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Streamlines Based Visualization of Air Flow in Clouds

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Abstract: The most important functionality of the hail suppression information system in Serbia is to enable timely and reliable detection of the formation of hail-containing clouds. Improvement of this functionality can be achieved by adequate visualization of air flow (wind) inside the cloud system. This was the motivation for implementing a 2D steady vector field visualization method, based on the streamlines method. The choice of this method is dictated by the requirements for the given appliance: efficiency (a crucial requirement in hail suppression systems), generality of use, an accurate and easily understandable display. By implementing algorithms for streamlines seeding strategy and streamlines points distance control, the infinite loop problem that occurs due to the existence of field vortices is eliminated and evenly spaced streamlines are obtained. For analysing the influence of the implemented method's parameters on performance and image quality, a framework for visualization is developed. The implemented method is successfully applied for visualization of data obtained from meteorological radars.

Keywords: Streamlines, Seeding strategy, Distance control, Visualization, Meteorological radars.

1 Introduction

The importance of information systems in modern meteorology, especially in hail suppression domain, is constantly increasing. Main purpose of hail suppression information systems is to enable timely and reliable detection of physical processes that take place inside the cloud. To achieve previously said, adequate visualization and acquired data analysis is necessary. Hail Suppression Information System (HASIS) has been successfully used in Republic of Serbia for more than 10 years [1]. This system is developed in Laboratory for Computer Graphics and Geographic Information Systems (CG&GIS Lab) at the Faculty of Electronic Engineering in Niš, in collaboration with Republic Hidrometeorological Service of Serbia (RHMSS). Current version of this information system, HASIS 3D, provides observation and monitoring of cloud

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systems in 2D and 3D space using stationary radars, measurement of hail-threatening cloud parameters, calculation of cloud seeding area and calculation of rocket launching ballistic parameters [2].

By visualizing vector data that represent air flow inside cloud systems, new information becomes available to meteorologists. Based on this information better estimation of potential hail cells creation and better prediction of movement and development of cloud systems can be achieved. Three meteorological radars in Republic of Serbia (Bajša, Fruška Gora and Samoš) have the ability of gathering information about air flow inside cloud systems. These radars can measure one component of air flow vector – projection of air flow vector to the straight line that connects radar and observed point of space. Current version of Hail Suppression Information System, HASIS 3D, provides visualization of intensity of previously mentioned component of air flow vector, so only part of the available information is used. By using data from two (three) radars it is possible to reconstruct real air flow vector in each point of the plane (space). Visualization of these vector data is primary motivation for research and practical implementation presented in this paper. The most important requirements that must be satisfied are efficiency, generality of use and accurate and easily understandable display. Crucial requirement for every hail suppression information system is efficiency, because of great speed of hail processes in cloud systems. Namely, hail suppression rockets launching time, after the decision to act, is limited to 2 minutes. Meteorological experts estimate that the complete calculation and visualization process resulting in the display of air flow inside the cloud has to last under 10 seconds in order to be practically useful. Given requirements are satisfied by using LIC (Line Integral Convolution) based method for visualization of reconstructed data from meteorological radars [3]. In this paper the same task is solved using the streamlines based method, which is faster than the LIC based method and also gives very clear and understandable display. Considering that the foundation for both methods is vector field integration, requirement for accuracy is also satisfied. Concerning generality of use, the problem is existence of field vortices that can lead to infinite loop occurrence when the basic algorithm is used. This problem is solved by implementing algorithms for streamlines seeding strategy and streamlines points distance control. These algorithms also contribute to the clearness of display, given that evenly spaced streamlines are obtained. For analyzing influence of implemented method parameters on performance and image quality, developed framework for visualization of 2D vector data given in [3] is extended. Implemented method is successfully applied for visualization of 2D vector data reconstructed from the real data obtained from meteorological radars.

In the second section of this paper theoretical basis of streamlines method for visualization of 2D steady vector fields is given. In the third section implementation details and testing environment are described. In the fourth section appliance of implemented method for visualization of real air flow data, acquired from radars on Fruška Gora and Samoš, is considered. In the last section, advantages of implemented method and future research are given.

