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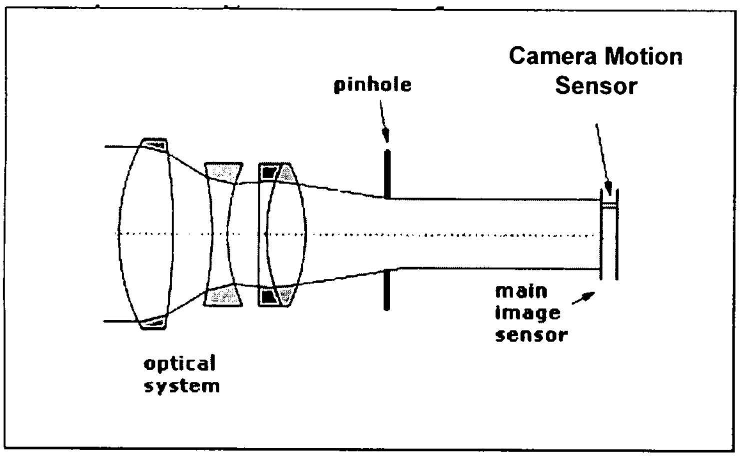

Figure 4A

(57) **Abstract:** A digital camera includes an optical system, a main image sensor and a camera motion sensor for estimating relative camera-object motion during image capture. A processor estimates camera motion based on information obtained by the camera motion photo-sensor while the camera is exposed to an image of a scene. The processor reduces or removes a motion blur effect from the main image permitting a processed version of the main image to be thereafter rendered.

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DETECTION AND ESTIMATION OF CAMERA MOVEMENT

PRIORITY AND RELATED APPLICATIONS

This application claims the benefit of priority to United States provisional patent application no. 60/913,331, filed April 23, 2007, and claims the benefit of priority to United States provisional patent application no. 60/945,558, filed June 21, 2007, and this application is a continuation-in-part (CIP) of United States patent application no. 10/985,657, filed November 10, 2004. This application is also related to United States patent applications nos. 10/985, 650 and 10/986,562. Each of these applications is incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This application relates to an apparatus capable of acquiring images, such as a digital still camera, including a processor that uses information provided by a separate motion sensor to detect and estimate relative camera motion during image acquisition.

2. Descritpion of the Related Art

Camera motion is dependent on a few parameters. First of all, the exposure speed. The longer the shutter is open, the more likely that movement will be noticed. The second is the focal length of the camera. The longer the lens is, the more noticeable the movement is. A rule of thumb for amateur photographers shooting 35mm film is never to exceed the exposure time beyond the focal length, so that for a 30mm lens, not to shoot slower than 1/30th of a second. The third criteria is the subject itself. Flat areas, or low frequency data, is less likely to be degraded as much as high frequency data.

Historically, the problem was addressed by anchoring the camera, such as with the use of a tripod or monopod, or stabilizing it such as with the use of gyroscopic stabilizers in the lens or camera body, or movement of the sensor plane to counteract the camera movement.

Mathematically, the motion blurring can be explained as applying a Point Spread Function, or PSF, to each point in the object. This PSF represent the path of the camera, during the exposure integration time. Motion PSF is a function of the motion path and the motion speed, which determines the integration time, or the accumulated energy for each point.

Given:

a two dimensional image I represented by I(x,y)

a motion point spread function MPSF(I)

The degraded image I'(x,y) can be mathematically defined as the convolution of I(X,Y) and MPSF(x,y) or

$$I'(x,y) = I(x,y) \otimes MPSF(x,y) \quad \text{(Eq. 1)}$$

or in the integral form for a continuous function

$$I(x,y) = \iint (I(x-x', y-y')MPSF(x'y')\partial x'\partial y' \quad \text{(Eq. 2)}$$

and for a discrete function such as digitized images:

$$I'(m,n) = \sum_j \sum_k I(m-j, n-k)MPSF(j,k) \quad \text{(Eq. 3)}$$

Another well known PSF in photography and in optics in general is blurring created by de-focusing. The different is that de-focusing can usually be depicted by a symmetrical Gaussian shift invariant PSF, while motion de-blurring is not.

The reason why motion de-blurring is not shift invariant is that the image may not only shift but also rotate. Therefore, a complete description of the motion blurring is an Affine transform that combines shift and rotation based on the following transformation:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} Cos\omega & Sin\omega & \Delta x \\ -Sin\omega & \cos\omega & \Delta y \\ 0 & 0 & 1 \end{bmatrix} \quad \text{(Eq. 4)}$$

The PSF can be obtained empirically as part of a more generic field such as system identification. For linear systems, the PSF can be determined by obtaining the system's response to a known input and then solving the associated inversion problems.

The known input can be for an optical system, a point, also mathematically defined in the continuous world as a delta function δ(x), a line, an edge or a corner.

An example of a PSF can be found in many text books such as "Deconvolution of Images and Spectra" 2nd. Edition, Academic Press, 1997, edited by Jannson, Peter A. and "Digital Image Restoration", Prentice Hall,1977 authored by Andrews, H.C. and Hunt, B.R.

The process of de-blurring an image may be done using de-convolution which is the mathematical form of separating between the convolve image and the convolution kernel. However, as discussed in many publications such as Chapter 1 of "Deconvolution of Images and Spectra" 2nd. Edition, Academic Press, 1997, edited by Jannson, Peter A., the problem of de-convolution can be either unsolvable, ill-posed or ill-conditioned. Moreover, for a physical real life system, an attempt to find a solution may also be exacerbated in the presence of noise or sampling.

One may mathematically try and perform the restoration via de-convolution without the knowledge of the kernel or in this case the PSF. Such methods known also as blind de-convolution. The results of such process with no a-priori knowledge of the PSF for a general optical system are far from acceptable and require extensive computation. Solutions based on blind de-convolution may be found for specific circumstances as described in “Automatic multidimensional deconvolution” J. Opt. Soc. Am. A, vol. 4(1), pp. 180-188, Jan. 1987 to Lane et al, “Some Implications of Zero Sheets for Blind Deconvolution and Phase Retrieval”, J. Optical Soc. Am. A,vol. 7, pp. 468-479, 1990 to Bates et al, Iterative blind deconvolution algorithm applied to phase retrieval”, J. Opt. Soc. Am. A,vol. 7(3), pp. 428-433, Mar. 1990.to Seldin et al and "Deconvolution and Phase Retrieval With Use of Zero Sheets," J. Optical Soc. Am. A,vol. 12, pp. 1,842-1,857, 1995 to Bones et al. However, as known to those familiar in the art of image restoration, and as explained in "Digital Image Restoration", Prentice Hall,1977 authored by Andrews, H.C. and Hunt, B.R., blurred images can be substantially better restored when the blur function is known.

The article “Motion Deblurring Using Hybrid Imaging”, by Moshe Ben-Ezra and Shree K. Nayar, from the Proceedings IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2003, determines the PSF of a blurred image by using a hybrid camera which takes a number of relatively sharp reference images during the exposure period of the main image.

It is desired to have a camera that determines a camera motion blur function in a captured digital image utilizing a camera motion sensor installed within the camera.

Lights with different wavelengths have different depths of penetration in the silicon of a photo-detector. Also, depth of light penetration varies with flux intensity. Figures 1(a)-1(b) illustrate the decay of light penetration in silicon. The equation describing it is:

$$\Phi(x) = \Phi_0 \exp(—ax) \text{ where } \Phi_0 = \Phi(x = 0) \qquad (1)$$

with Φ denoting light flux and with x the depth of penetration. Figure 1(a) illustrates the absorption of light in silicon showing a plot of absorption coefficient versus wavelength. Figure 1(b) includes four plots of incident light intensity versus depth for four different wavelengths. The photon flux generally decays exponentially with distance from surface. Figures 1(a) and 1(b) are taken from “Image sensors and Signal Processing for Digital Camera”, edited by Juinichi Nakamura, Taylor and Francis Group, pg 57, wherein this publication is incorporated by reference in its entirety.

A Foveon^{TM} sensor, such as the sensor illustrated at Figure 2, is built on the property that a blue detector is near the surface, a green detector is lower and a red is deeper (2.4 μm) in the silicon. All the layers are consecutive n respectively p. The X3 sensor is described in the patent “Color separation in an active pixel cell imaging array using a triple-well structure”, Merrill Richard Billings , US 5,965,875, Foveon Inc., which is incorporated by reference.

The charge integrated in an image sensor varies non-linearly if the camera is moved. Multiple captures (readings) applied to a CMOS sensor may provide information about the camera trajectory as shown in “Simultaneous Image Formation and Motion Blur Restoration via Multiple Capture”, Xinqiao Liu and Abbas El Gama1, Proceeding of IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 3, pp. 1841-1844, May 2001 (article that has attached a patent), which is incorporated by reference.

Figure 2 illustrates a Foveon^{TM} triple well sensor. If one considers a sequence of frames and the camera is moved or the scene is moving, then the charge of a single photo-detector varies. The detection of the movement between consecutive frames and movement compensation in a circuit attached to the photo-detector is the subject of “Active pixel image cell with embedded memory and pixel level signal processing capability", Merrill Richard Billings, Bergemont Albert, Chi Min-Hwa, US patent no. 5,962,844, Foveon Inc. and "TP 13.5: A 256.times.256 CMOS Active Pixel Image Sensor with Motion Detection", A. Dickinson et al., Digest of Technical Papers 1995 IEEE International Solid-State Circuits Conference, page 226 et seq., which are each incorporated by reference.

It is desired to have a camera that has a dedicated motion sensor to detect and estimate relative camera motion.

SUMMARY OF THE INVENTION

A digital camera is provided that includes an optical system and a main image sensor for capturing a main image provided through the optical system. The camera further includes a camera motion photo-sensor for estimating relative camera-object motion during image capture. The camera further includes a processor that estimates camera motion based on information obtained by the camera motion photo-sensor while the camera is exposed to an image of a scene, and that reduces or removes a motion blur effect from the main image permitting a processed version of the main image to be thereafter rendered, wherein the processed version includes the main image with the motion blur effect reduced or removed.

The camera motion photo-sensor may include a multi-layer sensor including multiple silicon layers. The processor may integrate photocurrent measurements between silicon layers of the multi-layer photo-sensor. The processor may estimate motion based on calculated variances of light flux or depths of light flux, or both, into the silicon layers based on the photocurrent measurements, or for a CCD or other camera motion photo-sensor, variances of a measured parameter are used to calculated camera motion. The photocurrent measurements may be carried out between successive p-type and n-type silicon layers of the multi-layer photo-sensor. The multi-layer photo-sensor may include successive wells of known depths of p-type and n-type silicon layers.

The optical system may include a series of one or more lenses and an aperture. Multiple photocurrent measurements may be performed during a single exposure period of the main image sensor. A quantity of camera movement may be estimated based on computing a degree of variance of a parameter measured by the camera motion sensor.

A direction of camera motion may be estimated as a direction of highest correlation. The camera may include one or more further camera motion photo-sensors also for estimating camera motion. The two or more camera motion photo-sensors may be randomly spatially-distributed.

A method of estimating camera motion during an exposure period for capturing a scene in a digital camera is also provided. A main image sensor and a camera motion photo-sensor are exposed through an optical system. A main image is captured by the main image sensor. One or more parameters are determined based on an analysis of one or more reference images acquired before, during and/or after the exposure period. Camera motion is estimated including calculating based on the one or more parameters. The method also includes removing or reducing a camera motion blur effect from the main image based on the estimated camera motion, thereby permitting rendering of a processed version of the main image.

The camera motion photo-sensor may include a multi-layer sensor including multiple silicon layers. The method may include integrating the measured photocurrent measurements; and calculating variances of light flux or depth of light flux, or both, into the layers of the multi-layer photo-sensor based on the photocurrent measurements, and wherein the camera motion estimating may be based on the calculated variances. The method may also include carrying out the photocurrent measurements between successive p-type and n-type silicon layers of the multi-layer photo-sensor. The multi-layer photo-sensor may include successive wells of known depths of p-type and n-type silicon layers.

The optical system may include a series of one or more lenses and an aperture. The method may include performing multiple measurements with the camera motion sensor during a single exposure period of the main image sensor. The estimating may include estimating a direction of camera motion as a direction of highest correlation. The estimating of camera motion may be performed using one or more further camera motion photo-sensors. Two or more camera motion sensors may be randomly spatially-distributed. The estimating may include estimating a quantity of camera movement based on computing a degree of variance of a parameter determined from the one or more reference images acquired by the camera motion sensor.

One or more processor-readable media are also provided having digital code embodied therein for programming one or more processors to perform any of the methods described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1(a) shows a plot of absorption coefficient versus wavelength of light in illustrating depth of penetrationof light.

Figure 1(b) shows plots of light flux versus penetration depth for multiple wavelengths.

Figure 2 illustrates a conventional Foveon^{TM} triple well sensor.

Figure 3 illustrates a multi-layer camera motion sensor in accordance with an embodiment.

Figure 4(a) illustrates a camera motion sensor replacing a photodetector or part of a photodetector of a main image sensor, and/or being disposed adjacent to the main image sensor.

Figure 4(b) illustrates a camera motion sensor which receives part of a beam separated from a main beam.

Figure 5 illustrates synchronization of the main imaging sensor with the motion sensor in accordance with certain embodiments.

Figures 6(a)-6(b) illustrate the charge of layers of an exemplary multilayer sensor respectively when there is motion and when the light is constant, and illustrate by contrast how motion affects the charge.

Figures 6(c)-6(d) illustrate by contrast how motion affects the depth of penetration of light in a camera motion sensor.

Figure 7 illustrates an example of determining quantity of movement including a temporal plot of colors and using certain thresholds.

Figure 8 illustrates determination of possible PSF pixels.

Figure 9 illustrates a representation of a non-blurred image, PSF and camera motion sensor records, and a representation of a blurred image acquired in the main imaging system.

