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Estimation of Velocity Field from Oceanographic Image Sequences

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Abstract

Oceanographers desire accurate methods of tracking features in satellite images of the ocean in order to observe and quantify surface layer dynamics. Infrared images of the ocean showing sea surface temperatures are widely used for the studies of this type.

Feature tracking from time series of satellite IR images poses two problems: First, the features of interest have weak edges and constantly evolving shapes from image to image. That means features merge, split, grow, shrink, disappear are created on time scales that are comparable to the sampling interval of the satellite imagery (12 hours). In other words, the phenomenology under investigation is Turbulent Fluid flow, not rigid body motion. The second problem which results from the first, is feature motion cannot be defined by parameters that are functions of scale as well as space and time. A simple example of different motions associated with different scales is seen in the ocean "front". Most ocean fronts exhibit shear across the frontal boundary.

In this paper we present some new results in our oceanographic velocity of the image flow and more specifically, we discuss a new approximation method to estimate the velocity field of Gulf stream from a sequence of satellite images. In this method, connected components of the region representing a stream is identified, triangulated and the velocity field on the region is estimated by the affine approximation on each triangle.

1 Introduction

Our primary objective is to get an estimate of the velocity vector field of moving regions in a given sequence of images. In oceanographic images, for example, we are interested in tracking the movement of mesoscale features such as Gulf streams and Eddies. We consider following two subproblems for the problem of estimating the velocity field of moving regions.

Boundary extraction and tracking — The boundaries of a region are extracted by applying segmentation and edge detection operators. The extracted boundary is approximated by a piecewise linear curve, which is a continuous concatenation of line segements. A piecewise linear curve is also called a polygonal curve. For example, a circular curve can be approximated by a regular polygonal curve. Though more elaborate higher degree spline approximation techniques are available, the standard linear approximation of the regions is suitable for our method of estimating the velocity vector field. The region itself is triangualted into a simplicial complex based on the piecewise linear boundary of the region. In other words, we triangulate (i.e., construct a piecewise linear approximation of) the region (a two dimensional object) based on the piecewise linear approximation of the boundary curve (a one dimensional object). Such approximation for any dimension is called triangulation. Those constructions can be applied to higher dimensional objects (surfaces, solids, or n-manifolds) recursively.

Motion estimation — Given simplicial complexes approximating the regions in the image sequence and simplicial maps of the complexes of lower dimensions (called skeletons), we construct a simplicial map of the whole complex approximating the motion of the regions by an affine interpolation of the simplicial maps of the skeletons (complexes of lower dimensions) of the regions. In our cases, the skeletons are the piecewise linear curves (together with their vertices) approximating the boundary of the region. The velocity vector field describing the motion of the regions will be estimated from the simplicial maps between the 2-dim simplicial complexes. The piecewise linear boundary curves are 1-dim simplicial complexes and the triangulated regions are 2-dim simplicial complexes.

In oceanographic image analysis and understanding, the estimation of velocity field is particularly difficult because of the non-rigidity of the motion of the features. Also, the chaotic nature (turbulence) of fluid dynamics exacerbates the problem.

The MCC (maximum cross correlation) method proposed by Emery et al. computes surface advective velocities by using information from lagged matrices between subareas of image sequences. However, this method is insensitive to rotational components of feature motion.

Sethi and Jain showed that spatio-temporal coherence in extended frame sequences can be used in computing object trajectories throughout an image sequence.

2 Noise removal and edge extraction

To obtain a grey level image with noise removed, we perform an adaptive threshold and median filter operation on the raw image data. We apply further noise removal, segmentation and edge extraction operations on the image. These operations can be done by applying mathematical techniques such as variational method or wavelet method.

Once we have a noise removed, segmented and edge detected images, the boundary curves of the regions are replaced by piecewise linear boundary (edge) curves obtained by approximating the points on the boundary curves with straight line segments. For step by step approximation procedure, we may assume the boundary points are ordered from left to right and from top to bottom.

