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(54) Title: IMAGE PROCESSING APPARATUS, IMAGE PICKUP APPARATUS, IMAGE PROCESSING METHOD, IMAGE PROCESSING PROGRAM, AND STORAGE MEDIUM

(57) Abstract: An image processing apparatus includes an image acquisition unit configured to acquire an image, a condition acquisition unit configured to acquire image capturing condition information of the image, a PSF acquisition unit configured to acquire point spread functions relating to an optical system, a number setting unit configured to set the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions, and an image restoration unit configured to perform repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, and the PSF acquisition unit is configured to acquire the point spread functions based on the image capturing condition information.

S101

ACQUIRE CAPTURED IMAGE

S102

ACQUIRE IMAGE CAPTURING CONDITION

S103

ACQUIRE OPTICAL TRANSFER FUNCTION

S104

REVISE OPTICAL TRANSFER FUNCTION

S105

GENERATE POINT SPREAD FUNCTION

S106

DETERMINE NUMBER OF REPLICATION TIMES

S107

IMAGE RESTORATION AND DEVELOPMENT PROCESSING
Description

Title of Invention: IMAGE PROCESSING APPARATUS, IMAGE PICKUP APPARATUS, IMAGE PROCESSING METHOD, IMAGE PROCESSING PROGRAM, AND STORAGE MEDIUM

Technical Field

[0001] The present invention relates to an image processing apparatus which corrects a deterioration of an image caused by an optical system.

Background Art

[0002] For an object captured via an image pickup optical system, light emitted from one point cannot be converged to another point and has a minute spread due to an influence of a diffraction, an aberration, or the like that occurs in the image pickup optical system. Such a minutely-spread distribution is referred to as a PSF (point spread function). Due to the influence of the image pickup optical system, the captured image is formed with the PSF convolved with the image, and accordingly, the image is blurred and its resolution is deteriorated.

[0003] Recently, the captured image is typically stored as electronic data, and a method (image restoration processing) of correcting the deterioration of the image caused by the optical system by using image processing has been proposed. The deterioration state of the image varies depending on a position in the image.

[0004] PTL 1 discloses an image processing method of performing optimum restoration processing depending on a deterioration state at each position in an image while reducing a calculation amount even when an image deterioration varies depending on the position according to a lens characteristic. NPL 1 discloses an image restoration method by a repetition calculation using so-called Lucy-Richardson method.

Citation List

Patent Literature


Non Patent Literature

[0006] [NPL 1] OSA VOLUME 62, NUMBER 1 JANUARY 1972 Bayesian-Based Iterative Method of Image Restoration

Summary of Invention

Technical Problem

[0007] However, PTL 1 describes neither setting the number of repetition times of calculation which is appropriate depending on each position when performing the image restoration processing, nor a specific method of the image restoration processing.
When the number of repetition times is not appropriately set in performing the image restoration processing by using the repetition calculation, the cost of calculation increases. Furthermore, in many cases, the number of repetition times of calculation is a dominant factor with respect to the intensity of the image restoration. For example, if the number of repetition times of calculation is insufficient, the degree of the restoration is insufficient. On the contrary, if the number of repetition times of calculation is too large, the degree of the restoration is excessive, which results in occurrence of a harmful effect such as ringing. Accordingly, it is necessary to set the number of repetition times appropriately depending on characteristics of the image deterioration at a position or a region in the image.

When the image on which the restoration processing is to be performed is extremely large or the deterioration characteristic of the image varies depending on the position or the region, the repetition processing cannot be finished appropriately by comparing the RMS of an image which is not updated with the RMS of an updated image. Especially, in conventional methods of using a lens-interchangeable type digital camera which is capable of combining various lenses and image pickup elements, the (shift-variant) deterioration characteristic which varies depending on a position in a captured image cannot be satisfactorily restored.

The present invention provides an image processing apparatus, an image pickup apparatus, an image processing method, and an image processing program, and a storage medium which are capable of satisfactorily restoring a deterioration of an image depending on a position in the image.

Solution to Problem

An image processing apparatus as one aspect of the present invention includes an image acquisition unit configured to acquire an image, a condition acquisition unit configured to acquire image capturing condition information of the image, a PSF acquisition unit configured to acquire point spread functions relating to an optical system, a number setting unit configured to set the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions, and an image restoration unit configured to perform repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, and the PSF acquisition unit is configured to acquire the point spread functions based on the image capturing condition information.