Figure 10 illustrates possible PSF supports including symmetrical choices according to an example embodiment.

Figure 11 illustrates a tree associated with a PSF computed trajectory according to an embodiment.

Figure 12 is a block diagram of a camera apparatus operating in accordance with an embodiment.

Figure 13 illustrates the workflow of the initial stage of a camera motion blur reduction technique using reference image data, such as preview and/or postview data, according to certain embodiments.

Figure 14 is a workflow illustrating an embodiment.

Figure 15 is a workflow illustrating an embodiment.

Figures 16, 17-a and 17-b are diagrams which assist in the understanding of the embodiment of Figure 15.

DETAILED DESCRIPTION OF THE EMBODIMENTS

According to certain embodiments, there is provided a digital image acquisition system, such as a digital camera, comprising an apparatus for capturing digital images including a main image sensor and a motion sensor, as well as a digital processing component. The processing component determines a camera motion blur function in a captured digital image based on a comparison of two or more images acquired either solely by the motion sensor or by the motion sensor and main image sensor. Each of the images is taken during, temporally proximate to or overlapping an exposure period of a main captured image and of nominally the same scene.

The two or more images may include the main captured image captured by the main image sensor, and another image or reference image acquired by the motion sensor, or two or more reference images acquired by the motion sensor. The images may be captured during, before or after the exposure period of the captured image, although preferably at least one of these reference images is acquired as a preview image before capture of the main image.

In one embodiment, the digital processing component identifies at least one characteristic in a reference image which is relatively less blurred than the corresponding feature in the captured image, and calculates a point spread function (PSF) in respect of the characteristic. The characteristic may include a well-defined pattern. For example, the better the pattern is differentiated from its surroundings, such as by local contrast gradient, local color gradient, well-defined edges, or otherwise, then the better such pattern can be used to calculate the PSF. In an extreme case, the pattern forming the characteristic might be only a single pixel in size.

In another embodiment, the digital processing component calculates a trajectory of at least one characteristic in multiple reference images acquired by the camera motion sensor, extrapolates such characteristic on to the captured image, and calculates a PSF in respect of the characteristic.

In either case, based on the calculated PSF, the captured image can be significantly de-blurred using any of a number of de-convolution techniques.

Corresponding de-blurring function determining methods are also provided in this application. One or more storage devices are also provided having digital code embedded thereon for programming one or more processors to perform the de-blurring function determining methods.

In certain embodiments, the camera motion sensor includes a fast, relatively low resolution CCD detector, or alternatively a CMOS detector, silicon detector or other photodetector that may be known or available or may become available to those skilled in the art that has the ability to acquire reference images to meet the performance expectations of the described embodiments. Preferably, the camera motion sensor is separate from the main image sensor, for example, as illustrated at Figures 4(a)-4(b), or a single sensor may be divided into pixel subsets configured with same or separate imaging optics or a combination of same and separate imaging optics. In other embodiments, the camera motion sensor may include a multi-layer silicon sensor as specifically illustrated at Figures 2-3. Other sensors and methods may be used for measuring and estimating camera motion, including those described in references cited hereinbelow and hereinabove, for example as illustrated at any one or a combination of US patents nos. 6,269,175, and US published patent applications nos. 2006/0098890, 2006/0098237, 2006/0098891, 2006/0285754, 2007/0189748, 2001/0036307, 2004/0212699 and 2007/0269108, and US patent applications nos. 11/573,713, 11/753,098, 12/038,777, 11/752,925, 60/944,046, 11/856,721, 60/913,331, 11/859,164, 60/945,558, 60/390,336 and 61/023,774, and/or European patents nos. EP1779322, and EP1800259, all of which are incorporated by reference.

MULTI-LAYER SENSOR

In the example of the Foveon^{TM} sensor, as illustrated at Figure 3, the idea is that if the camera is moved, then the penetration depth of the flux changes with a function different from that used as if the flux intensity would be constant.

We propose the use of a multi-layer (ML) sensor. An image of it may be seen in the figure 2. Let *N* be the number of layers. The layers are consecutively n and p. Each layer has a depth of a thickness d_i.

The depth (respectively the thickness) will be chosen so to offer a straight-forward color meaning interpretation.

The readout technology may be based on a charge coupled device (CCD) or by the use of CMOS technology. The light will produce by means of photo-voltaic effect the set of N values of current intensities. These are integrated to produce charges.

A period of integration (of exposure) of this ML sensor will provide a set of N values $u_i,\ldots,u_N$. Each set of values will correspond to a set of colors. For instance, the triple layer sensor (Foveon) will provide:

$$\begin{aligned} u_1 &= u_{Blue} + u_{Green} + u_{red} \\ u_2 &= u_{Green} + u_{red} \\ u_3 &= u_{red} \end{aligned} \qquad (2)$$

Figure 3 illustrates a multi-layer sensor in accordance with an embodiment.

PLACING THE CAMERA MOTION SENSOR IN THE CAMERA

Whether a multi-layer sensor or other sensor is used, the camera motion sensor, or set of multiple camera motion sensors, can be placed in the main imaging sensor, in a precisely determined position(s), replacing normal photo-detectors. Two examples are provided in Figure 4(a) and 4(b) below, although various other arrangements of the main image sensor and camera motion sensor or sensors may be utilized. In Figure 4(a), the camera motion sensor replaces a photo-detector subset from the main image sensor or is arranged next to the main image sensor. In Figure 4(b), the camera includes a beam splitter or beam separator or beam divider in the path of light or other optical device that reflects some of the light to the camera motion sensor and the rest, preferably a majority percentage between 50% and 90% or perhaps 95% or more, transmits the light. The main portion of the light may be reflected to the main image sensor while a small reference portion may be transmitted. A certain flux goes to the main image sensor, while the second goes to the camera motion sensor (beam splitter). In different embodiments, an optical device may be used to split the main light flux in two directions. One will fall on the main imaging sensor and another one will cross a pin-hole (or a set of pin-holes) and fall onto the camera motion sensor.

In another embodiment, the same optics or certain overlapping optics may also shift or otherwise be changed to allow one or more reference images, preview and/or postview, to be acquired by the motion sensor, and then to allow the main image sensor to capture the main image in a second orientation or operational position or state. For example, a electo-actuated mirror may be turned on or off to reflect or transmit images respectively to the main sensor and the camera motion sensor or sensors. One or more optics may also rotate slightly or otherwise move to change the optical path of the light to be incident upon either the main sensor or the motion sensor.

READING AND SYNCHRONIZATION WITH MAIN IMAGING SYSTEM

An examplary process of reading and synchronization with the main imaging system is described with reference to Figure 5. While the diaphragm of the main imaging system is open (the main image sensor is exposed), a set of *M* reading operations may be performed. In the example of the multi-layer cmera motion sensor, charge integration may be performed on each of multiple layers. For a single exposure in the main imaging system, a set of $M \times N$ charge values may be obtained: u_{ij} (where $i= 1,N$ spawns the number of layers and $j= 1,M$ spawns the indices/order of reading). The small periods of reading may be equal as illustrated at Figure 5, or may be varied.

MOVEMENT DETECTION

By considering values, such as luminance, intensity, color, charge, current, contrast, or parameter depending on which sensor or detector is used, that are recorded in or determined from pixels of the camera motion sensor, or for example in the layers of the multi-layer sensor, it is possible to detect movement. In the mult-layer sensor example, if there are differences in the charge accumulated by a layer at consecutive moments, then there is motion. If the scene remains unchanged, and the intensity, luminance, or color of pixels on a CCD or other image sensor are changing, then there is determined to be motion. By comparing these values between pixels and between reference images, it can be determined the direction and magnitude of the motion of the camera. Thus, motion blur can be removed or reduced in the main captured image.

Also in the example of the main image sensor, if the depth (distance from the surface) where the recorded charge is larger than a threshold varies from one period to the next, there is determined to be movement. Thresholds may be used with a CCD or other sensor that does not utilize the multiple, alternating p-n silicon layers that the multi-layer sensor does . Exemplary situations are illustrated in Figures 6(a)-6(d) below.

Referring to Figures 6(a)-6(d), a function, g( ), may be defined that takes as input the set of N values measured and returns the largest index of the recorded value greater than a pre-defined value, U_0:

$$g_j(u_1 \ldots, u_N) = k \text{ if } u_1 >= \ldots >= u_k >= U_0 \text{ and } U_0 >= u_{k+1} >= u_N \qquad (3)$$

where g_j is the function g() applied at the moment $j=1,M$.

Figures 6(a)-6(b) illustrate the charge of the layers if there is motion (light changing) and if the light is constant. Similar plots may be made for a CCD or other pixelated detector or other image sensor for intensity, color, luminance, contrast, or otherwise. Figures 6(a)-(b) present by contrast how motion affects charge (or other parameter). Figures 6(c)-(d) present by contrast how motion affects the depth (graph of the g function) in the multi-layer sensor example.

While the camera is acquiring a picture (exposing) the camera motion sensor will provide $M \times N$ values of charge, luminance, color or other parameter depending on the detector used. The cases motion / no motion will generally influence the values as follows:

For the case of no motion, the light does not change between reference images. For example in the multi-layer sensor, the depth of penetration will stay constant. In another sensor, the luminance, color and/or other parameter would not be detected as having changed between referenc images.

$$\begin{cases} \begin{cases} u_{11} = u_{12} = \ldots = u_{1M} \\ \ldots \\ u_{N1} = u_{N2} = \ldots = u_{NM} \end{cases} \\ g1 = g2 = g_3 = \ldots = g_M \end{cases} \qquad (4)$$

For the case of motion, the light does change between reference images. For example in the multi-layer sensor, the depth of penetration changes. In another sensor, the luminance, color or other parameter may change between reference images.

$$\begin{cases} \exists i, j, k \leftrightarrow u_{ki} \neq u_{kj} \\ \exists i, j \leftrightarrow g_i \neq g_j \end{cases} \qquad (5)$$

MOVEMENT ESTIMATION

A blurring process may increase a correlation of an image along a PSF trajectory. It may be estimated how this property may be exploited for determining the exact values and support pixels of the PSF. A full example description of the method imagined along with one example is provided with reference to Figure 7-11.

It is desired in performing the PSF estimation to use small periods for the camera motion sensor integration or comparing or reference images, and multiple readings (although one reading may be used in conjunction with information from the main captured image), so that the PSF length (the size of the camera movement, in pixels) can be accurately determined. Larger light intensity and/or color or contrast variation measured by the camera motion sensor generally signifies a larger movement.

The direction with higher correlation may be used to indicate the PSF orientation. This hypothesis is not original, and it has been investigated in several articles, like Y. Yitzhaky, I. Mor, A. Lantzman, and N. S. Kopeika "Direct method for restoration of motion-blurred images" Journal of Optical Society of America, Vol. 15, No. 6/June 1998, pg 1512-1519, incorporated by reference.

Depending on camera contraints, it is useful to have multiple camera motion sensors. If the camera motion sensors are arranged with no pattern (pseudo-random spatially distributed), then an increased accuracy of estimation of the PSF can be obtained.

PSF ESTIMATION FOR A SINGLE CAMERA MOTION SENSOR

The PSF estimation process may be divided into two steps: a first one, which takes place during image acquisition, where the photons from the camera motion sensor are measured and/or counted, as described in the previous section and a second one, of post-processing where the trajectory of the camera is estimated along with the PSF weights.

The post-processing may also have two steps: estimating the PSF length and weights (in which examples are provided in the steps 1-5 in the algorithm below) and a second step of finding the support or trajectory (in regard to which the example of step 6 in provided below).

Preferences for PSF estimation include:

- For estimating the PSF size : the larger variation of light measured by the camera motion sensor, the larger is the estimated camera shift; and
- For computing the PSF support (camera movement orientation): the closer are the pixels from one direction (e.g., pixels placed at the left of the pixel corresponding to the camera motion sensor), then the more likely is the camera moved in that direction.

We will describe the process of estimating the PSF for the case of beam splitter (see Figure 4(b)), where the camera motion sensor is available in parallel to the main imaging sensor photo-detectors. The estimation in this example uses the records from the camera motion sensor, and the colors (intensity) of the pixels from the main imaging sensor.

By integration, M values are available at the end of the camera motion sensor reading periods. Taking into account the structure of the sensor, e.g., for the ML sensor (the number of wells, the depth of each, etc.) one can provide the associated color or other parameter. The color will be represented in a meaningful space like RGB, HSV, Lab, etc. In conclusion, at each exposure there will be a M-dimensional array of colors: $[C1, C2, ..., CM]$. In the case of $N= 3$ (Foveon sensor, see, e.g., Figure 2), an array of colors may be simply: $Ck=[Rk, Gk,Bk]$.

The number of periods, M, for integrating the pixel parameters, e.g., for the multi-layer sensor, the layers will have charges to be integrated over than periods M which should be carefully chosen. If the number is too small, then it is hard to track the camera movement. If it is too large, then the integration process will not be performed easily. The method to determine the number of periods starts from the movement detected on the previous frames. By applying a predictive filter (e.g. like Kalman filtering described in Peter Maybeck's "Stochastic Models, Estimation, and Control", Volume 1, Academic Press, Inc, chapter 1, entire Volume and series incorporated by reference), it is possible to estimate the quantity of movement and by that to determine the desired number of readings. That should be preferably at least equal, or more preferably larger, with twice the size of the predicted movement given in pixels.

Using an understanding of hand jitter, the small period should be preferably equal or smaller than 1/50 secs for 5400, zoom 1X. The cases where a movement equal with one pixel that took place faster than 1/50 are rare.

On the other hand, by investigating the records of the multi-layer sensor example, or to be more precise, by comparing the variation of voltage sets from multiple layer sensors with a predefined threshold, or a threshold of another parameter for a CCD detector, a CPU will decide if the movement is small enough so that it is able to estimate and restore the true image in good conditions or it is not.