2 Streamlines Method

Vector field V is defined by function (1) where x denotes position vector, t denotes time, E denotes open Euclidean space R^n, R^n denotes n-dimensional vector of real numbers and J denotes time interval $a \le t \le b$. Function V satisfies well known conditions concerning continuity and derivates features [4]. Due to the nature of the problem considered in this paper, primary focus will be set on **steady** (time independent) **2D vector fields** ($n = 2$), specified by a set of samples in vertices of regular rectangular grid.

$$V(x,t): E \times J \to R^n . \tag{1}$$

Numerous phenomena in nature can be described by a vector field: fluid flow, wind flow, electromagnetic field etc. Visualization of vector fields is a very productive field of science and there are many developed techniques and methods [5 – 7]. There are four basic groups of methods for vector field visualization:

– local (direct) methods,
– texture based methods,
– geometric methods, and
– feature based methods.

Streamlines method belongs to the group of geometric methods, which use geometry of the object to represent global features of the field [5]. Streamlines method is based on vector field integration, so lines that very intuitively describe vector field flow are obtained. For steady vector fields, streamlines are defined as curves $x = x(t)$ that satisfy condition $\mathrm{d}x/\mathrm{d}t = V(x)$. For initial condition $x(t_k) = x_k$ and vector $V(x)$ given for every point x of space, streamline points can be determined using one of the numerical integration methods. All numerical integration methods are derived from Taylor expansion by discarding terms of higher order. The simplest method is Euler method, obtained by using first two terms of Taylor expansion. Euler method is defined by (2) for positive integration and (3) for negative integration. To gain greater accuracy Runge-Kutta methods are used. Time step Δt can be constant or variable. By connecting obtained streamline points streamline is formed. Streamline points can be connected with straight lines or using some interpolation function (usually polynomial).

$$x_{i+1} = x_i + \Delta t\, V(x_i) , \tag{2}$$

$$x_{i-1} = x_i - \Delta t\, V(x_i) . \tag{3}$$

When implementing streamlines method there are three most important goals: to generate long streamlines, to generate evenly spaced streamlines and to efficiently visualize field vortices i.e. to eliminate the infinite loop problem. There are numerous developed techniques and algorithms for dealing with above mentioned issues. By implementing simple and efficient algorithms for streamlines seeding strategy and streamlines points distance control, very satisfying results in all of the above mentioned categories are obtained [8]. By selecting new streamline initial point so it is the farthest from currently generated streamlines, length of obtained streamlines is increased [9]. By using more accurate numerical integration method (RK4) and cubic Hermite interpolation function, number of sample points for streamline generation is decreased [10]. This enables more efficient use of the algorithm for streamlines points distance control. New strategy for initial streamline points selection resulting in more evenly spaced streamlines and new algorithm for streamline loops detection resulting in better visualization of field vortices is given in [10]. Downside of this approach is that it requires extra processing.

3 Streamlines Method Implementation Details

Crucial requirement in hail suppression systems is efficiency, as stated in the first section. This is the reason why algorithms and techniques with low computational complexity were preferred for streamlines method implementation. At the same time, satisfying results have to be obtained concerning streamlines length, position and efficient visualization of field vortices.

