Time-Coherent Streamline Placement

Bachelor's Thesis

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Abstract

Vector field visualizations are used in many fields like aerospace engineering, fluid dynamics, or physics. A common graphical representation of such fields are instantaneous integral lines, called streamlines. The placement of such streamlines for a continuous and steady vector field is subject of contemporary research, with a multitude of algorithms that can generate such streamline placements in an optimal way w.r.t different criteria. This thesis's focus will be on the time-coherent placement of streamlines, i.e. minimizing streamline movement during changes of the underlying continuous, but unsteady vector field. We present an iterative procedure that starts by seeding streamlines with a greedy algorithm for a single timestep. The seeds are then optimized to make them time coherent for as many lines a possible. The performance and complexity using different streamline seeding and modification strategies are examined and compared. Finally some limitiations, possible imporovements, and ideas for future work will be listed.

Zusammenfassung

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Contents

1 Introduction

A vector field is a space that maps to each point it contains a vector. There are several ways such fields can be obtained, a simple algebraic definition could be e.g. $u(x,y) = (x,y)$. These vector fields are called "steady" because they do not change over a period of time. Accordingly, time-dependent fields are reffered to as "unsteady" fields and can be defined like $u(x,y,t) = (x+t, y+t)$ or $F(x,y,z) = (-z+t, -y, -x)$. For steady fields, there are several papers showing different strategies to generate streamlines according to different criteria. Commonly preferred attributes are high streamline length, and uniform line density, which are often labelled as "coherence". Both of which greatly enhance the information uptake by preventing visual clutter; thereby allowing a focus on more important features and characteristics of the field at hand. As soon as a change in the field is introduced, however, these methods are no longer optimal when examined over the entire time span. Therefore, we will start by introducing a new criterion termed "temporal coherence" (opposed to the aforementioned spatial coherence). This essentially defines how lines move through time; low coherence means a lot of movement. For a more detailed explanation, see the next section. The procedure outlined by this paper has a simple modus operandi: We start by generating a spacially coherent streamline structure for every time step using a greedy algorithm. Then we start walking along the generated lines, trying to find those of high temporal cohrence, and keep them. The others we try to optimize by moving their seeds around, or, if no sensible movement is possible, simply delete them. In the final step, we fill the blank spaces left by the deletion according to the chosen seeding algorithm, and are finished.

1.1 Problem Statement

Creating animations containing streamlines is difficult because streamlines are not time-coherent when generated using conventional methods described in ...

1.2 Proposed Solution

By adding the time coherence constraint, animated streamline visualizations look much better and do not introduce aritfacts etc. etc.

2 Related Work

Most of the works published in the field of streamline placement present algorithms that can be divided into two categories:

2.0.1 Image-Guided

The goal of this approach is to achieve a very uniform, almost "hand-drawn" appearance. Generated images will usually have high visual quality, at the risk of potenitally missing or misrepresenting important features.

One of the first and most prominent examples in this category was written by Greg Turk and David Banks [96]. In their research paper, a function (called the "Energy Function") is defined such that it maps an input image containing the potential streamlines to a scalar. The scalar represents the quality of the image, roughly defined as the uniformity of the grey scales it contains. Adding/moving/removing/resizing streamlines is done randomly, at every step the energy function is used to determine whether the change gets accepted or discarded. The algorithm is finished when the energy function reaches a minimal threshold, or a maximum number of consecutive rejected steps is exceeded.

2.0.2 Feature-Guided

Feature-Guided algorithms examine the underlying field structure before placing seeds. They search for critical points or patterns in the field and then seed around them, capturing them in much higher detail. The resulting images inherently represent the critical points much better, at the cost of some visual appeal compared to the aforementioned group.

2.0.3 Other Relevant Works

- Time Coherence in 2D

- Approach I've used so far due to simplicity

Do not forget to use references [Han+19] like done here [HS19] to enable the bibliography [Jun+17; SJMS19; SRS18; ZRLS19].

3 Fundamentals

3.1 Vector Fields

3.1.1 Definitions

3.1.2 Critical Points

3.2 Streamlines

3.2.1 Spatial Coherence

3.2.2 Maybe Temporal Coherence?

4 Method

At first, a heuristic criterion for temporal coherence between stream lines is defined. Then ...

4.1 Temporal Coherence

Temporal Coherence refers to how a vector field behaves through different time steps. Intuitively, we consider areas within the field to be of high temporal coherence if the lines drawn on them are relatively stationary. Vice versa, we can say that an area of high fluctuation will be of low temporal coherence. A more formal definition employed in our algorithm is as follows: Given a field F and a starting point S_0 (called the "seed"), we can integrate over the field. This yields a set of points S^0 which define a streamline containing every reached point, written as $S^0 = \int(S_0, F)$. We can therefore assign a streamline to every point in our field (and vice versa). Given S_0 and an unsteady field $F(t)$, compute for each timestep $t_1 ... t_n$ the streamline $S^{0,t_i} = \int(S_0, F(t_i))$. In order to convert these sets of lines to a scalar, we use the Hausdorff Distance $dist(S^i, S^j)$, giving us the greatest minimal distance between any pair of two sets. We can therefore create a map $coh(S_i, F(t)) : max(dist(\int(S_i, F(t_k)), \int(S_i, F(t_l))))$, sending each point in an unsteady vector field to a scalar, and thereby determining its temporal coherence.