After exposure there will be a set of colors *[C1, C2, ..., CM]*. For the simplicity of explanation here, the colors will be described as being mono-chrome (gray-scale levels). This means that the camera motion sensor example of the multi-layer sensor may be turned into a single layer sensor (again for simplicity of writing). The extension to multi-channel color may be done by replacing the absolute subtraction with *L2* distance.

Let *[C1, C2, ..., CM]* be the set of colors measured by the camera motion sensor.
Basically the steps of PSF computation are:

1. Compute the color vector gradient *D1, D2, ..., DM-1,* $^{\text{where}}$ D1=C2-C1, *D2=C3-C2,, ...,Dk= Ck+1-Ck.*
   These are the variation of the colors recorded by the sensor.
   In this step, the gradient is computed over a set of measured colors. There are different ways to compute the gradient over a discrete vector: the derivative in 2 points (finite differences - used here), the derivative in 3 points, 4, 6 points, etc. Choosing one way from the mentioned methods is not a key feature or requirement of the algorithm.

2. The thresholds are *T1< T2< T3<* ... . The thresholds are chosen so to express the shift over a pixel (*T1*), over 2 pixels (*T2*), etc. The thresholds *Tk* are normalized in respect to the local gradient.

A method to compute the first thresholds is

$$T_1 = \frac{\frac{t_{\exp}}{T_{\exp}}}{DI} \quad (6)$$

where:

- *Texp* is the exposure period of the main imaging system
- *texp* is a single exposure period of the camera motion sensor. There are *M* exposures in the *Texp*. However *Mtexp* does not lead to *Texp,* because of the gap between two consecutive readings.
- *DI* is the averaged image Laplacian. It gives a measure of the edges in the pixels from the vicinity of the camera motion sensor

The chose of the Laplacian is not crucial. Any realistic measure of edges (like bidirectional gradient, high frequency weight) will do.

The other threshold are computed by:

$$T_k = a \cdot k \cdot T_1, k=1,2,... \; (7)$$

where a simple choice for *a* is *a= 1*. Posterior tuning may be used efficiently.

3. Decide for each period (moment of camera motion sensor reading) if there has been movement. This decision is taken by comparing the absolute value of the differences with the thresholds. For instance:

- if the $|D1| < T1$ there has not been any movement;
- if $T1 < |D1| < T2$ there has been a movement over 1 pixels.
- if $T2 < |D1| < T3$ there has been a movement over 2 pixels.

Form that, build the movement array. Such a vector will look like: *[m1,m2,m3, ..., mM-1],* where

$$m_k = \begin{cases} 0,\ if\ the\ camera\ stayed\ still, |D_k| < T_1 \\ 1,\ if\ the\ camera\ moved\ over\ 1\ pixel, T_1 < |D_k| < T_2 \\ 2, if\ the\ camera\ moved\ over\ 2\ pixel, T_2 < |D_k| < T_3 \\ \ldots \end{cases} \quad (8)$$

However, a proper choice of the number of camera motion sensor reading period, *M,* should prevent many values larger than 1. A value larger than 1 means that we will have points where there is no precise information of the camera movement.

The movement size estimation may use the principle: “If the variation recorded, in time, by the camera motion sensor is larger than the averaged spacial variation of the colors from the neighboring pixels of the photo-detector corresponding to ML sensor, then the camera moved”. The thresholds encode “larger than”.

Figure 7 illustrates an example of deciding quantity of movement. Colors represented are obtained after integration in respect to time. In the left are plotted the established thresholds. The associated array of movement is [0,0,1,0,0]

4. The movement array correction. Computation of a gradient by subtracting one value from the prior one will allow detection of the rapid movement. If the movement is slower, the differences between consecutive movements are small and no-movement will be detected. What we will do is to perform subtraction over values placing farther. These steps of increasing of the gap may be performed until the sum over the movement array is at least equal to the value of motion detected by subtracting the last value from the first.

5. The next step in estimating the weights is to find the 2-dimensional support of the PSF. The CPU will start to build all the scenarios of possible movements. The possible paths are placed in a hierarchical graph (tree), like the one illustrated at Figure 8.

Lei Iij be the value of pixel from the main image that corresponds to the same pixel at the camera motion sensor, where “i”spans the row from the image while “j” spans the column. The Iij value may be obtained by mixing the set with [C1, C2, ..., CM] colors measured by the camera motion sensor.

That pixel has 4 neighbors (spatially adjacent): *Ii-1,j* , *Ii+1,j, Ii,j-1, Ii,j+1.* These pixels also correspond to the possible paths of the PSF. The moment of movement is recorded by the first non-zero value from the array movement.

In the tree illustrated at Figure 8, each parent node will have 4 sons corresponding to the 4 neighbor pixels. So each son may represent a direction where the camera moved. In the nodes, the probability may be provided of that pixel to be part of the PSF; in other words the probability that the camera moved in that direction. The computation of the node weights may be performed as follows:

- The root , $P_1 0$ appears for surely in the PSF, therefore its probability is 1
- At least one of its 4 sons will be part of the PSF. It may be determined that the camera moved; so it could not jump so one of the four neighbors should be part of the PSF. The weights of the 4 son-nodes will sum to 1:

$$\sum_{k=1}^{4} P_k^1 = P_1^0 = 1 \quad (9)$$

- The weights distribution may be computed by comparing the measured color with the ones of the corresponding image pixels.

Figure 8 illustrates the investigating of possible PSF pixels.

$$\begin{aligned}
P_1^1 &\sim \frac{1}{D_1 - (I_{i,j-1} - I_{i,j})} = \frac{1}{\left|(C_2 - C_1) - (I_{i,j-1} - I_{i,j})\right|} \\
P_2^1 &\sim \frac{1}{\left|(C_2 - C_1) - (I_{i-1,j} - I_{i,j})\right|} \\
P_3^1 &\sim \frac{1}{\left|(C_2 - C_1) - (I_{i,j+1} - I_{i,j})\right|} \\
P_4^1 &\sim \frac{1}{\left|(C_2 - C_1) - (I_{i+1,j} - I_{i,j})\right|}
\end{aligned} \quad (10)$$

The four sons weights of some node will have to sum to the parent value.

$$\sum_{k=1}^{4} P_{4j-k}^i = P_j^i \, (11)$$

The terminal node (leaf) with the highest value indicates the most likely PSF path. The length of the hierarchical graph must be equal to the sum of displacement.

Different schemes of building the hierarchy may prove useful as well. The previously described choice gives more importance to the points nearer to the starting point and less importance to the ones placed farther. If one will desire to balance all the PSF pixels, he will simple replace the normalization condition of:

$$\sum_{k=1}^{4} P_{4j-k}^{i} = P_{j}^{i} \, (12)$$

With:

$$\sum_{k=1}^{4} P_{4j-k}^{i} = 1 \, (13)$$

Other meaningful choices would be:

$$\sum_{k=1}^{4} P_{4j-k}^{i} = \frac{1}{i+1} \text{ or } \sum_{k=1}^{4} P_{4j-k}^{i} = 2^{-(i+1)}$$

In these cases the most likely PSF support is given by comparing the sum of the nodes from the rot to the terminal leaf.

The PSF is completely determined in this example. A restoration method will be implied to remove the motion blur effect from the recorded image.

PSF ESTIMATION FOR A MULTIPLE CAMERA MOTION SENSORS

In the previous example, an embodiment was described wherein the estimation will fail unless the camera motion sensor falls in the middle of an uniform area, and also, the movement detection will fail. All the nodes from the same level of the graph may have equal values. At the end, there may be many PSF possible supports with the same probability. To avoid such a situation, several camera motion sensors, or at least two, may be used. Preferably, these multiple sensors are disposed at random or selectively unaligned positions.

In this embodiment, the PSF estimation algorithm may be run in the same manner for each one of the sensors. Before deciding which is most probable PSF support, the computed graphs may be computed, and afterwards the leaf weights are compared.

The PSF estimation proposed method may be applied to an image acquired with a Bayer Color Filter Array, but where the resolution was decreased to the level where the pixels have three color components. The resolution may be reduced at 25%; a group of 4 pixels G1,R,B,G2 may be transformed into a single pixel with the components: [R, 0.5(G1+G2),B].

EXAMPLE OF ESTIMATING THE PSF

In this section, an example is provided of how the PSF estimation algorithm. For the ease of writing, it is assumed that the camera motion sensor provides scalar color (single tone).

It is assumed for the writing of this section that the original image, the PSF, the motion sensor records and the blurred image are the ones illustrated at Figure 9.

The averaged Laplacian is DI=23.6. Texp=1 sec while texp=1/10sec. The thresholds are (using eq. (7))

$$T_1=2,\ T_2=4,\ T_3=6,..$$

The gradient, computed as finite differences over the camera motion sensor measured color vector is

$$D=[0\ 0\ \ 2\ \ 0\ \ 0\ \ 0\ \ -2\ \ -2];$$

The movement array is (given by eq.

$$m=[0\ 0\ \ 1\ \ 0\ \ 0\ \ 0\ \ 1\ \ \ 1];$$

Therefore, the non-normalized (and not oriented) PSF is:

$$PSF=[2,\ 4,\ 1,\ 1];$$

The normalized PSF weights are

$$PSF=[0.25,\ 0.25,\ 0.125,\ 0.125];$$

In this moment, the weights of the PSF are determined, but its support might not be known. Possible situations of the support are illustrated in Figure 10. Figure 10 illustrates possible PSFs. Also the symmetrical ones (towards the center) are possible choices.

The first moment where the movement appears is in the three period of the camera motion sensor readings:

D3= C4-C3=5-3=2

The corresponding pixel from the image is (marked with gray in Figure 9) I44=46. The differences are (using eq. (10)):

$$
\begin{aligned}
I_{43} - I_{44} &= 33 - 46 = -13 \Rightarrow P_1^1 \sim \frac{1}{|10 \cdot 2 + 13|} = \frac{1}{33} \\
I_{34} - I_{44} &= 56 - 46 = 10 \Rightarrow P_2^1 \sim \frac{1}{|10 \cdot 2 - 10|} = \frac{1}{10} \\
I_{45} - I_{44} &= 65 - 46 = 19 \Rightarrow P_3^1 \sim \frac{1}{|10 \cdot 2 - 19|} = \frac{1}{1} \\
I_{54} - I_{44} &= 51 - 46 = 5 \Rightarrow P_4^1 \sim \frac{1}{|10 \cdot 2 - 5|} = \frac{1}{15}
\end{aligned}
$$

The normalization of the probabilities leads to (using eq. (13))

[0.025 0.084 0.835 0.056]

The most probable path is that camera moved to the left. Therefore the current pixel is now I45=65. In that case the differences are:

$$
\begin{aligned}
I_{44} - I_{45} &= 46 - 65 = -19 \Rightarrow P_9^2 \sim \frac{1}{|10 \cdot (-2) + 19|} = \frac{1}{1} \\
I_{35} - I_{45} &= 69 - 65 = 4 \Rightarrow P_{10}^2 \sim \frac{1}{|10 \cdot (-2) - 4|} = \frac{1}{24} \\
I_{46} - I_{45} &= 54 - 65 = -11 \Rightarrow P_{11}^2 \sim \frac{1}{|10 \cdot (-2) + 11|} = \frac{1}{9} \\
I_{55} - I_{45} &= 41 - 65 = -25 \Rightarrow P_{12}^2 \sim \frac{1}{|10 \cdot (-2) + 25|} = \frac{1}{5}
\end{aligned}
$$

The weights normalized so to sum to 1 will provide the values:

[0.739 0.031 0.082 0.148].

And so on. The corresponding graph (tree) and the associated PSF are illustrated at Figure11. Figure 11 illustrates a tree associated with PSF computed trajectory (up to three PSF pixel).

Figure 12 shows a block diagram of an image acquisition system such as a digital camera apparatus operating in accordance with another embodiment. The digital acquisition device, in this case a portable digital camera 20, includes a processor 120. It can be appreciated that many of the processes implemented in the digital camera may be implemented in or controlled by software operating in a microprocessor (μProc), central processing unit (CPU), controller, digital signal processor (DSP) and/or an application specific integrated circuit (ASIC), collectively depicted as block 120 and termed as "processor". Generically, all user interface and control of peripheral components such as buttons and display is controlled by a μ-controller 122.

The processor 120, in response to a user input at 122, such as half pressing a shutter button (pre-capture mode 32), initiates and controls the digital photographic process. Ambient light exposure is determined using light sensor 40 in order to automatically determine if a flash is to be used. The distance to the subject is determined using focusing element 50 which also focuses the image on image capture element 60. If a flash is to be used, processor 120 causes the flash 70 to generate a photographic flash in substantial coincidence with the recording of the image by image capture element 60 upon full depression of the shutter button. The image capture element 60 digitally records the image in colour. The image capture element may include a CCD (charge coupled device) or CMOS to facilitate digital recording, and a separate camera motion sensor may be CCD or CMOS or otherwise, while the main image sensor may be CCD or CMOS or otherwise. The flash 70 may be selectively generated either in response to the light sensor 40 or a manual input 72 from the user of the camera.

The image recorded by image capture element 60 is stored in image store 80 which may comprise computer memory such a dynamic random access memory or a non-volatile memory. The camera is equipped with a display 100, such as an LCD at the back of the camera or a microdisplay inside the viewfinder, for preview and post-view of images. In the case of preview images, which are generated in the pre-capture mode 32, the display 100 can assist the user in composing the image, as well as being used to determine focusing and exposure. A temporary storage space 82 is used to store one or plurality of the preview, postview or other images (for example, that may temporally overlap wholly or partially with the main image) and be part of the image store 80 or a separate component. The preview or other reference image may be generated by the same image capture element 60, or a separate element. In the former, for speed and memory efficiency reasons, the reference image may be generated by subsampling the image 124 using software which can be part of the general

processor 120 or dedicated hardware, before displaying 100 or storing 82 the preview or other reference image. In the latter (separate reference image sensor case), the reference image sensor may originally acquire lower resolution than the main image sensor, or sub-sample images compared with those captured by the main image sensor 60.
Upon full depression of the shutter button, a full resolution image may be acquired and stored at 80. The image may go through image processing stages such as conversion from the RAW sensor pattern to RGB, format, color correction and image enhancements. These operations may be performed as part of the main processor 120 or by using a secondary processor such as a dedicated DSP. Upon completion of the image processing, the images may be stored in a long term persistent storage such as a removable storage device 112.