For streamlines points calculation Euler numerical integration method is used. For streamlines method only directional characteristics of the field are of interest, so before using Euler method input vectors normalization is performed. Magnitude of Euler method error and spatial distance between neighbor points of a streamline are directly proportional to the time step Δt. When drawing, calculated streamline points are connected with straight lines. By increasing the time step Δt number of calculations is decreasing, but on the other hand magnitude of Euler method error is increasing and quality of display is decreasing. Thus, adjusting the time step Δt requires compromising. In order to eliminate infinite loop problem in the case of field vortices existence and obtain long and evenly spaced streamlines, strategy given in [8] is used. Input parameters d_{min} and d_{sep} are introduced. At the beginning of the algorithm, several points from 2D plane are randomly chosen and placed in a queue of potential initial streamline points. Potential initial streamline point becomes initial streamline point if the minimal distance between this point and streamline points of previously determined streamlines is greater or equal d_{min}. Starting from the initial streamline point, streamline grows in both directions (positive and negative integration), until one of the stopping criteria is satisfied – field vector is equal zero or minimal distance between the last calculated point and streamline points of previously determined streamlines (including the current streamline) is under d_{sep}. Previously said to be valid, inequality $d_{sep} < \Delta t$ has to be satisfied. Described strategy prevents the occurrence of infinite loops in the case of field vortices existence. For $d_{sep} = d_{min}/2$ best results are obtained considering streamlines length and clarity of display. To obtain evenly spaced streamlines, after calculation of new streamline point x_i, in the queue of potential initial streamline points two new points are placed. These points are positioned on the straight line containing point x_i which is perpendicular to the field vector in point x_i. Distance between either of these points and point x_i is d_{min}.

For purposes of testing and analyzing influence of implemented method parameters on performance and image quality, developed framework for visualization of 2D vector data given in [3] is extended. Fig. 1 shows the architecture of the developed framework, focusing on the part concerning implemented streamlines method.

The class *VectorField2DStreamlines* (which is derived from the class *VectorField2D*) models 2D vector field with the 2D matrix (*m_matrix*). Elements of this matrix are instances of the class *Vector2DStreamlines* (which is derived from the class *Vector2D*). In the class *Vector2DStreamlines*, along with field vector coordinates, there is an array of calculated streamline points (instances of the class *StreamlinePoint*) residing inside the rectangular grid cell which is joined to the mentioned field vector. Memorizing this array of calculated streamline points increases the efficiency of distance checking. Namely, it is sufficient to check the distance between the new point and points nearby (points residing in the same grid cell and neighbor grid cells). The class *VectorField2DStreamlines* provides the capability of generating 2D vector fields with various characteristics (vortices, sources, junctions etc.) and loading vector data from file (functions *Generate* and *ImportFromFile*, respectively). In the class *StreamlineDrawer* streamlines method is implemented. For submitted input parameters (structure *StreamlinesParams*), function *GetStreamlinesImage* returns streamlines display of vector field (in bitmap format). Input parameters of implemented streamlines method are Δt (*m_dTimeStep*) and d_{min} (*m_dMinDistance*). Parameter d_{sep} is calculated as $d_{sep} = d_{min}/2$. The class *CDlgStreamlines* realizes a dialog for adjusting vector field parameters (dimensions and required characteristics or file path) and implemented streamlines method parameters, as well as for invoking functions of the class *StreamlinesDrawer*. The resulting bitmap is drawn in the main dialog, realized by the class *CDlg*.

