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Partial Motion Blur Removal

Andriy Klyuvak
ABTO Software LLC
Lviv, Ukraine
klyuvak@ukr.net

Oksana Kliuva
Department of Business Economy and Information Technology
Lviv University of Business and Law
Lviv, Ukraine
oksana_klyuvak@ukr.net

Ruslan Skrynkovskyy
Department of Business Economy and Information Technology
Lviv University of Business and Law
Lviv, Ukraine
uan_lviv@ukr.net

***Abstract*—The work is focused on two types of images partial blur (a single object blur and background blur). Complex approach to the deblurring of such images is proposed. It includes such aspects as automated blur detection, blurred image PSF estimation, blurred patches extraction and processing etc.**

Keywords—image deblurring, motion blur, single object, PSF, computer vision, image reconstruction, partial blur.

I. Introduction

One of the most difficult problems in the field of digital images processing is deblurring of images, distorted by partial blur. In contrast to stochastic blur caused by shaking of camera, the partial blur occurs in two following cases: Motion of one or more objects with fixed camera. Here we have blurred object image against unblurred back-ground (type 1); Camera strictly follows the moving object. Here we have the opposite situation: unblurred object image against blurred background (type 2).In the present paper we suggest a complex approach to removal of the first type of partial blur as well as some aspects of second type motion blur elimination. The complicity of this task is caused by the necessity of defining moving object shape, its motion's parameters (i.e. PSF – Point Spread Function also known as a convolution kernel), its deblurring without influencing image background, and, the most difficult, separation of areas which simultaneously belong to foreground (i.e. moving object) and background.

II. General Approach

In the initial time t0 camera shutter opens and elements of sensitive matrix start acquiring some colours. At this infinitely short time period both moving foreground and background can be treated as not blurred. At time point tn the shutter closes. During exposure time moving object covers some distance, which, taking into account discrete nature of digital photography, can be estimated as some number of points, say m. Hence, time interval dt = tn-t0 can be subdivided into m equal intervals. During each of these subintervals every point of moving object image puts its colour onto different picture point, adding its value to the value formed in this point before. Inner points of object apply its values to other inner points values, so here we have ordinary deblurring problem, which can be solved by applying of one of known deblurring algorithms, for example Richardson-Lucy's. But the picture on edges is quite different. These edges occupy the areas on the object perimeter on both sides of motion direction, and it as m points thick. As a result, the interfusion of background and foreground (moving object points) colours is observed. As whole exposure time is subdivided to m intervals, we can state that every buffer point (point of mixed edges) of the 1/m time interval is influenced in 1/m by a moving object's corresponding point and in 1–1/m by other points, both background point colour and other foreground points, which also 'flew' over that position. If this point lies in the uttermost edge position, the point's colour is comprised of 1/m of foreground colour and 1-1/m of background colour. If this point is next, its colour is comprised of 1/m of this point's colour and 1-2/m of background colour and so on for whole buffer area depth, the last point of which would be comprised for 1/m of background colour[1;2].This would be true in the case of uniform motion, in the case of nonuniform motion these proportions would shift (the shorter time some point stays in some position, the smaller impact it makes on forming the resulting colour in this position) but overall regularity would be the same. In order to deblur this blurred segment we need, first, to estimate blur parameters i.e. to calculate PSF (Point Spread Function) values. Discrete PSF in general case is a matrix which represents a blur kernel that influences an image.The sum of all elements of PSF matrix equals to 1. Signal distortion described by some blur kernel is that the distorted image's every point's value is calculated as follows:

$$d_i = \sum_j p_{i,j} u_j \quad (1)$$

where pi,j is a element of PSF matrix in position (i,j) which denotes what part of j point colour is observed in i point; di - i-th point colour value after convolution operation; uj - j-th point ideal colour value (not distorted).