According to this embodiment, the system includes a motion de-blurring component 100. This component can be implemented as firmware or software running on the main processor 120 or on a separate processor. Alternatively, this component may be implemented in software running on an external processing device 10, such as a desktop or a server, which receives the images from the camera storage 112 via the image output mechanism 110, which can be physical removable storage, wireless or tethered connection between the camera and the external device. The motion de-blurring component 100 includes a PSF calculator 110 and an image de-convolver 130 which de-convolves the full resolution image using the PSF. These two components may be combined or treated separately. The PSF calculator 110 may be used for qualification, such as determining if motion blur exists, while the image de-convolver 130 may be activated after the PSF calculator 110 has determined if de-blurring is needed.

Figure 13 is a flow chart of one embodiment of calculating the PSF in accordance with an embodiment. While the camera is in preview or reference mode, 210, the camera continuously acquires preview or other reference images, and calculates exposure and/or focus and/or displays the composition. When such an image satisfies some predefined criteria 222, the preview or other reference image is saved, 230. As explained below, such criteria may be preferably defined based on image quality and/or chronological considerations. An exemplary criteria may be to always save the last image. More advanced image quality criteria may include analysis as to whether the preview or other reference image itself has too much motion blurring. In general, the preview or other reference images will have less blurring due to camera motion, because the reference images will have reduced exposure times compared with the main image. As an alternative to saving a single image, multiple images may be saved, 240, for example, the newest preview image being added to the list, replacing the oldest one, 242 and 244. The definition of oldest can be chronological, as in First In First Out. Alternatively it can be the image that least satisfies criteria as defined in stage 222. The process may continue, 211, until the shutter release is fully pressed, 280, or the camera is turned off.

The criteria, 222, that a preview or other reference image is held to satisfy can vary depending on specific implementations of the algorithm. In one preferred embodiment, such criteria may be whether the image is not blurred. This may be based on the assumption that even if a camera is constantly moving, being hand held by the user, there are times where the movement is zero, whether because the user is firmly holding the camera or due to change of movement direction the movement speed is zero at a certain instance. Such criteria may not need to be absolute. In addition such criteria may be based on one or more 1-dimensional vectors as opposed to the full two dimensional image. In other words, the criteria 222 may be satisfied if the image is blurred horizontally, but no vertical movement is recorded and vice versa, due to the fact that the motion may be mathematically described in orthogonal vectors, thus separable. More straight forward criteria would be chronological, saving images every predefined time which can be equal or slower to the speed the preview or other reference images are generated. Other criteria may be defined such as related to the exposure, whether the reference image reached focus, whether flash is being used, etc.

Finally, the full resolution image acquired at 280 is saved, 282.

After the full resolution image is saved, 282, it is loaded into memory 292 and the preview or other reference image or images are loaded into memory as well, 294. Together the reference and final images are the input of the process which calculates the PSF, 110.

A description of two different exemplary methods of calculating the PSF are described with reference to Figures 14 and 15.

Figure 14 illustrates an embodiment 500 for extracting a PSF using a single preview, postview or temporally overlapping image.

In this embodiment, the input is the finally acquired full resolution image 511, and a saved preview or other reference image 512. Prior to creating the PSF, the reference and final images are preferably aligned. The alignment can be a global operation, using the entire images, 511 and 512. However, the two images may not be exact for several reasons.

When the reference image and the final full resolution image differ temporally, there may not be a perfect alignment. In this case, local alignment, based on image features and using techniques known to those skilled in the art, will ordinarily be sufficient. The process of alignment may be performed on selected extracted regions 520, or as a local operation. Moreover, this alignment may be used in the neighborhood of the selected region(s) or feature(s) used for the creation of the PSF. In this case, matching regions of the full resolution and preview or other reference image are extracted, 521 and 522. The process of extraction of such regions may be as simple as separating the image into a grid, which can be the entire image, or fine resolution regions. Other more advanced schemes may include the detection of distinct regions of interest based on a classification process, such as detecting regions with high contrast in color or exposure, sharp edges or other distinctive classifiers that will assist in isolating the PSF. One familiar in the art is aware of many algorithms for analyzing and determining local features or regions of high contrast; and frequency transform and edge detection techniques are two specific examples that may be employed for this purpose, which may further include segmentation, feature extraction and classification operations.

The reference image 512 is normally, but not necessarily, of lower resolution than the full resolution image 511, typically being generated by clocking out a subset of the sensor cells or by averaging the raw sensor data. Therefore, the two images, or alternatively the selected regions in the images, may be matched in pixel resolution, 530. In the present context “pixel resolution” means the size of the image, or relevant region, in terms of the number of pixels constituting the image or region concerned. Such a process may be done by either upsampling the reference image, 532, downsampling the acquired image, 531, or a combination thereof. Various techniques may be best used for such sampling methods.

Now we recall from before that:

A two dimensional image I may be given as I(x,y).

A motion point spread function describing the blurring of image I may be given as MPSF(I).

The degraded image I'(x,y) can be mathematically defined as the convolution of I(X,Y) and MPSF(x,y) or

$$I'(x,y) = I(x,y) \otimes MPSF(x,y) \quad \text{(Eq. 1)}$$

Now where a mathematical function, such as the aforementioned MPSF*(x,y),* is convoluted with a Dirac delta function $\delta(x,y)$, that original function is preserved. Thus, if within a reference image a sharp point against a homogenous background can be determined, it is equivalent to a local occurrence of a 2D Dirac delta function within the un-blurred or relatively un-blurred or less blurred reference image. If this is now be matched and aligned locally with the main, blurred image $I'(x,y)$ then the distortion pattern around this sharp point will be a very close approximation to the exact PSF which caused the blurring of the original image $I(x,y)$. Thus, upon performing the alignment and resolution matching between reference and main images, the distortion patterns surrounding distinct points or high contrast image features may be, in effect, representations of the 2D PSF, for points and representation of a single dimension of the PSF for sharp, unidirectional lines.

The PSF may be created by combining multiple regions. In the simple case, a distinguished singular point on the reference image and its corresponding motion blurred form of this point which is found in the main full-resolution image is the PSF.

However, as it may not always be possible to determine, match and align, a single distinct point in both preview and full resolution image, it is alternatively possible to create a PSF from a combination of the orthogonal parts of more complex features such as edges and lines. Extrapolation to multiple 1-D edges and corners should be clear for one familiar in the art. In this case multiple line-spread-functions, depicting the blur of orthogonal lines need to be combined and analysed mathematically in order to determine a single-point PSF.

Due to statistical variances this process may not be exact enough to distinguish the PSF based on a single region. Therefore, depending on the processing power and required accuracy of the PSF, the step of finding the PSF may include some statistical pattern matching or statistical combination of results from multiple regions within an image to create higher pixel and potentially sub pixel accuracy for the PSF.

As explained above, the PSF may not be shift invariant. Therefore, the process of determining the right PSF may be performed in various regions of the image, to determine the variability of the PSF as a function of location within the image.

Figure 15 shows a method 600 of extrapolating a PSF using multiple preview or other reference images.

In this embodiment, the movement of the image is extrapolated based on the movement of the preview or other reference images. According to Figure 15, the input for this stage is multiple captured reference images 610, and the full resolution image 620. All images are recorded with an exact time stamp associated with them to ensure the correct tracking. In most cases, reference images will be equally separated, in a manner of several images per second. However, this is not a requirement for this embodiment as long as the interval between images, including the final full resolution image, is known.

One or more distinctive regions in a reference image are selected, 630. By distinctive, one refers to a region that can be isolated from the background, such as regions with noticeable difference in contrast or brightness. Techniques for identifying such regions may include segmentation, feature extraction and classification.

Each region is next matched with the corresponding region in each reference image, 632. In some cases not all regions may be accurately determined on all reference images, due to motion blurring or object obscurations, or the fact that they have moved outside the field of the reference image. The coordinates of each region are recorded, 634, for the preview or other reference images and, 636, for the final image.

Knowing the time intervals of the reference images, one can extrapolate the movement of the camera as a function of time. When the full resolution image 620 is acquired, the parameter that is recorded is the time interval between the last captured preview image and the full resolution image, as well as the duration of the exposure of the full resolution image. Based on the tracking before the image was captured, 634, and the interval before and duration of the final image, the movement of single points or high contrast image features can be extrapolated, 640, to determine the detailed motion path of the camera.

This process is illustrated in Figure 16. According to Figure 16, multiple reference images 902, 904, 906, 908 are captured. In each of them a specific region 912, 914, 916, 918 is isolated which corresponds to the same feature in each image. The full resolution image is 910, and in it the region corresponding to 912, 914, 916, 918 is marked as 920. Note that 920 may be distorted due to motion blurring.

Tracking one dimension as a function of time, the same regions are illustrated in 930 where the regions are plotted based on their displacement 932, as a function of time interval 932. The objects 942, 944, 946 948 and 950 correspond to the regions 912, 914, 916, 918 and 920.

The motion is calculated as the line 960. This can be done using statistical interpolation, spline or other curve interpolation based on discrete sampling points. For the final image, due to the fact that the curve may not be possible to calculate, it may also be done via extrapolation of the original curve, 960.

The region of the final acquired image is enlarged 970 for better viewing. In this plot, the blurred object 950 is depicted as 952, and the portion of the curve 690 is shown as 962. The time interval in this case, 935 is limited to the exact length in which the exposure is being taken, and the horizontal displacement 933, is the exact horizontal blur. Based on that, the interpolated curve, 952, within the exposure time interval 935, produces an extrapolation of the motion path 990.

Now an extrapolation of the motion path may often be sufficient to yield a useful estimate of the PSF, if the motion during the timeframe of the principle acquired image can be shown to have practically constant velocity and practically zero acceleration. A camera in accordance with one embodiment may incorporate a sensitive gyroscopic sensor, such that it may be feasible to determine such information and verify that a simple motion path analysis is adequate to estimate the motion blur PSF. However, when this is not the case (or where it is not possible to reliably make such a determination), it is still possible to estimate the detailed motion blur PSF from a knowledge of the time separation and duration of reference images and a knowledge of the motion path of the camera lens across an image scene. This process is illustrated in Figures 17-a and 17-b and will now be described in more detail.

$$\iint k(x,y)\,dx\,dy = 1,$$

Any PSF is an energy distribution function which can be represented by a convolution kernel *k(x,y) --> w* where *(x,y)* is a location and *w* is the energy level at that location. The kernel *k* satisfies the following energy conservation constraint: which states that energy is neither lost nor gained by the blurring operation. In order to define additional constraints that apply to motion blur PSFs, a time parameterization may be used of the PSF as a path function, f(t) --> (x,y)and an energy function *h(t)--> w*. Note that due to physical speed and acceleration constraints, *f(t)*should be continuous and at least twice differentiable, where *f'(t)* is the velocity of the reference image frame and *f''(t)* is the acceleration at time *t*. By making the assumption that the scene radiance does not change during image acquisition, the additional constraint arises:

$$\int_{t}^{t+\delta t} h(t)\,dt = \frac{\delta t}{t_{end} - t_{start}},\ \delta t > 0,\ t_{start} \le t \le t_{end} - \delta t,$$

where [t_{start}, t_{end}] is the acquisition interval for a reference image. This constraint states that the amount of energy which is integrated at any time interval is proportional to the length of the interval.

Given these constraints, an estimate may be made of a continuous motion blur PSF from discrete motion samples as illustrated in Figures 17-a and 17-b. First, the motion path, *f(t)*, may be estimated by spline interpolation as previously described above and as illustrated in Figure 16. This path [1005] is further illustrated in Figure 17-a.

Now in order to estimate the energy function *h(t)*along this path we need to determine the extent of each image frame along this interpolated path. This may be achieved using the motion centroid assumption described in Ben-Ezra et al. (cited above and incorporated by reference) and splitting the path into frames with a 1-D Voronoi tessellation as shown in Figure 17-a. Since the assumption of constant radiance implies that frames with equal exposure times will integrate equal amounts of energy, one can compute *h(t)* for each frame as shown in Figure 17-b. Note that as each reference frame will typically have the same exposure time thus the rectangles in Figure 17-b, apart from the main image acquisition rectangle, will have equal areas. The area of the main image rectangle, associated with capture frame 5 [1020] in this example, will typically be several times larger than reference image frames and may be significantly more than an order of magnitude larger if the exposure time of the main image is long.

The resulting PSF determined by this process is illustrated in Figure 17-b and may be divided into several distinct parts. Firstly there is the PSF which is interpolated between the reference image frames [1052] and shown as a solid line. Secondly, there is the PSF interpolated between the last reference image and the midpoint of the main acquired image [1054]. Thirdly, there is the extrapolation of the PSF beyond the midpoint of the main acquired image [1055] which, for a main image with a long exposure time – and thus more susceptible to blurring – is more likely to deviate from the true PSF. Thus it may be desirable to acquire additional reference images, such as postview images, which may include images acquired through the same in-camera mechanism as preview images, except that they are acquired after the main image has been acquired, and also temporally-overlapping reference images may be used whose exposure periods overlap with that of the main image (particularly useful in the preferred embodiment wherein a separate camera motion sensor from the main image sensor is used to acquire the reference images). This technique will allow a further interpolation of the main image PSF [1056] with the PSF determined from at least one reference image.

The process may not be exact enough to distinguish the PSF based on a single region. Therefore, depending on the processing power and accuracy desired, the step of finding the PSF may include some statistical pattern matching of multiple regions, determining multiple motion paths, thus creating higher pixel and potentially sub pixel accuracy for the PSF.