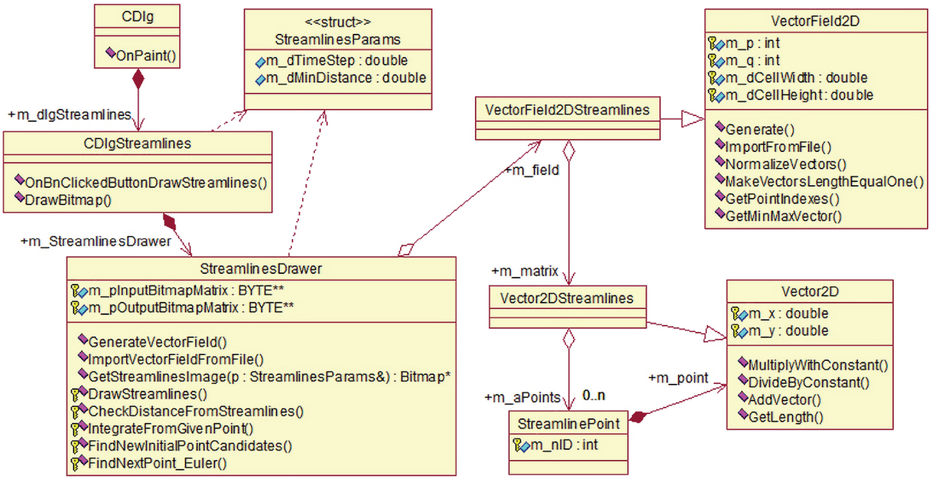
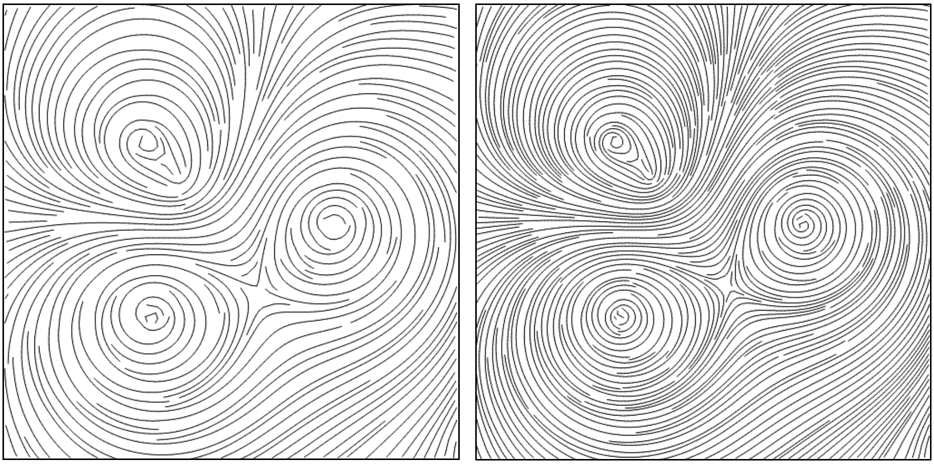


Fig. 1 – *Visualization framework architecture.*

Using the developed framework, testing of the implemented streamlines method was performed on both generated and real data. Fig. 2 shows the visualization of generated test data (vector field contains three vortices, dimension of a rectangular grid is 500×500, dimension of a grid cell is 1×1), for different values of implemented method input parameters.



(a) (b)

Fig. 2 – *Visualization of generated test data:*
(a) $\Delta t = 6$ *and* $d_{min} = 10$; (b) $\Delta t = 4$ *and* $d_{min} = 6$.

4 Visualization of Air Flow in Clouds

As stated in the first section, three meteorological radars in Republic of Serbia (Bajša, Fruška Gora and Samoš) have the ability to measure one component of air flow vector – projection of air flow vector to the straight line that connects radar and observed point of space. Real data from meteorological radars on Fruška Gora and Samoš, measured in the same point of time, were used for 2D vector reconstruction in horizontal planes. Fig. 3 shows the position of used radars and geographic location of an area (marked with the rectangle) for which data was available. Also, Fig. 3 illustrates the procedure of 2D reconstruction of air flow vector ***c***, based on measured projections ***a*** and ***b***.

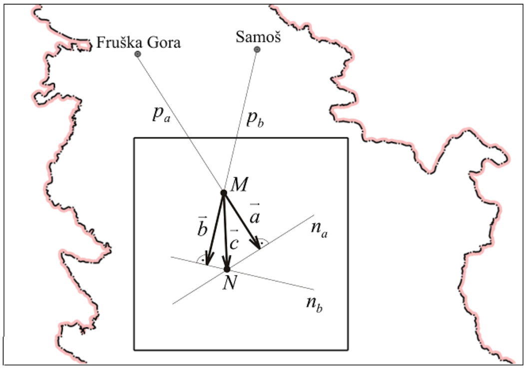
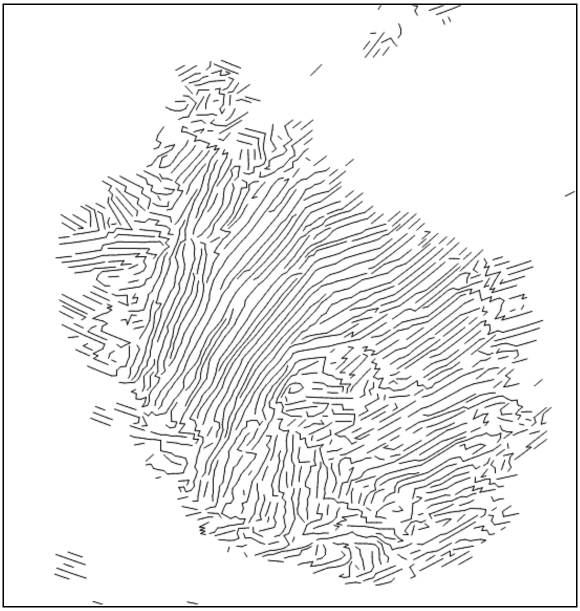