PSF dimensions and nonzero elements distribution depend on motion speed, uniformity and trajectory and also on exposure duration. Nonzero PSF elements are situated on trajectory lines, drawn by moving object, while camera is taking the picture. Their values correspond to motion speed between time intervals tn and tn+1, which equals to 1/m exposure time, where m – nonzero PSF elements number. Hence, all nonzero PSF elements are equal in case of uniform motion and placed in line in case of rectilinear motion. Horizontal motion would create PSF in form of row vector and vertical motion – column vector. Taking that, we can conclude that this buffer zone follows PSF matrix configuration: if PSF matrix is column vector 5 elements long, then buffer zone is 5 points (pixels) thick and is situated above and below moving object's image. That's why motion parameters estimation must precede all other operations with blurred domain.

III. Moving Object PSF estimation

A. Motion blur PSF peculiarities

There are two approaches to image reconstruction:

- Non blind reconstruction based on preliminary calculated PSF. PSF estimation can be based on information about distortion character. Hence, at first we can try to estimate a PSF, and then deconvolute an image using one of standard deconvolution methods with known PSF;

- Blind reconstruction by one of iterative algorithms. At first image undergoes reconstruction and then PSF is extracted, using the difference between distorted and reconstructed images. The sense of PSF estimation in this case is to obtain information about distortion character [2].

Let's take type 1 blur. During blur, every point of the moving object moves the trajectory of the whole object. That is why successively overlapping onto points of its trajectory moving point leaves its trace. If this point is situated in the zone with small gradients of colour, then its trace is overlapping with the traces of neighbouring trajectory points, which are similar by colour value. Quite a different situation would be with the points that differ in their background. Since almost every object is not absolutely homogeneous, there exist such points of interest. They could be corners, edge points, or other separated points. During their motion these points will be surrounded by other points of uniform background, and will leave their traces, which reproduces the trajectory of whole moving object. In fact, points, located on the motion trajectory in both sides, have colour of background, which by overlapping give approximately the same colour. Similarly, the neighbour points that are not on motion trajectory also form a colour of background near key points traces. This idea can be illustrated on Fig. 1. As shown on Fig. 1, a corner of a different colour A (within positions A1-A2-A3) and point with the other colour B (within positions B1-B2-B3) are performing motion together with whole moving object, to which they belong. Since they are related to the same object and have invariable positions, they move along the same trajectory. At the initial moment of frame's exposure corner's position is A1, whereas initial position of the point is B1. Final positions (at the final moment of frame's exposure) are A3 and B3 respectively. Positions A2 and B2 are represented in a moment of time between initialization and finalization of current frame exposure. As it is shown in Fig. 1, whole area a (from initial position of zone A1 to final position A3) will have colours clearly distinctive from those of neighbourhood, because area a is the result of spreading of the corner A with some admixture of background colours (at some places – «bufferzone» – these colours are mixed in definite proportions, and in other places only colours of the corner are mixed), whereas outside areas *a* and *b* only background colours influenced resulting points' colours.

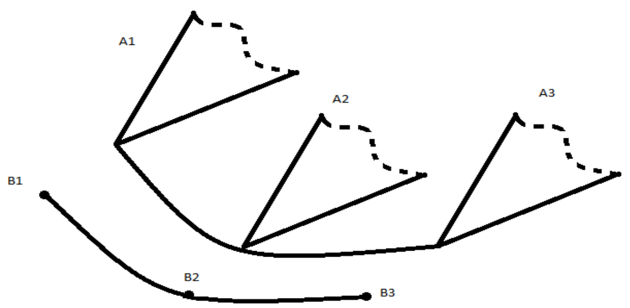

Fig. 1. Motion tracking inside moving object image.

The bottom edge of blurred area a will duplicate motion trajectory of the object. The same is observed for motion trace of point B: this trace will be standing out against a background and be coincident with motion trajectory of feature point. This can be illustrated using image and its corresponding PSF, which can be found in the paper [2]. Figure 2 illustrates how a small region with different colour has left its visual trace on the image and that this trace clearly corresponds to non-zero elements distribution of PSF matrix.