Advantageously, a determination may be made whether a threshold amount of camera motion blur has occurred during the capture of a digital image. The determination is made based on a comparison of a least two images acquired during or proximate to the exposure period of the captured image. The processing occurs so rapidly, either in the camera or in an external processing device, that the image blur determination occurs in "real time". The photographer may be informed and/or a new image capture can take place on the spot due to this real time image blur determination feature. Preferably, the determination is made based on a calculated camera motion blur function, and further preferably, the image may be de-blurred based on the motion blur function, either in-camera or in an external processing device in real time or later on.

While an exemplary drawings and specific embodiments of the present invention have been described and illustrated, it is to be understood that that the scope of the present invention is not to be limited to the particular embodiments discussed. Thus, the embodiments shall be regarded as illustrative rather than restrictive, and it should be understood that variations may be made in those embodiments by workers skilled in the arts without departing from the scope of the present invention.

In addition, in methods that may be performed according to preferred embodiments herein and that may have been described above, the operations have been described in selected typographical sequences. However, the sequences have been selected and so ordered for typographical convenience and are not intended to imply any particular order for performing the operations, except for those where a particular order may be expressly set forth or where those of ordinary skill in the art may deem a particular order to be necessary.

In addition, all references cited herein as well as the background, invention summary, abstract and brief description of the drawings, are incorporated by reference into the detailed description of the embodiments as disclosing alternative embodiments. The following are incorporated by reference: "Automatic multidimensional deconvolution" J. Opt. Soc. Am. A, vol. 4(1), pp. 180-188, Jan. 1987 to Lane et al, "Some Implications of Zero Sheets for Blind Deconvolution and Phase Retrieval", J. Optical Soc. Am. A,vol. 7, pp. 468-479, 1990 to Bates et al, Iterative blind deconvolution algorithm applied to phase retrieval", J. Opt. Soc. Am. A, vol. 7(3), pp. 428-433, Mar. 1990.to Seldin et al and "Deconvolution and Phase

Retrieval With Use of Zero Sheets," J. Optical Soc. Am. A, vol. 12, pp. 1,842-1,857, 1995 to Bones et al., "Digital Image Restoration", Prentice Hall, 1977 authored by Andrews, H.C. and Hunt, B.R, and “Motion Deblurring Using Hybrid Imaging”, by Moshe Ben-Ezra and Shree K. Nayar, from the Proceedings IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2003.

What is claimed is:

1. A digital camera, comprising:

an optical system;

a main image sensor for capturing a main image provided through the optical system;

a camera motion photo-sensor for estimating relative camera-object motion during image capture; and

a processor that estimates camera motion based on information obtained by the camera motion photo-sensor while the camera is exposed to an image of a scene, and that reduces or removes a motion blur effect from the main image permitting a processed version of the main image to be thereafter rendered, said processed version including the main image with said motion blur effect reduced or removed.

2. The camera of claim 1, wherein the camera motion photo-sensor comprises a multi-layer sensor including multiple silicon layers.

3. The camera of claim 2, wherein the processor integrates photocurrent measurements between silicon layers of the multi-layer photo-sensor.

4. The camera of claim 3, wherein the processor estimates motion based on calculated variances of light flux or depths of light flux, or both, into the silicon layers based on the photocurrent measurements

5. The camera of claim 4, wherein the photocurrent measurements are carried out between successive p-type and n-type silicon layers of the multi-layer photo-sensor.

6. The camera of claim 4, wherein the multi-layer photo-sensor comprises successive wells of known depths of p-type and n-type silicon layers.

7. The camera of claim 1, wherein the optical system comprises a series of one or more lenses and an aperture.

8. The camera of claim 1, wherein multiple camera motion sensor measurements are performed during a single exposure period of the main image sensor.

9. The camera of claim 1, wherein a direction of camera motion is estimated as a direction of highest correlation.

10. The camera of claim 1, further comprising one or more further camera motion photo-sensors also for estimating camera motion.

11. The camera of claim 10, wherein two or more camera motion photo-sensors are selectively spatially-distributed in an unaligned manner.

12. The camera of claim 1, wherein a quantity of camera movement is estimated based on computing a degree of variance of a measured parameter between two or more reference images.

13. A method of estimating camera motion during an exposure period for capturing a scene in a digital camera, comprising:

exposing a main image sensor through an optical system for an exposure period thereby capturing a main image of a scene;

acquiring one reference images of substantially the same scene with a camera motion photo-sensor before, during or after the exposure period, or combinations thereof;

determining one or more parameters based on analysis of the one or more reference images;

estimating camera motion including calculating based on the one or more parameters; and

removing or reducing a camera motion blur effect from the main image based on the estimated camera motion, thereby permitting rendering of a processed version of the main image, said processed version including the main image with the camera motion blur effect removed or reduced.

14. The method of claim 13, wherein the camera motion photo-sensor comprises a multi-layer sensor including multiple silicon layers.

15. The method of claim 14, further comprising integrating the measured photocurrent measurements; and calculating variances of light flux or depth of light flux, or both, into the layers of the multi-layer photo-sensor based on the photocurrent measurements, and wherein the camera motion is based on the calculated variances.

16. The method of claim 15, further comprising carrying out the photocurrent measurements between successive p-type and n-type silicon layers of the multi-layer photo-sensor.

17. The method of claim 15, wherein the multi-layer photo-sensor comprises successive wells of known depths of p-type and n-type silicon layers.

18. The method of claim 13, wherein the optical system comprises a series of one or more lenses and an aperture.

19. The method of claim 13, further comprising performing multiple measurements with the camera motion photo-sensor during a single exposure period of the main image sensor.

20. The method of claim 13, wherein the estimating comprises estimating a direction of camera motion as a direction of highest correlation.

21. The method of claim 13, further comprising performing the estimating of camera motion using one or more further camera motion photo-sensors.

22. The method of claim 21, wherein two or more camera motion photo-sensors are selectively spatially-distributed in an unaligned manner.

23. The method of claim 13, wherein the estimating comprises estimating a quantity of camera movement based on computing a degree of variance of one or more parameters measured by the camera motion photo-sensor.

24. One or more processor-readable media having digital code embodied therein for programming one or more processors to perform a method of estimating camera motion

during an exposure period for capturing a scene in a digital camera, wherein the method comprises:

exposing a main image sensor through an optical system for an exposure period thereby capturing a main image of a scene;

acquiring one reference images of substantially the same scene with a camera motion photo-sensor before, during or after the exposure period, or combinations thereof;

determining one or more parameters based on analysis of the one or more reference images;

estimating camera motion including calculating based on the one or more parameters; and

removing or reducing a camera motion blur effect from the main image based on the estimated camera motion, thereby permitting rendering of a processed version of the main image, said processed version including the main image with the camera motion blur effect removed or reduced.

25. The one or more processor-readable media of claim 24, wherein the camera motion photo-sensor comprises a multi-layer sensor including multiple silicon layers.

26. The one or more processor-readable media of claim 25, wherein the method further comprises integrating the measured photocurrent measurements; and calculating variances of light flux or depth of light flux, or both, into the layers of the multi-layer photo-sensor based on the photocurrent measurements, and wherein the camera motion is based on the calculated variances.

27. The one or more processor-readable media of claim 26, wherein the method further comprises carrying out the photocurrent measurements between successive p-type and n-type silicon layers of the multi-layer photo-sensor.

28. The one or more processor-readable of claim 26, wherein the multi-layer photo-sensor comprises successive wells of known depths of p-type and n-type silicon layers.

29. The one or more processor-readable of claim 24, wherein the optical system comprises a series of one or more lenses and an aperture.

30. The one or more processor-readable of claim 24, wherein the method further comprises performing multiple measurements during a single exposure period of the main image sensor.

31. The one or more processor-readable of claim 24, wherein the estimating comprises estimating a direction of camera motion as a direction of highest correlation.

32. The one or more processor-readable of claim 24, wherein the method further comprises performing the estimating of camera motion using one or more further camera motion photo-sensors.

33. The one or more processor-readable of claim 32, wherein two or more camera motion photo-sensors are selectively spatially-distributed in an unaligned manner.

34. The one or more processor-readable of claim 24, wherein the estimating comprises estimating a quantity of camera movement based on computing a degree of variance of a parameter measured with the camera motion photo-sensor.