It is sometimes convenient to use a metric other than the usual euclidean metric on R^2 given by $d_3((x_1, y_1), (x_2, y_2)) = \sqrt{(x_2 - x_1)^2 + (y_1 + y_2)^2}$ We can use a metric given by $d_1((x_1, y_1), (x_2, y_2)) = |x_2 - x_1| + |y_1 + y_2|$ or by $d_2((x_1, y_1), (x_2, y_2)) = max\{|x_2 - x_1|, |y_1 + y_2|\}$ where $(x_i, y_i) \in R^2$. These three metrics are all equivalent in the sense that they define the same metric structure and topological structure on the space R^2. The geometries, however, are different. With the euclidean metric d_3, the set of equidistant points from a point is a circle. With the other metrics d_1 and d_2, the set of equidistant points from a point is a square. For example, The set of all points of the unit distance from the origin $(0,0)$, $\{(x,y) : d_1((0,0),(x,y)) = 1\}$ is the (boundary of the) square with vertices at $(1,0), (0,1), (-1,0)$ and $(0,-1)$. We may use any of these metric, denoted by d, in this paper. It may be assumed that d is the usual euclidean metric, if necessary.

3 Break points, extreme points and piecewise linear approximation

Suppose we already have found the boundary. More specifically, assume we have the (ordered) list of all the boundary points. We want to construct a sublist of the boundary points to serve as the vertices of the piecewise linear approximation of the boundary. We will start with the first three boundary points, say p_1, p_2, p_3. If p_i, the i-th boundary point, is within the given threshold distance from the line segment $[p_{i-1}, p_{i+1}]$, then we replace the point p_i by p_{i+1} in the list. However, if the distance is greater than the threshold, p_i is kept and it becomes the initial point of the next approximation step. That is, we check if the point p_{i+1} is within the distance threshold from the line segment $[p_i, p_{i+2}]$. Iterate this procedure until there is no reduction of points in the list. The points in this reduced list is used to construct a polygonal curve (piecewise linear curve) approximating the boundary of the region. The points in the sublist are the vertices of this polygonal curve (the end points of the line segments in the polygonal curve), and they are called the break points on the boundary.

It is obvious that the polygonal curve makes a turn (changes direction) at each break point. The amount of turning at the break point will be measured by the cosine value of the angle of turning at the break point p_i, which is computed by the usual inner product in R^2 $\cos\theta_i = \frac{(p_i - p_{i-1})\cdot(p_{i+1}-p_i)}{\|(p_i-p_{i-1})\|\cdot\|(p_{i+1}-p_i)\|}$ For example, consider three points $p_{i-1} = (-4,3)$, $p_i = (0,0)$, and $p_{i+1} = (4,0)$. The angle of turning at p_i is computed by $\cos\theta_i = \frac{(4,-3)\cdot(4,0)}{5\cdot 4} = \frac{4}{5}$ and θ_i, the angle of turning, is about 37 degrees. The angle of turning and the interior angle at a point add up to 180 degrees, in other words, they angles are supplementary. The cosine value will be close to 1 if the change of the direction is small and will be much less than 1 or even negative if the change of direction is substantial. If the cosine value at p_i is less than a predetermined threshold, we will call the point p_i an extreme point. We may consider this definition of extreme point as an analog of the points where the curvature of the curve attain local extrema.

We use the extreme points to estimate the velocity vector field at each stage of the image sequence. In the following example we consider, for simplicity, a pair of extreme points only in the image sequence. Suppose a_1, a_2 are extreme points in the image and b_1, b_2 are the correponding extreme points in the next image in the sequence. The velocity vector at a_1 is estimated by $b_1 - a_1$ and the one at a_2 is estimated by $b_2 - a_2$. The velocity vectors at a_1 and at a_2 are linearly extended to a vector field on the line segment joining a_1 and a_2 as follows. Any point p on the line segement joining a_1 and a_2 can be written as $p = ta_1 + (1-t)a_2$ for some $0 \le t \le 1$. We estimate the velocity vector at p by $t(b_1 - a_1) + (1-t)(b_2 - a_2)$ More specifically, let $a_1 = (0,1)$, $a_2 = (0,0)$ and $a_3 = (1,0)$ be extreme points and $b_1 = (1,3)$, $b_2 = (2,1)$ and $b_3 = (3,1)$ be corresponding extreme points in the subsequent image. Then the velocity vector at $p = (x,y) = xa_1 + ya_3$ is estimated by $x(b_1 - a_1) + y(b_3 - a_3) = x(1,2)+y(2,1) = (x+2y, 2x+y)$ This computation can be extended to the entire region using the triangulation based upon the piecewise linear approximation of the boundary curve. This procedure is called a simplicial approximation of the velocity vector field.