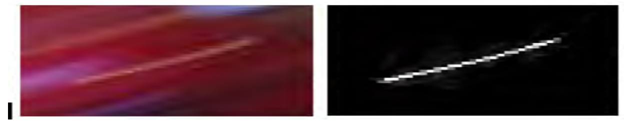

Fig. 2. Blur visual trace and corresponding PSF

So, in our case, the blurred image has the following: there are two regions in the image, which differ by colour from average colour of the background, and the shapes of bottom borders of those regions are equal. Using this, we can establish the main postulate of this method: the distribution of non-zero elements of PSF matrix of an image distorted by motion blur will correspond to the most frequent variant of edges of zones with colour distinguishable from neighbourhood.

B. Moving Object trajectory estimation.

As far as the method is based on colour segmentation, the algorithm involves gradients processing. Those gradients get checked for occurrence of frequent elements. The algorithm consists of following steps: conversion of an input coloured image to greyscale; gradients calculation; absolute values calculation; processing of partial derivatives in horizontal and vertical directions (two passes): a) calculation of maximum value; b) for every value of partial derivatives from 50 to 100% of maximum value the following is done:

I. Threshold determination. Every run of «sifting» loop iteration differs only by threshold value. Using these values regions with different colour contrast can be outlined at every iteration.

II. Estimation of regions where the values of partial derivatives are greater or equal to threshold value (estimation of blobs).The result of this step is a set of blob (mask).

III. Excluding blobs with an area that is equal to 1.Isolated points with colours different from their neighbours are always present in images because of camera noise, but neither of these points can be PSF candidates, because such PSF represents no changes: after convolution with single element PSF any image transforms to itself.

IV. Extraction of right and left or upper and bottom edges of every blob. Hence every blob gives us two new edge blobs; herewith the old one is to be discarded.

V. Excluding blobs with an area that is equal to 1.

VI. Searching for identical blobs.

Here we substituted the principle of absolute identity with the principle of almost identity [3]. We formulate this principle as: blobs are considered to be identical, either if they are absolutely equal to each other or if one of them completely duplicates a part of another, i.e. can completely be located in it. We can determine that one blob is equal to some part of another one using such method: two arrays – sums of all columns and sums of all rows of smaller blob –

must be subarrays of corresponding arrays of a larger blob, with the beginning in the same point. This case is shown in Fig. 3, where two subarrays of smaller blob start from point (x1, y1) in larger blob. Sometimes however starting point of a smaller blob lies on either strictly vertical or strictly horizontal segment of a larger blob (Fig. 4).

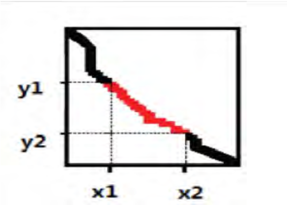

Fig. 3. Almost identical blobs

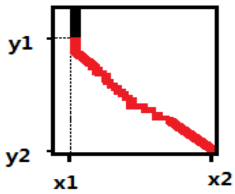

Fig. 4. Almost identical blobs with common point in vertical region

With such comparing on almost identity, the comparison function returns the larger blob. This larger blob will further be used for pairwise comparing process instead of previously used blob. Also, two blobs cannot be identical, if one of them significantly (more than 5 times) larger than the other blob, or if one of them contains gaps.

5. The variant, wherein the maximum of identities was found, is returned as final result.

Developed algorithm was implemented using MATLAB and was tested using a set of images with known motion blur PSF. In all cases the motion direction was estimated correctly. Received results completely reproduce trajectory of distorting motion, and its length deviates from its real value by 15-20%. Input images and results of processing in the form of binary PSF matrices are shown in Fig. 5, 6 and 7.


