance between the streamlines is close to 4 unit pixels, the streamline generation is terminated.

IV. COMPARISON AND ANALYSIS OF UNIFORM PLACEMENT ALGORITHMS

The uniform streamline placement algorithm should fit the real texture better on the basis of the uniform distribution of the streamlines. It mainly includes the following two aspects:

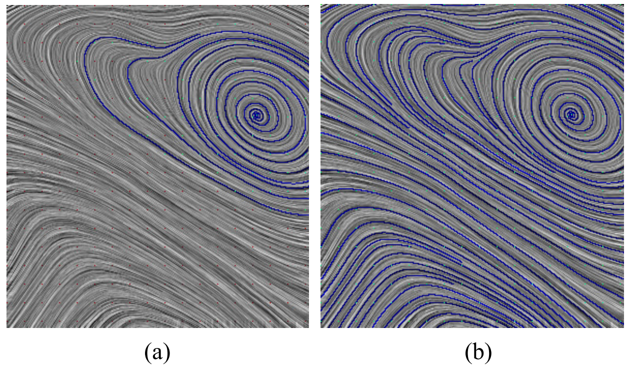


FIGURE 7. Overlay display of vector texture and streamlines. (a) Streamlines partial generation, (b) streamlines complete generation.

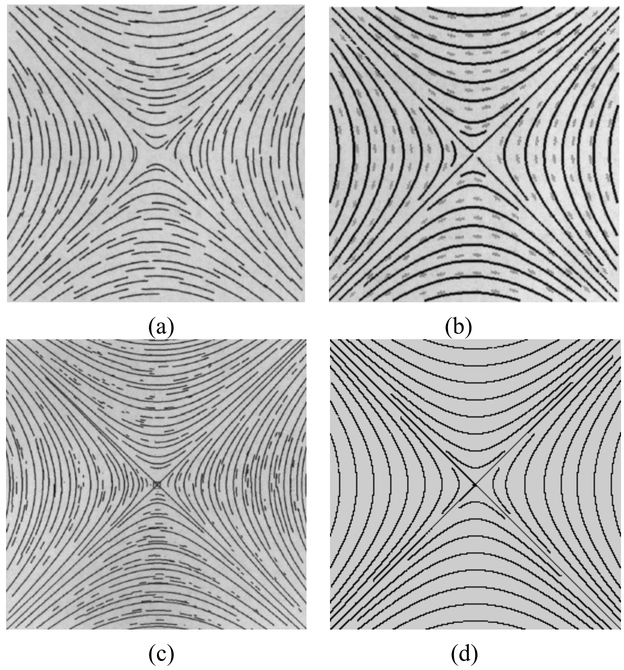


FIGURE 8. Comparison of the results of different streamline uniform placement algorithms. (a) Image-guided placement method, (b) farthest distance seed points placement method, (c) topology-driven placement method, (d) our method.

whether the streamline direction is consistent with the texture direction, and whether the streamline can accurately express the characteristics of the texture. That is, vector feature points are not ignored or misrepresented. Sometimes because the calculation accuracy is not enough, it will cause the center point structure to be expressed as the focus structure.

In Fig. 7, Fig. 7(a) is the result of partial streamlines and vector texture overlay display, and Fig. 7(b) is the result of all streamlines and vector texture overlay display. From the figure, we can see that the generated streamlines and vector texture fit well, and streamlines distribution are uniform, streamline is long, with good continuity, almost no short streamlines.

Fig. 8 shows the effect of the proposed streamline uniform placement algorithm, in comparison with the image-guided

TABLE 2. Comparison of streamline placement algorithms (unit s).