4 Estimating Velocity vectors from the approximation of region boundaries

Suppose a region in the image sequence is identified and its boundary curves are approximated by piecewise linear curves. Suppose also extreme points on each piecewise linear approximation of the boundary curves are found. We are assuming the features in the oceanographic images are such that the extreme points of one image move to the extreme points of the next image in the sequence. Under this assumption, we can track extreme points and the boundary curve and eventually every point inside the region by interpolation based on the simplicial approximation of the region.

Let C be a boundary curve in an image and C' be the corresponding boundary curve in the next image of the sequence. Let $[q_0, q_1, \ldots, q_k]$ be a piecewise linear approximation of C and $[q'_0, q'_1, \ldots, q'_k]$ be a piecewise linear approximation of C'. Suppose $\{e_1, \ldots, e_m\}$ is the set of all the extreme points of the curve C and $\{e'_1, \ldots, e'_m\}$ the set of all extreme points of the corresponding curve C'. Note the sequence $\{e_1, \ldots, e_m\}$ of extreme points (resp. $\{e'_1, \ldots, e'_m\}$) is a subsequence of $\{q_0, q_1, \ldots, q_k\}$, the sequence of all break points of C (resp. $\{q'_0, q'_1, \ldots, q'_l\}$, the sequence of all break points of C'.)

We are assuming the number of extreme points on two curves are the same. This can be done by adjusting the preset value A (resp. A') which determines the extreme points on C (resp. C'). Since we assume the flow of the image is such that the extreme point e_i on C corresponds to e'_i on C', we approximate the velocity vector at e_i representing the movement of the curve at e_i by taking the differences $e'_i - e_i$. We can extend this approximation of the velocity vector to generate a velocity vector field on the polygonal approximation $[q_0, q_1, \ldots, q_k]$ of C by affine extension as follows.

Let $p = f(t)$ be a point on the polygonal curve $[q_0, q_1, \ldots, q_k]$ such that p is between the extreme points $e_i = f(s_i)$ and $e_{i+1} = f(s_{i+1})$. Let the corresponding extreme points be $e'_i = f'(s'_i)$ and $e'_{i+1} = f'(s'_{i+1})$. Then we assign the vector $f'(t') - f(t)$ to the point p where $t' = s'_i + \frac{s'_{i+1} - s'_i}{s_{i+1} - s_i}(t - s_i)$.

This is an obvious extension to the velocity vector field on the polygonal approximation of the curve C. We will denote the vector field on C by V. If the curve C is closed so that it bounds a region then we can extend V to a velocity field, also denoted by V, on the simplicial approximation of the region by extending V on each simplex $[p_i, p_{i+1}, p_{i+2}]$ in the approximation as $V(f(p)) = tV(f(p_i)) + sV(f(p_{i+1}) + rV(f(p_{i+2}))$ where t, s, r are real numbers $0 \le s, t, r \le 1$ such that $s + t + r = 1$ and $p = tp_i + sp_{i+1} + rp_{i+2}$.

5 Conclusion

A well established mathematical tool of simplicial approximation of regions on a plane (or on a surface) and simplicial approximation of continuous mappings between regions were applied to locate and approximate connected regions in image sequence. Once the regions of interest were approximated by simplices (called triangulation), vertices of the simplices in the approximation were identified and used to evaluate the velocity vector field of the features in the image sequence. We need to identify the corresponding points in each image in the image sequence to be able to estimate the velocity vector field. This is done by locating extreme points on the boundary curves of the region in the image sequence by assuming that extreme points on one image move to extreme points on the following image in the sequence. From these estimates of the velocity vectors, we interpolate the velocity field on the whole region by an affine approximation. This approach can also be applied for computing the velocity field induced by rigid motion of objects in dynamic scenes.

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