Fig. 5. Example 1


Fig. 6. Example 2


Fig. 7. Example 3

C. PSF values calculation.

The result of first step is PSF matrix structure, i.e. its dimensions and position of non-zero elements. On the second step the motion continuity of each point is estimated. Though in case of partial blur this step is performed after blur detection (4), it is integral part of PSF estimation algorithm. To determine this estimation we have to consider features of forming of blurred image. As far as digital image is obtained during quantization by photosensitive matrix, then every point during its motion appears in several positions. At that, the value of its colour saturation depends from time of this point being in current position. And time, in its turn, is defined by influence of point velocity – the less velocity, the greater time point stays in the position. Naturally the sum of influences of a point in every position of its trajectory equal to one.

$$\sum_{i=1}^{m}\sum_{j=1}^{n} a_{i,j} = 1 \qquad (2)$$

where ai,j is dispersion coefficient of i-th point in j-th position of motion trajectory, n is the length of trajectory, equal to count of non-zero elements of PSF matrix.

If the i-th point is distributing its colour along of the entire trajectory, then its influences are present at every position of this trajectory. This makes a ground to assume, that between j-th positions of trajectories of all points of blurred image area there exists a relative correlation. Let's go into the matter of correlation in detail on example of two neighbour positions j and j+1 on a motion trajectory of two different points with dispersion coefficients $a_{1,j}$ and $a_{2,j}$ respectively. Let's denote their colours as c_1 and c_2. In a blurred image there are four points with colours $S_{1,j}$, $S_{1,j+1}$, $S_{2,j}$, $S_{2,j+1}$.

$$S_{1,j} = a_{1,j}c_1 + \omega_{1,1} \qquad (3)$$

$$S_{1,j+1} = a_{1,j+1}c_1 + \omega_{1,2} \qquad (4)$$

$$S_{2,j} = a_{2,j}c_2 + \omega_{2,1} \qquad (5)$$

$$S_{2,j+1} = a_{2,j+1}c_2 + \omega_{2,2} \qquad (6)$$

where $\omega_{1,1}$, $\omega_{1,2}$, $\omega_{2,1}$, $\omega_{2,2}$– are the other colour components in blurred image, except a part, that is super induced in the result colour by colours c_1 and c_2 of two examined points of original image.

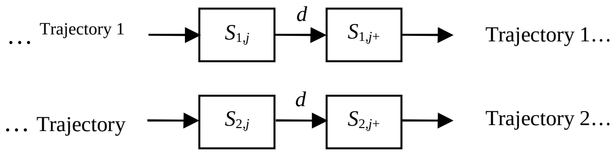

Fig. 8. Schematic relative positions of points in a blurred image

Two points move two parallel trajectories, both as translation result of each other (fig. 8). Let's calculate colour differences between two neighbour points in every trajectory:

$$d_1 = S_{1,j+1} - S_{1,j}; \qquad (7)$$

$$d_2 = S_{2,j+1} - S_{2,j}. \qquad (8)$$

Since displacements of two points are equal, their ratio can be found using (3)-(6):

$$\frac{d_1}{d_2} \sim \frac{\left(a_{1,j+1}c_1 + \omega_{1,2}\right) - \left(a_{1,j}c_1 + \omega_{1,1}\right)}{\left(a_{2,j+1}c_2 + \omega_{2,2}\right) - \left(a_{2,j}c_2 + \omega_{2,1}\right)} \qquad (9)$$

$\omega_{i,j}$ are formed as the result of identical process of points' colours overlaying. That is why in the respect to trajectory neighbouring points' gradients they can be omitted. Formula (9) hence can be transformed as follows:

$$\frac{d_1}{d_2} \sim \frac{c_1\left(a_{1,j+1} - a_{1,j}\right)}{c_2\left(a_{2,j+1} - a_{2,j}\right)} \qquad (10)$$

Unknown coefficients a_{ij} are equal in both cases, hence:

$$\frac{d_1}{d_2} \sim \frac{c_1}{c_2} \qquad (11)$$

It may be concluded that, colour differences between pixels lying along trajectory lines have statistical significance and are correlating with those of other parallel trajectory lines.