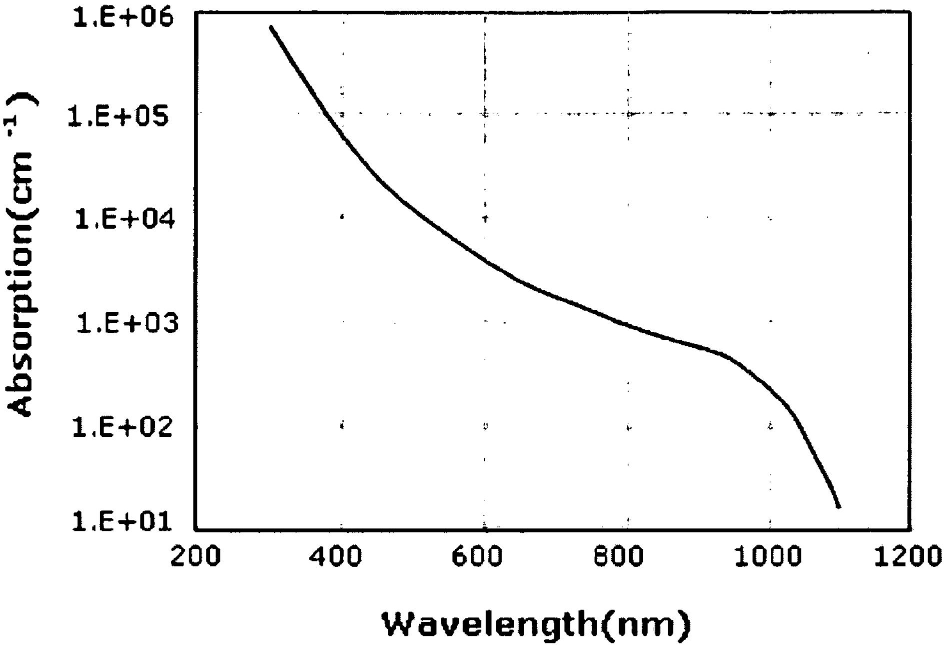


Figure 1A

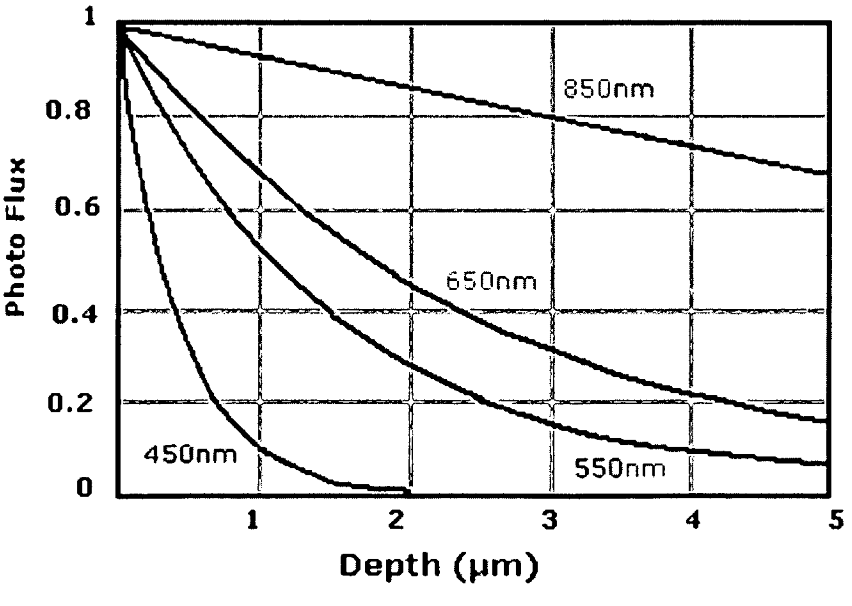


Figure 1B

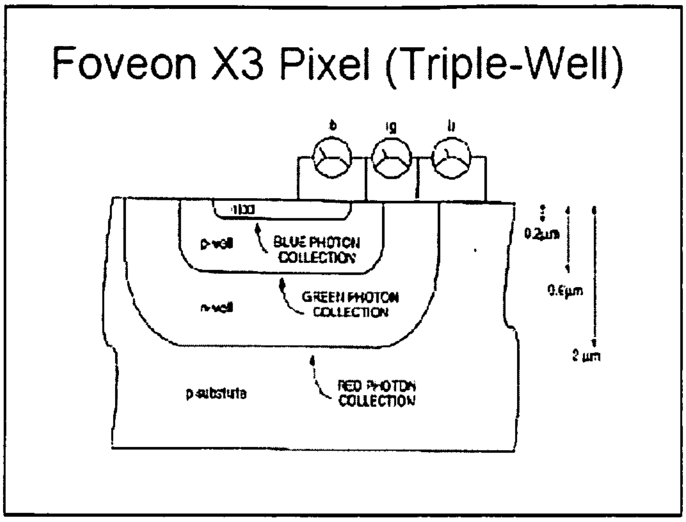


Figure 2

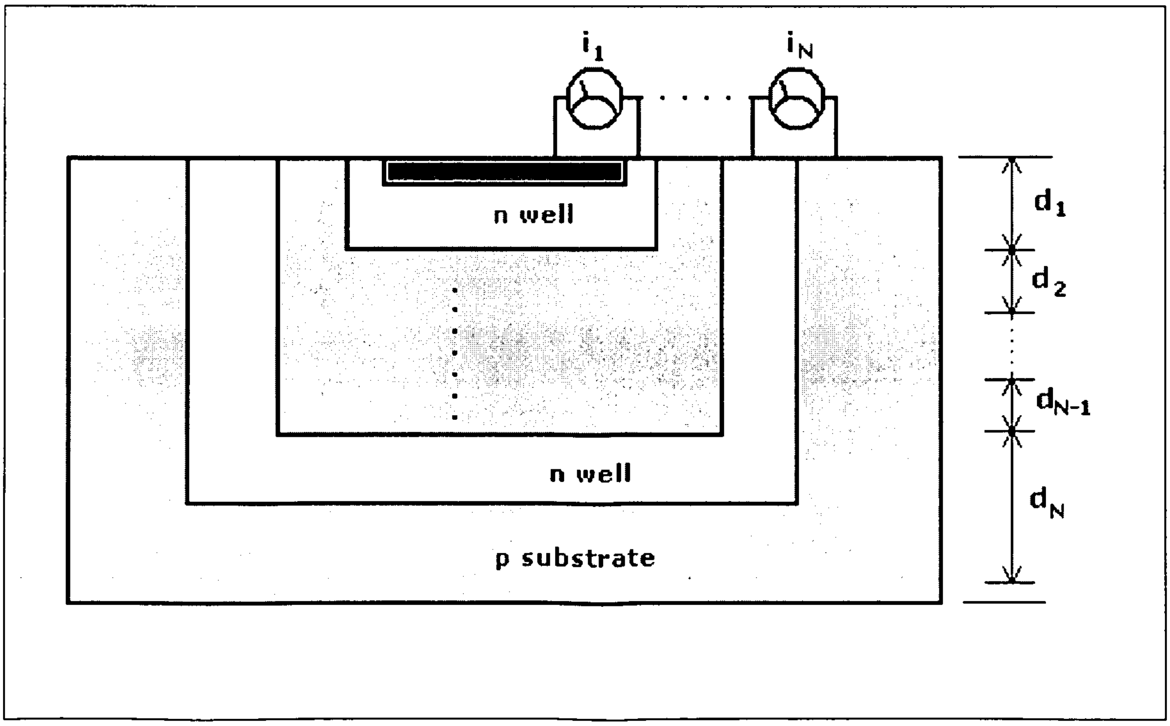


Figure 3

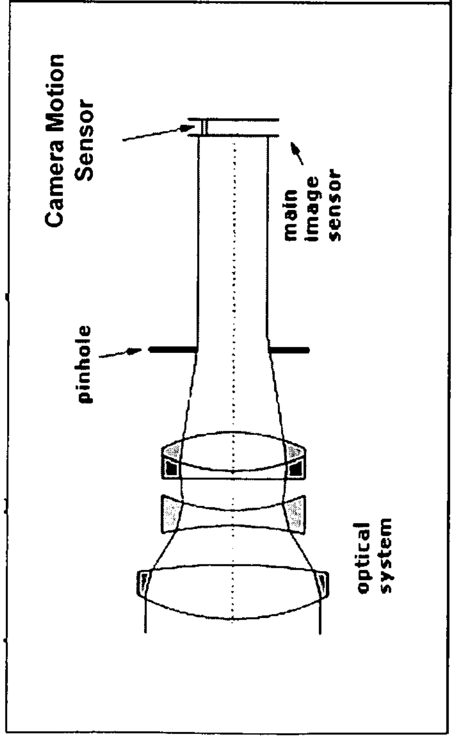


Figure 4A

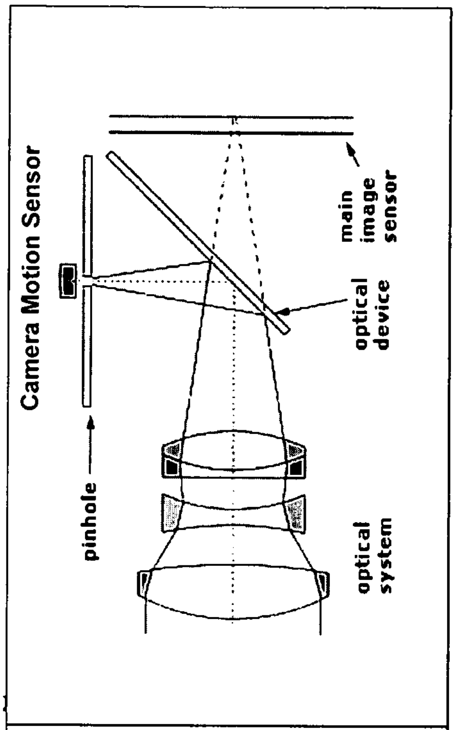


Figure 4B

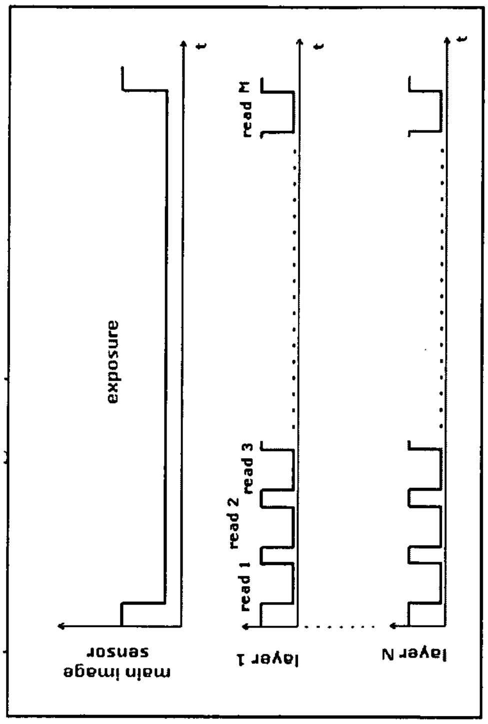


Figure 5

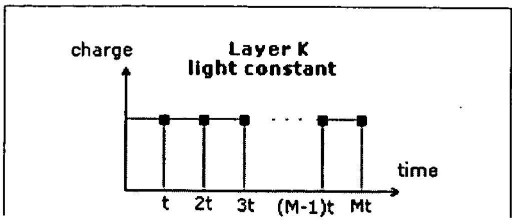


Figure 6A

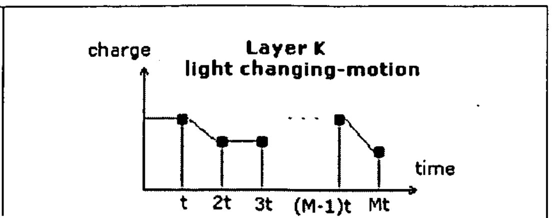


Figure 6B

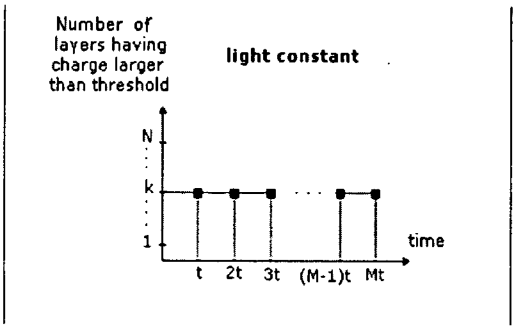


Figure 6C

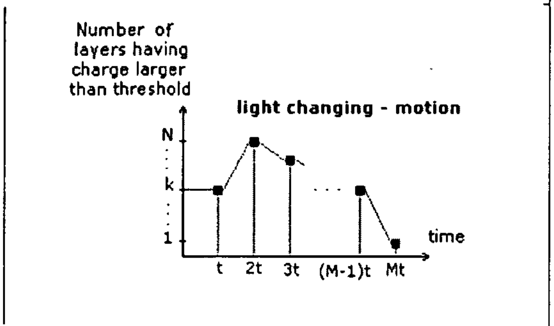


Figure 6D

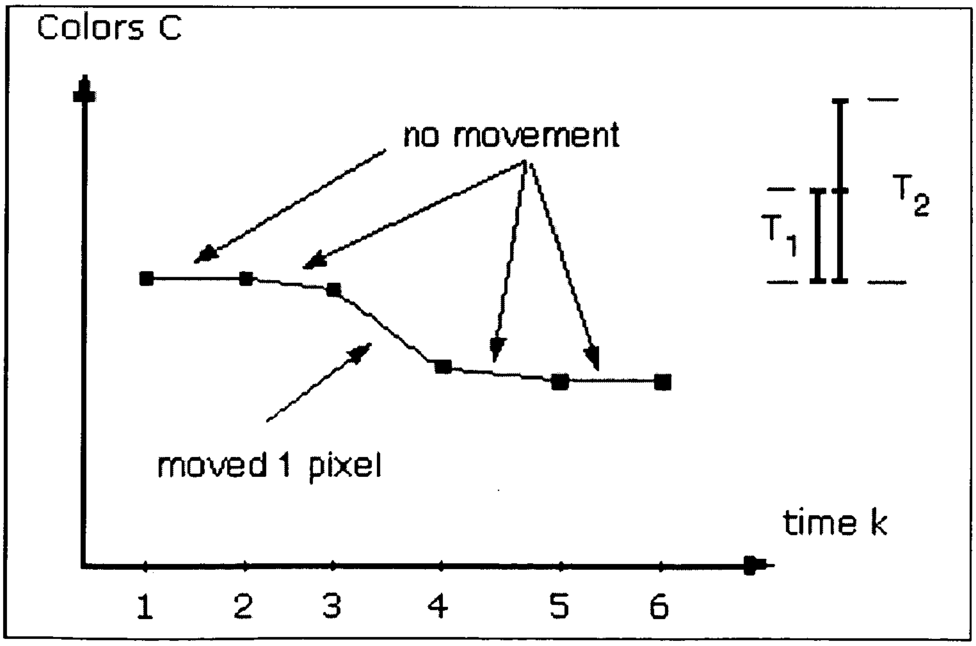


Figure 7

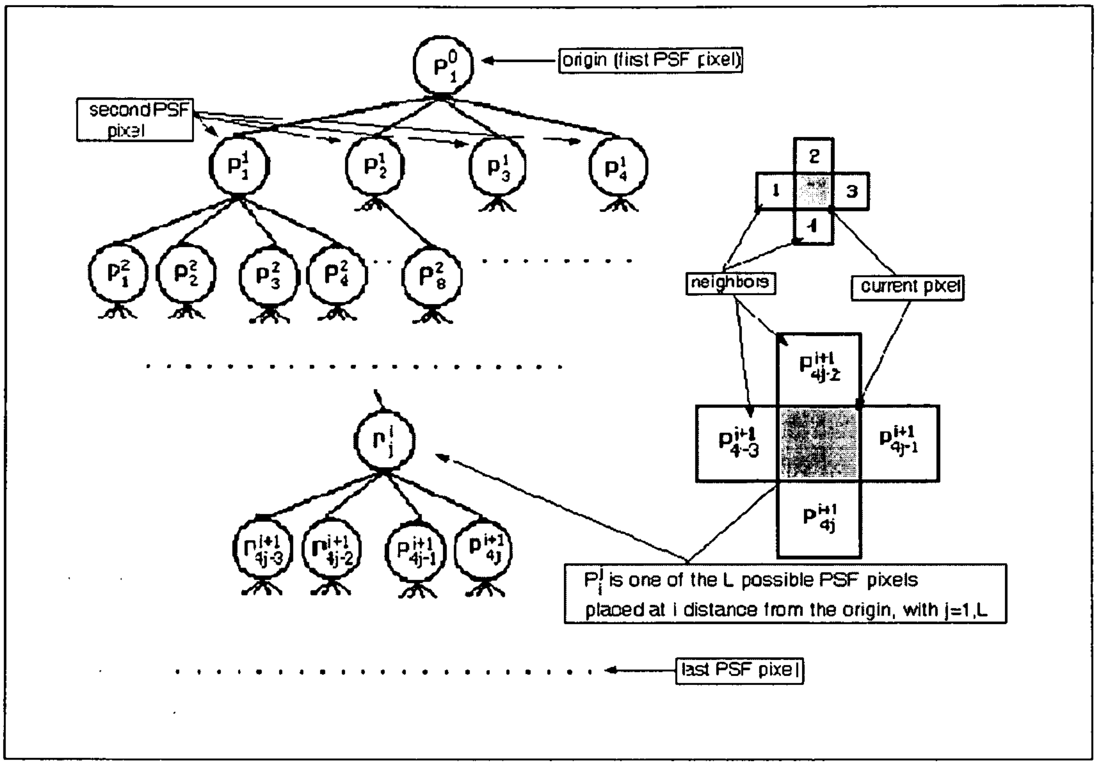
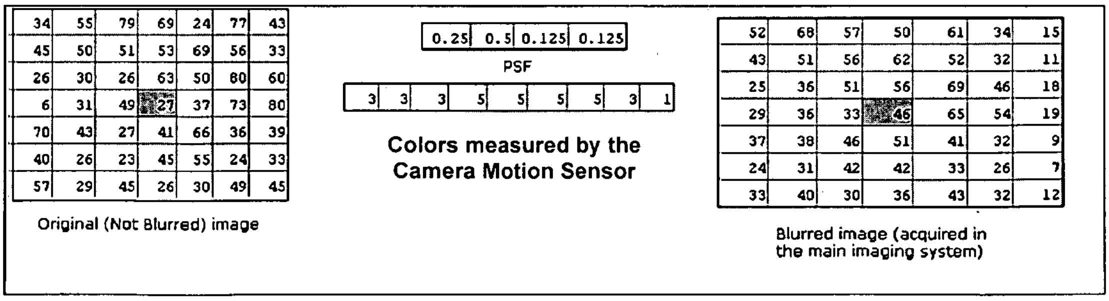


Figure 8



34	55	79	69	24	77	43
45	50	51	53	69	56	33
26	30	26	63	50	80	60
6	31	49	27	37	73	80
70	43	27	41	66	36	39
40	26	23	45	55	24	33
57	29	45	26	30	49	45

Original (Not Blurred) image

0.25	0.5	0.125	0.125

PSF

3	3	3	5	5	5	5	3	1

Colors measured by the Camera Motion Sensor

52	68	57	50	61	34	15
43	51	56	62	52	32	11
25	36	51	56	69	46	18
29	36	33	46	65	54	19
37	38	46	51	41	32	9
24	31	42	42	33	26	7
33	40	30	36	43	32	12