Fig. 3 – *2D reconstruction of air flow vector based on real data from meteorological radars on Fruška Gora and Samoš.*

Result of the reconstruction is a 2D matrix of vector data. The dimension of this matrix is 572×572. Obtained matrix of vector data is visualized using implemented streamlines method for visualization of 2D steady vector fields (method parameters are set to: $\Delta t = 5$ and $d_{min} = 6$). Fig. 4a shows the visualization of reconstructed data in the area marked in Fig. 3. Considering the radars have the ability of measuring air flow parameters only inside the cloud, vector field does not cover the entire observed area. Despite the existence of local errors in data acquired from radars, implemented method gives very understandable display, on which streamlines are very clearly observable. It should be emphasized that the lower part of the picture matches the area in which measured vector projections form an angle that deviates the most from the right angle. Reconstruction procedure in that area is the most sensitive to errors in measured data. Fig. 4b shows the visualization of reconstructed data in the upper left part of the original area. By decreasing the size of observed area, density of sampled data is increased, i.e. dimension of 2D matrix of vector data remains the same.



(a)

(b)

Fig. 4 – *Visualization of real data from meteorological radars on Fruška Gora and Samoš on elevation $H =$* 5750 m:
(a) *complete area marked in* Fig. 3;
(b) *Upper left part of the area marked in* Fig. 3.

Efficiency of the implemented method is tested on the laptop computer of average configuration (Intel Core2Duo T5800, 4GB RAM, NVIDIA GeForce 9300M GS). The time needed to generate the picture shown in Fig. 4a is 0.078 s. The time needed to generate the picture shown in Fig. 4b is 0.125 s. By comparison, the time needed to visualize the same data set on the same computer using the LIC based method is 1.8 s [3]. Therefore the streamlines based method is one order of magnitude *faster* than the LIC based method. Defined 10 s timeframe is more than enough to examine several horizontal planes on different elevations and obtain very informative illustration of processes taking place inside the cloud.

5 Conclusion

By visualizing vector data that represent air flow inside cloud systems, new information becomes available to meteorologists. Based on this information better estimation of potential hail cells creation and better prediction of movement and development of cloud systems can be achieved. Efficiency of Hail Suppression Information System (HASIS) is of crucial importance, considering the great speed of hail processes inside the cloud systems. Meteorological experts estimate that the complete calculation and visualization process resulting in the display of air flow inside the cloud has to last under 10 seconds in order to be practically useful. Other important requirements that must be satisfied are generality of use and accurate and easily understandable display. All given requirements are satisfied by using LIC (Line Integral Convolution) based method for air flow vector field visualization [3]. In this paper the streamlines based method for air flow vector field visualization is presented. This method also satisfies all given requirements, but is also one order of magnitude faster than the LIC based method. For analyzing influence of implemented method parameters on performance and image quality, developed framework for visualization of 2D vector data given in [3] is extended. Implemented method is successfully applied for visualization of 2D air flow vector data, obtained by reconstruction of real data from meteorological radars on Fruška Gora and Samoš. There are three main goals of future research: to improve accuracy by using more accurate numerical integration methods (but at the same time retain the same level of efficiency), to enrich the display with information about vector direction and intensity and to adapt the implemented method for visualization of 3D vector fields.

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