The subsequent operations are carried out for every point of blurred image, if the aperture in this point does not outstep the blurred region of an image. Absolute values of chaining differences between neighbouring points are calculated starting from a current point of an image and along all non-zero elements of PSF matrix (since they are always arranged in a line):

$$d_{ij} = \left| C_{i+x,\, j+y} - C_{k+x,l+y} \right| \tag{12}$$

where C is processed image; i,j are coordinates of PSF matrix elements; x,y are coordinates of a point that is an input point for current iteration; k,l are coordinates of the next non-zero element of PSF matrix (that is trajectory neighbouring point to the current). Depending on trajectory character there are several variants available: 1)$k=i+1$; $l=j$; 2) $k=i$; $l=j+1$; 3)$k=i+1$; $l=j+1$.

After examining of all points, the mean values of differences for each element can be calculated.

$$D_{ij} = \frac{\sum_{k=1}^{p} d_{ijk}}{p} \tag{13}$$

where p is number of obtained matrices.

To meet condition, which was defined by restriction (2), the obtained result is to be normed:

$$PSF_{ij} = \frac{D_{ij}}{\sum_{j=1}^{m} \sum_{i=1}^{n} D_{ij}} \tag{14}$$

where m, n are dimensions of PSF matrix.

The overall result of this processing is PSF:

$$PSF = \left\langle PSF_{i,j} \right\rangle_{j=\overline{1..m}}^{i=\overline{1..n}} \tag{15}$$

IV. Blur Detection

It follows from the above that **every pixel of a blurred image must have smaller colour difference with its trajectory neighbours than with other neighbours**. This statement is the basis of motion blur detection method, proposed in this work.

Blur detection starts with calculation of colour standard deviations. It is carried imposing PSF-trace. PSF-trace reveals motion trajectory, hence we know trajectory neighbours of every pixel in an image. Every pixel has two major trajectory neighbours. Standard deviation of an every pixel is calculated in respect to these neighbours only. To this end we impose PSF-trace to an every pixel in its central element. These calculations are carried separately for every colour channel, and the final value for every pixel is the maximal value among all colour channels for that pixel. After that matrix values are normalized to be in range [0; 1].

As the result of previous action we get the matrix of trajectory-neighbour oriented standard deviations. But this matrix is to be binarized in order to become blur mask. If some point lies in blurred zone, its deviation value must be significantly lesser. So in order to find unblurred area these values are to be segmented by some minimal threshold, that is, if some value is greater than threshold value, then this pixel belong to unblurred area, otherwise to the blurred one. Blurred area mask is inverted unblurred area mask. Usually calculated or selected threshold value lies in range [0.05; 0.1]. The result of standard deviation matrix binarization is the mask of not blurred zone. The following example of blur detection shows the result of the following MATLAB code execution. The code is based on not blind detection method.

Listing1. Nonblind blur detection MATLAB code

```
s = stdfilt(f, PSF > 0 );
s = max(s,[],3);
bw = normal(s)>threshold;
```