Blurred image (acquired in the main imaging system)

Figure 9

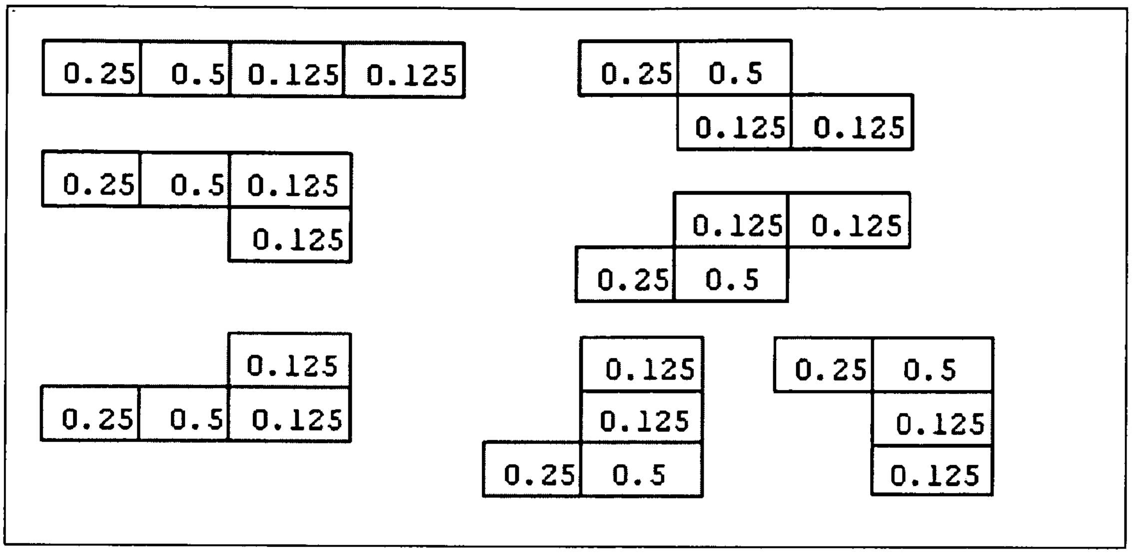


Figure 10

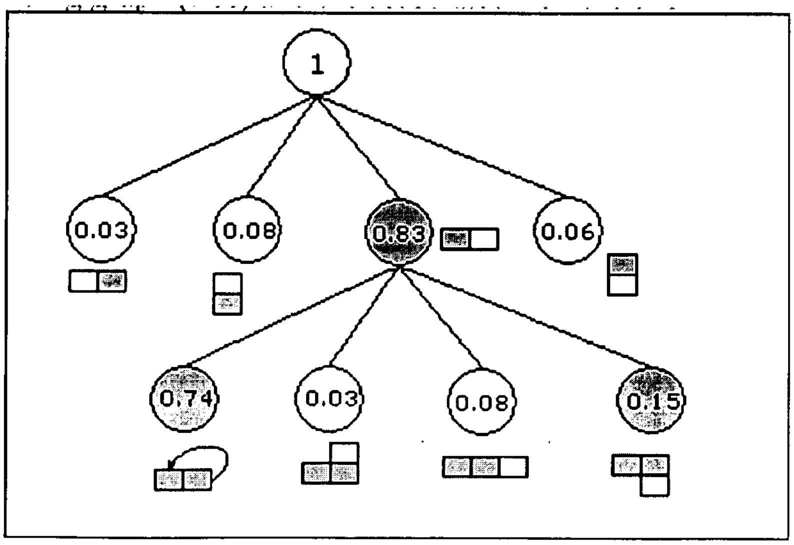


Figure 11

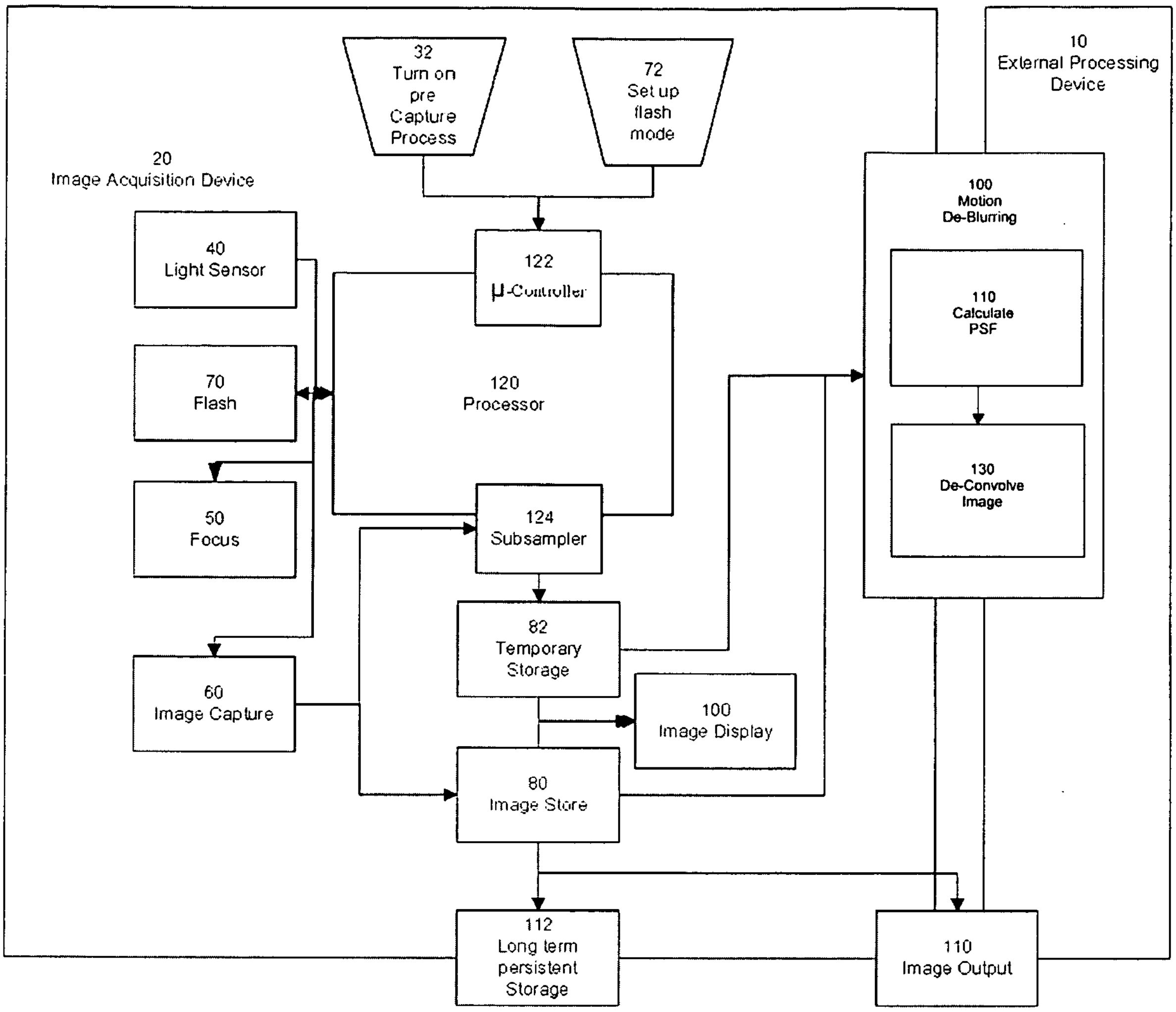

32
Turn on pre Capture Process
72
Set up flash mode
10
External Processing Device
20
Image Acquisition Device
40
Light Sensor
122
μ-Controller
70
Flash
120
Processor
50
Focus
124
Subsampler
82
Temporary Storage
60
Image Capture
100
Image Display
80
Image Store
112
Long term persistent Storage
110
Image Output
100
Motion De-Blurring
110
Calculate PSF
130
De-Convolve Image

Figure 12

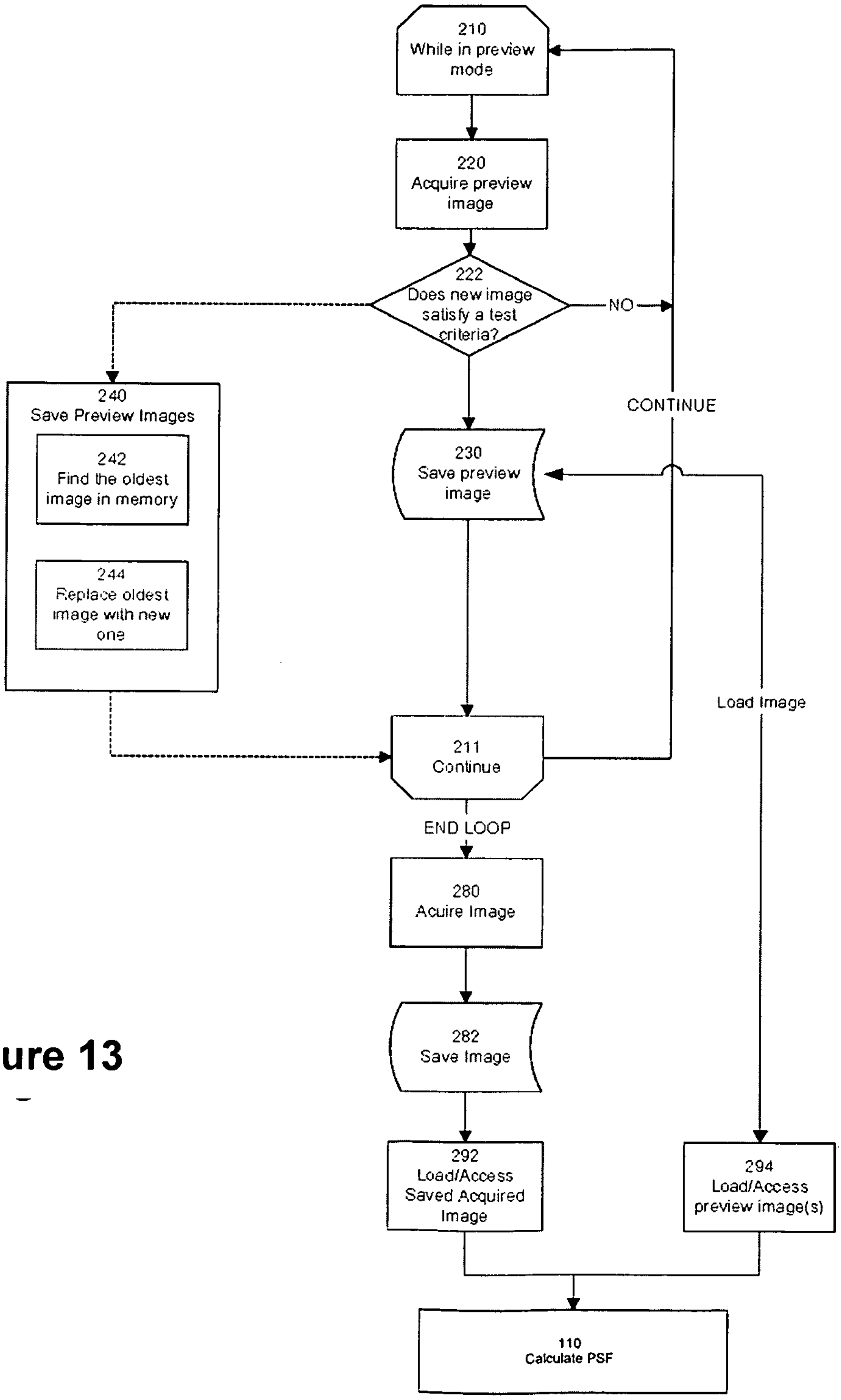

210
While in preview mode
220
Acquire preview image
222
Does new image satisfy a test criteria?
NO
CONTINUE
240
Save Preview Images
242
Find the oldest image in memory
244
Replace oldest image with new one
230
Save preview image
Load Image
211
Continue
END LOOP
280
Acuire Image
282
Save Image
292
Load/Access Saved Acquired Image
294
Load/Access preview image(s)
110
Calculate PSF