5 Implementation

This chapter briefly mentions the used libraries, and focuses on the initial implementation of - and iterative additions to - the proposed algorithm.

5.1 Libraries

The algorithm is implemented in python3.10, and heavily relies on three libraries which are not part of the python3.10 standard library:

- Paraview v.5.12.0: A Scientific visualization software, combining data science and interactive visualization while providing custom algorithm support via the VtkPythonAlgorithm base class.
- VTK v.9.3.20231030 : The library used to manage anything related with the data to be visualized in Paraview.
- Numpy v.1.23.4: Widespread data manipulation/scientific computing library, which is used to edit the data encapsulated by VTK's objects.

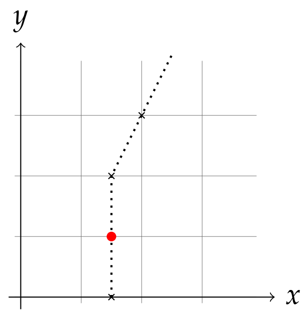
5.2 Steady Field Streamline Placement in 2D

We start with a simple algorithm to generate streamlines in a 2D slice of a vector field. The local z-component of the Cartesian grid is simply set to zero for the relevant sections of the algorithm. The algorithm uses two operations: Streamline Traversal and Seed Filtering, which are executed round-robin.

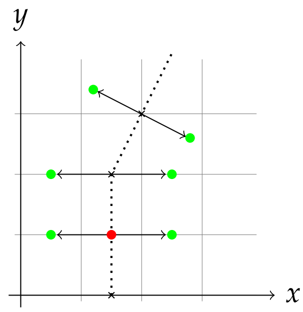
5.2.1 Streamline Tarversal

The Streamline Traversal process works as follows:

- **Step 1:** Choose a seed point from a list of candidates (initially an arbitrary point from the dataset) and remove it from the list. Then integrate forward and backward to obtain the other points on the streamline, until a number of steps is reached, we cross the bounding box, or we get too close to another streamline.



- **Step 2:** Compute the normals, add and subtract them to the succeeding point. The first point (according to step count in backward iteration) will not have a preceding normal, and is not used in this step. These points are new seed candidates for further streamline placement.



5.2.2 Seed Filtering

Since after the 1st iteration, roughly half of the points added by step 2 will be very close to the preceding iteration's points, we store the parent's points and remove any new points from the current step if they are too close to the parent's points. Furthermore, a grid is used to track the global state of the field w.r.t to lines existing in individual segments. This is used to determine whether a line is getting too close to another or if it has room to expand. Streamlines are removed if their length is shorter than 10 iteration steps.

5.3 Steady Field Streamline Placement in 3D

Instead of the trivial normal(s), we now use a normal plane around the streamline trajectory, created via numpy's QR-decomposition. The algorithm returns orthonormalized vectors, the first column vector's direction being equal to the first provided input vector. We can therefore feed it the streamline trajectory and two basis vectors, and receive 2 orthonormal basis vectors b_0, b_1.
With i being the complex number, we obtain k roots of unity via

$$n_j = e^{ji2\pi/k}, j = 0, 1, ..., k-1$$

We then transform them into our 3D frame of reference using

$$v_i = re(n_i) * b_0 + im(n_i) * b_1$$

This gives us k uniformly placed vectors in the normal plane around the current streamline segment. The rest of the algorithm stays largely the same, the grid is simply extended into the 3rd dimension.

5.4 Unsteady Field Streamline Placement in 3D

5.5 Complexity Analysis

6 Results

In Chapter 6, Section 6.1, we will see bla, specifically in Section 6.1.1 this will be emphasized. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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6.1 Section

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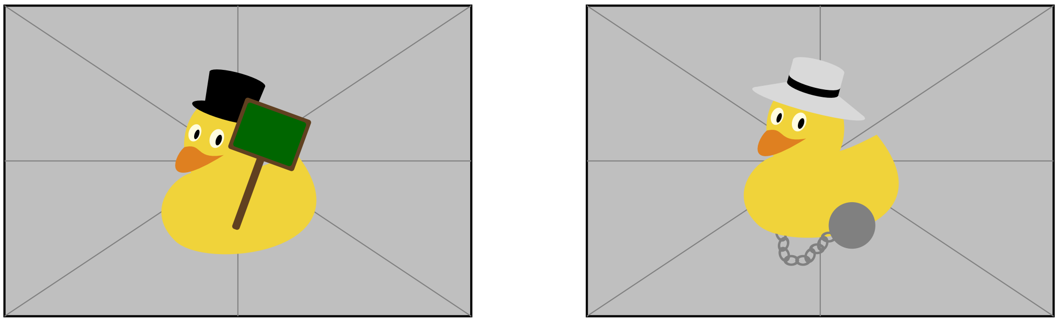

(a) (b)

Figure 6.1: Example for two (a) sub-figures (b).

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6.1.1 Subsection

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7 Conclusion

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