Algorithm	time
Image-guided placement	15. 23
Farthest distance seed point placement	1. 21
Topology-driven placement	1. 53
Ours	0. 671

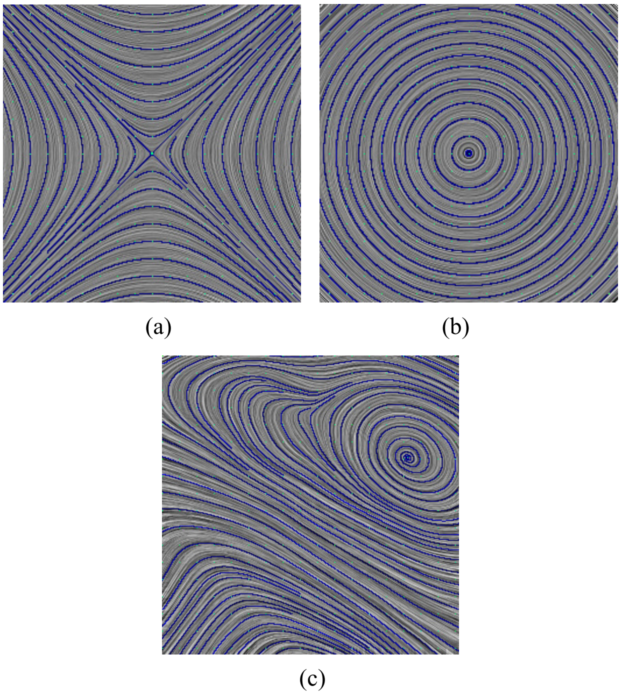


FIGURE 9. The results of streamlines generation for different vector fields by our algorithm.

placement method [23], The farthest distance seed points placement method [26], and the topology-driven placement method [31].

As can be seen from Fig. 8, Fig. 8(a) is the visualization effect of the image-guiding placement method, which has many short streamlines, and the core position intersecting diagonal lines are not generated, and the streamlines continuity are poor. Fig. 8(b) is the visualization effect of the farthest distance seed points placement method. The continuity of the streamlines are good, but the middle part is obviously asymmetrical and lacks key feature information of the vector field. Fig. 8(c) is the visualization effect of the topology-driven placement method. There are many short streamlines and the streamlines continuity is not good. Fig. 8(d) is the visualization effect of the dynamic seed points placement method based on the critical point and grid proposed in this paper. The streamlines obtained are entirely symmetrical, with uniform streamlines distribution, long streamlines length, good continuity and almost no short streamlines.

As can be seen from the compare results of Fig. 8, the image-guided placement algorithm has short streamlines, a long consuming time, poor continuity and low efficiency. The farthest distance seed points placement method and topology-driven placement method both have longer streamlines than the image-guided placement algorithm, and the former lacks key information, and the latter has many short streamlines. Our algorithm has the shortest execution time and high efficiency, and the generated streamlines are long and evenly distributed, and the continuity is good, which is better than the above three algorithms.

The vector field size shown in Fig. 8 is 400X400. The running environment of the experiment is Windows 7, and this algorithm is implemented by using VS2010 and qt5.2. The computer processor is Intel (R) Core (TM) i7-4790 CPU 3.6GHz, with 8GB memory. The comparison of the execution time of the four algorithms is shown in Table 2.

Fig. 9 shows the result of the uniformly distributed streamlines in three different vector fields by using the proposed algorithm. The cyan points are the seed points that are removed from the original seed points during the even distribution of the streamlines. When all the seed points become cyan, it means that the streamlines generation are completed. The streamlines fit the texture in the background very well. The streamlines effectively express the characteristics of the vector field, and the distribution is relatively uniform, and the length is long.

V. CONCLUSION

Streamlines are an important representation of vector field visualization. How to place streamlines reasonably is a very important research topic. The streamlines uniform placement algorithm can distribute the streamlines evenly and better express the vector field information. The effect of streamline visualization depends mainly on the selection of the seed points, in order to make the streamline layout look reasonable. In this paper, a new seed points selection method is proposed for streamline generation, and a better vector field streamlines effect is obtained. The main contributions of this paper are as follows: (1) A dynamic seed points placement method based on critical points and grid points is proposed. This results in evenly distributed streamlines and long streamline length and there are almost no short streamlines. (2) For the classification of the critical points of the vector field, different processing strategies are adopted for different critical point types, so that the obtained streamlines could express the characteristic information of the vector field. (3) We introduce a grid to control the vector field streamlines density, and use the grid points as a seed points to generate streamlines. As a result, the generated streamlines are evenly distributed.

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