Fig. 9. Blurred image of type 2

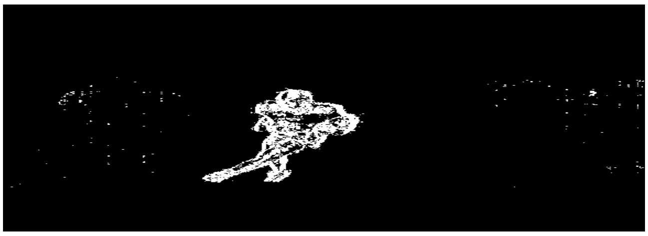

Fig. 10. Unblurred area mask before additional morphological processing

V. Blurred/Unblurred Patch Extraction and Deblurring

For type 1 motion blur burred domain must be extracted from the native background and carried to homogeneously black background. Black background is chosen because black points are represented with zero values, hence are unable to influence results of subsequent operations and distort the resulting image. Simple copying of blurred object image with buffer zone has no sense, because part of admixed background will be copied as well. That’s why foreground and background components of buffer zone must be properly separated taking into account rules of their mutual interference. The separation is carried with known PSF which is calculated while processing inner areas of moving object blurred image. Having PSF values we can estimate what part of buffer zone point colour is represented by foreground and background components. Removal of background component is equivalent to taking moving object image to black background. To do that we copy object’s image to black background and calculate new values of buffer zone point’s colours starting with edge points to the whole PSF depth using this formula:

$$u_j^* = \frac{u_j - b + a}{a} \tag{16}$$

where: uj- point’s colour old value; b- background colour; a – sum of PSF matrix values for current point and previously calculated points [4].

When we face opposite situation – the not blurred part must be preserved in its primitive state and must not affect the rest of the image at deblurring. We do not need to carry anything to the black background, but unblurred patch is simply extracted according to the mask of unblurred patch.

Hence, the resulting background gets black hole in this place, which is to be filled by the method of image integration, otherwise black blot will distort the whole image. Reconstructing an image out of its derivatives using Frankot-Chellappa method [5] a new image with filled hole can be obtained [6]. This reconstructed image is suitable for successive deblurring.

In both cases deblurring is most often performed by one of non blind deblurring algorithm i.e. deblurring with known PSF (Viener filtration, Richardson-Lucy etc). In case of type 2 blur or total blur the technique of 4-sided mirroring can be applied in order to reduce the well-known ringing effect. After deblurring, processed image has to be placed back to its native canvas.

VI. Processed Zone Imposition

The processed part of the image (foreground moving object), extracted and stuck to black background earlier, is to be imposed back to the native background. All pixels of the input unprocessed image that correspond to the blurred image are removed, i.e. substituted with black colour. To determine, which pixels are to be removed we impose the mask of blurred image, calculated previously (IV Blur detection). Hence the blurred zone is cut out of the canvas. Deblurred image is added to the background image. In this step two matrices are simply added: black pixels values cannot affect resulting values. Only nonzero values of both matrices remain in the resulting image, and deblurred patch takes its place.

Since deblurred image is always smaller than blurred, double-sized buffer zone on one of the edges of deblurred patch will remain black. It is filled with dominant colours on the background side of the edge. In case of second type motion blur this step is omitted, as the shapes of the patch and of the filled hole on the image background coincide. Foreground/background edge is smoothened, since after the imposition and colour refilling the edge may seem to be excessively sharp and hence look unnatural. For the first thing seam area is to be selected to perform smoothing over it. It is defined as the perimeter of the blurred zone mask, but expanded in both directions. Secondly, averaging filter is applied to the area, selected with this mask. This averaging creates more natural colour distribution and the image as whole looks now more natural, since the seam fades. Hence, whole image is assembled again (fig. 11) [7;8;9].

Fig. 11. Deblurred image.

VII. Conclusion

The paper is devoted to the methods of reconstruction of images distorted by partial motion blur – motion blur that affects not whole image but some part of it. The paper contains approaches to the deblurring of two types of partial blur: a) an image of a blurred moving object against unblurred background and b) an image of unblurred object surrounded with blurred background. One of the most important points of the paper is Point Spread Function (PSF) estimation method. It is based on the method of distorting motion trajectory estimation. Trajectory estimation method involves sharp edges motion tracing by means of colour gradients exploration. Hence the proposed method is able to calculate the trajectory and PSF from single image without any other preliminary data. Other developed methods are: the method of automated blur detection and the methods of blurred/unblurred areas separation. The first is used to detect the shape of blurred area and is based on pixels' colours standard deviation statistics and information about PSF character. This approach enables to detect a blur caused by some definite PSF with higher accuracy. The separation methods are utilised to separate blurred area for different partial blur types.

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