Figure 13

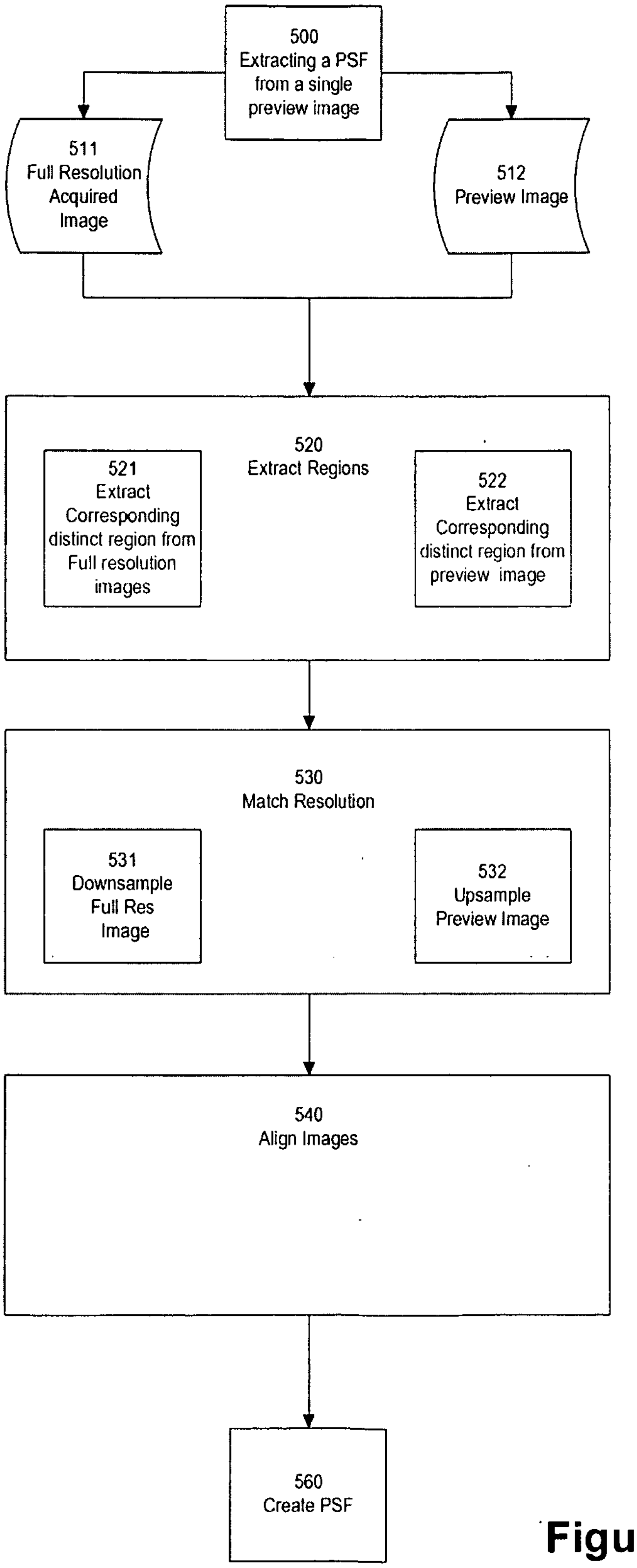

500
Extracting a PSF from a single preview image
511
Full Resolution Acquired Image
512
Preview Image
520
Extract Regions
521
Extract Corresponding distinct region from Full resolution images
522
Extract Corresponding distinct region from preview image
530
Match Resolution
531
Downsample Full Res Image
532
Upsample Preview Image
540
Align Images
560
Create PSF

Figure 14

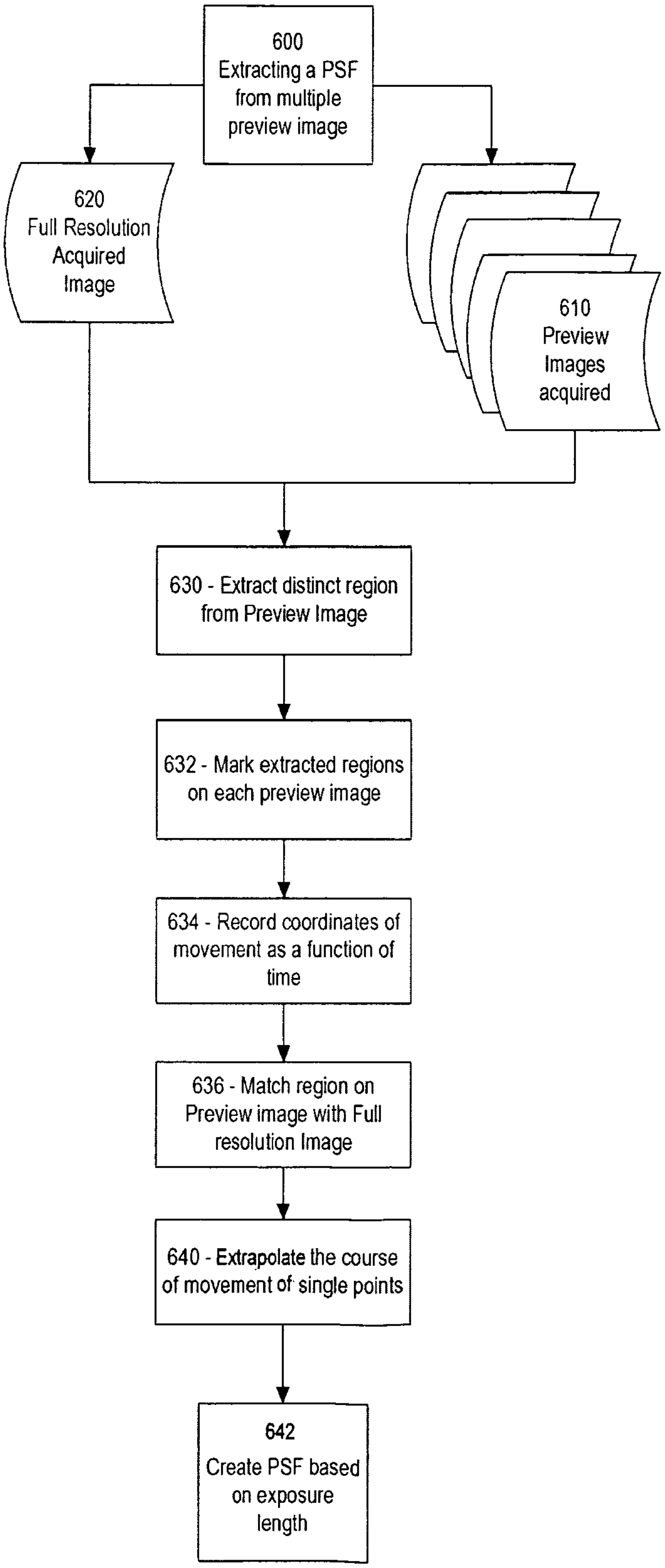

600
Extracting a PSF from multiple preview image
620
Full Resolution Acquired Image
610
Preview Images acquired
630 - Extract distinct region from Preview Image
632 - Mark extracted regions on each preview image
634 - Record coordinates of movement as a function of time
636 - Match region on Preview image with Full resolution Image
640 - Extrapolate the course of movement of single points
642
Create PSF based on exposure length

Figure 15

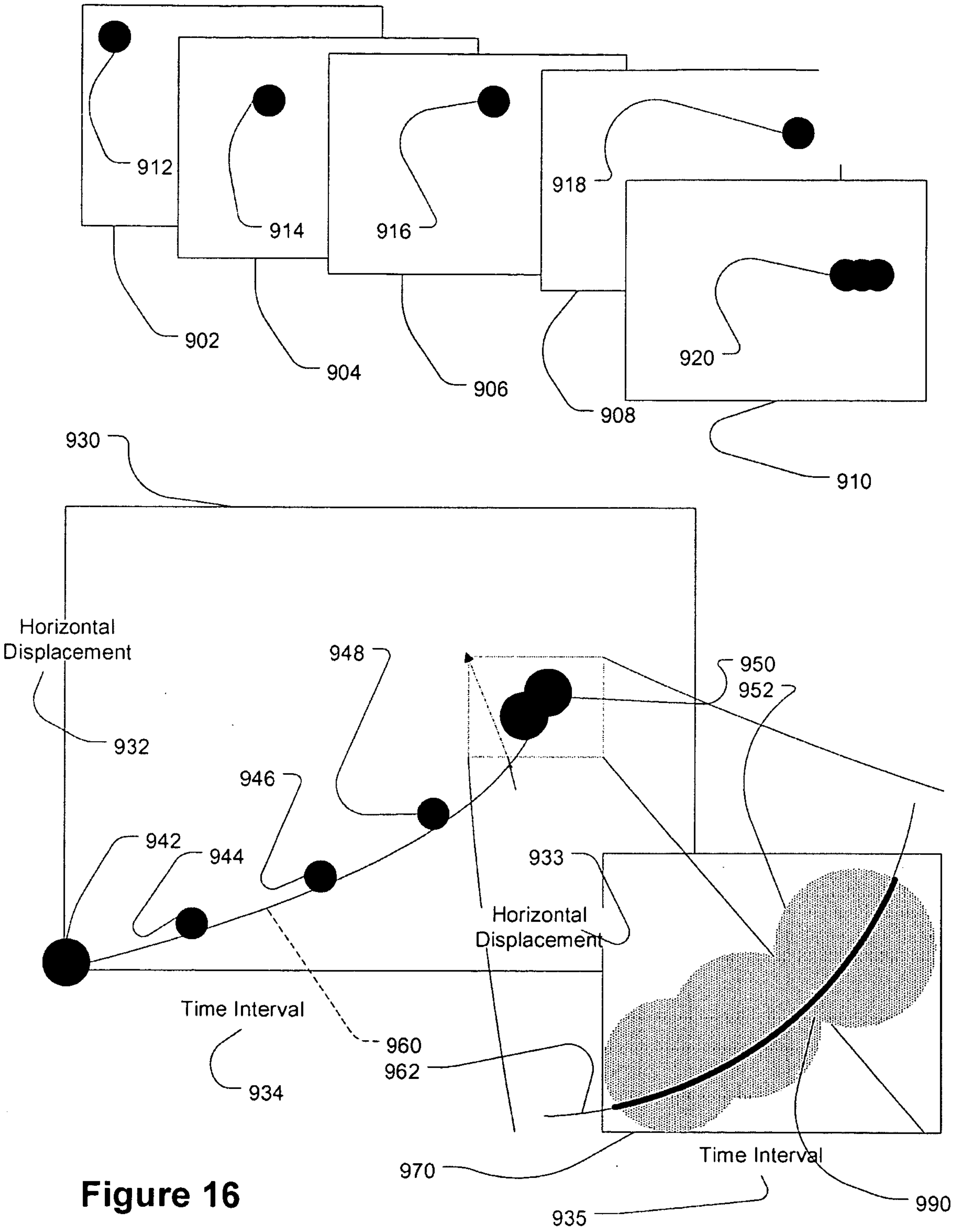

912
914
916
918
920
902
904
906
908
910
930
Horizontal Displacement
932
948
950
952
946
942
944
933
Horizontal Displacement
Time Interval
934
960
962
970
Time Interval
935
990

Figure 16

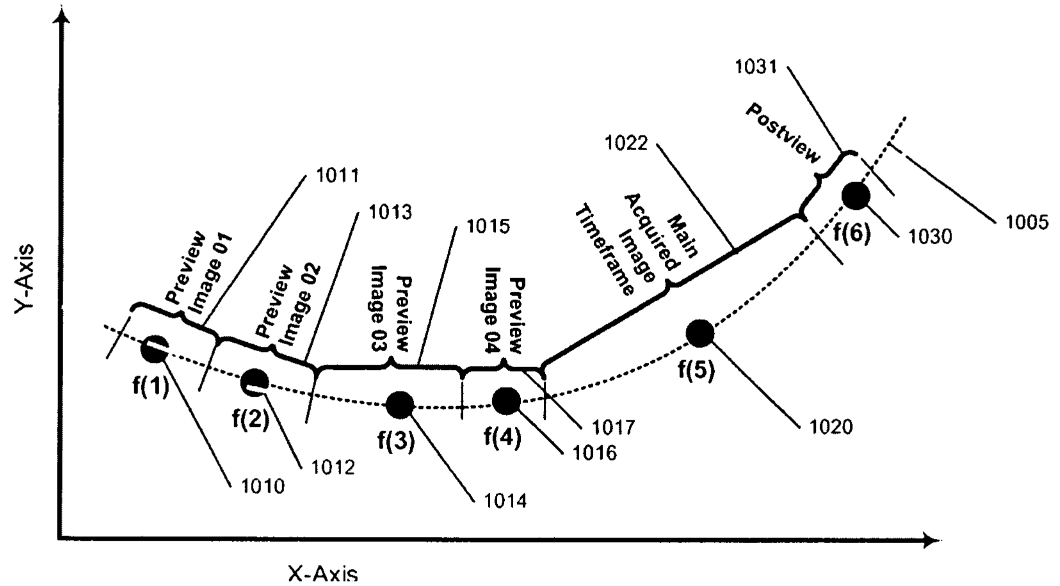


Figure 17A

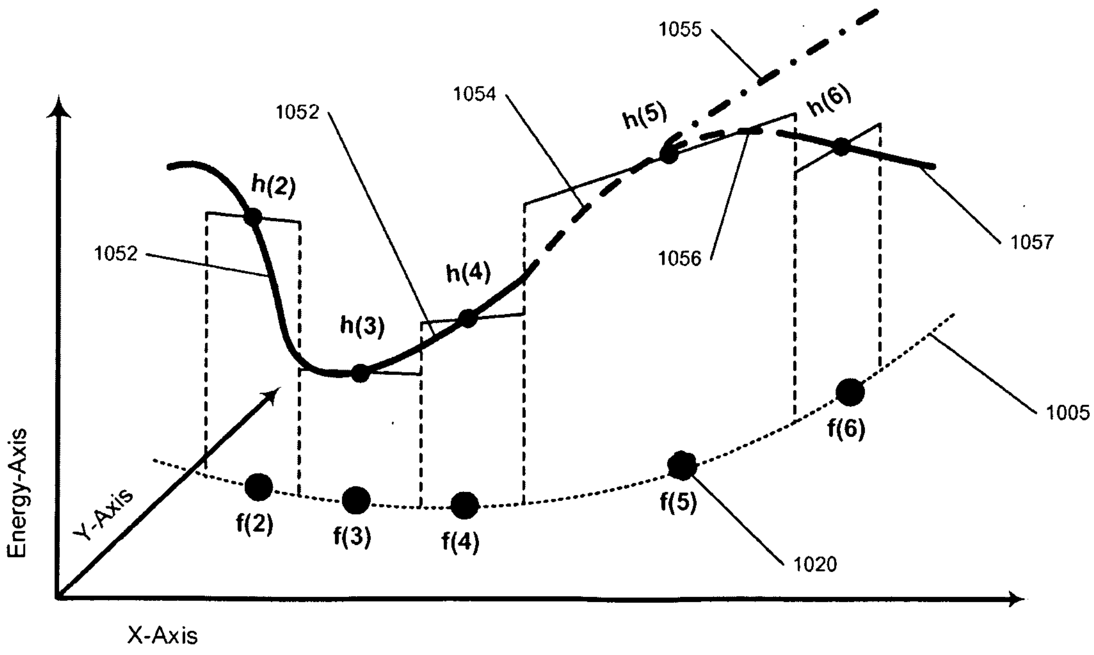


Figure 17B