An image pickup apparatus as another aspect of the present invention includes an image pickup element configured to photoelectrically convert an optical image formed via an optical system to output an image signal, an image acquisition unit configured to
acquire an image generated based on the image signal, a condition acquisition unit configured to acquire image capturing condition information of the image, a PSF acquisition unit configured to acquire point spread functions relating to the optical system, a number setting unit configured to set the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions, and an image restoration unit configured to perform repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, and the PSF acquisition unit is configured to acquire the point spread functions based on the image capturing condition information.

[0013] An image processing method as another aspect of the present invention includes the steps of acquiring an image, acquiring image capturing condition information of the image, acquiring point spread functions relating to an optical system, setting the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions, and performing repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, and in the step of acquiring the point spread functions, the point spread functions are acquired based on the image capturing condition information.

[0014] An image processing program as another aspect of the present invention causes a computer to execute a process including the steps of acquiring an image, acquiring image capturing condition information of the image, acquiring point spread functions relating to an optical system, setting the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions, and performing repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, and in the step of acquiring the point spread functions, the point spread functions are acquired based on the image capturing condition information.

[0015] A storage medium as another aspect of the present invention stores the image processing program.

[0016] Further features and aspects of the present invention will become apparent from the following description of exemplary embodiments with reference to the attached drawings.

**Advantageous Effects of Invention**

[0017] According to the present invention, an image processing apparatus, an image pickup
apparatus, an image processing method, and an image processing program, and a
storage medium which are capable of satisfactorily restoring a deterioration of an
image depending on a position in the image can be provided.

**Brief Description of Drawings**

[0018] [fig.1] FIG. 1 is a flowchart of an image processing method in Embodiment 1.
[fig.2A] FIG. 2A is an explanatory diagram of an image processing method which
corrects a shift-variant deterioration characteristic in Embodiment 2.
[fig.2B] FIG. 2B is an explanatory diagram of the image processing method which
corrects the shift-variant deterioration characteristic in Embodiment 2.
[fig.3A] FIG. 3A is an explanatory diagram of the number of repetition times of cal-
culation in Embodiment 2.
[fig.3B] FIG. 3B is an explanatory diagram of the number of repetition times of cal-
culation in Embodiment 2.
[fig.4] FIG. 4 is a configuration diagram of an image processing system in Embodiment
3.
[fig.5] FIG. 5 is a block diagram of an image processing apparatus in Embodiment 4.
[fig.6] FIG. 6 is a block diagram of an image pickup apparatus in Embodiment 5.

**Description of Embodiments**

[0019] Exemplary embodiments of the present invention will be described below with
reference to the accompanied drawings.

[0020] First of all, an outline of an image processing method (image restoration processing)
in this embodiment will be described. The following expression (1) is satisfied where,
in a real space (x,y), f(x,y) is an image which is not deteriorated by an optical system,
h(x,y) is a PSF (point spread function), and g(x,y) is a deteriorated image.

\[
g(x,y) = \int \int f(X,Y)^* h(x-X, y-Y) dX dY \quad \ldots (1)
\]

[0021] The image restoration processing by using the Lucy-Richardson method (LR
method) is represented by the following expression (2) in a real space.

[Math.1]

\[
f_n(x, y) \leftarrow f_{n-1}(x, y) \int \int \frac{h(x - x', y - y') g(X, Y)}{\int \int h(X - s, Y - t) f_{n-1}(s, t) ds dt} dX dY \ldots (2)
\]

[0022] In expression (2), symbol \( f_n \) is an image which is updated (updated image) and
symbol \( f_{n-1} \) is an image before updating. Symbol h is a deterioration characteristic of
the optical system, and for example it is a PSF. Symbol g is a deteriorated image.

[0023] In the image restoration processing by using the LR method, the image \( f_{n-1} \) is se-
quentially updated until the processing is discontinued according to, for example, a predetermined evaluation criterion, and then the image \( f_n \) is output. The evaluation criterion for the processing includes, for example, a value of root mean square (RMS) of the images \( f_n \) and \( f_{n,i} \). The image restoration processing may start with the setting of \( f_{o=g} \) as an initial value (when starting the LR method).

In order to apply the image restoration processing to an image captured by a digital camera, various measures are necessary. First, an image captured by using a typical digital camera has a deterioration characteristic which varies depending on a position in the image. Furthermore, in many cases, the image may be asymmetrically deteriorated in the periphery of the image because an aberration of an image pickup optical system is large. This means that an amount of the image deterioration which is to be corrected varies depending on a position or a region in the image, and accordingly it is necessary to perform appropriate processing on each region. In addition, assuming an environment in which there are a number of combinations of the image pickup optical system and the image pickup element as in the case of the lens-interchangeable camera, a satisfactory result cannot be obtained only by applying expression (2).

In each of the following embodiments, a configuration and a method of satisfactorily restoring the deterioration of an image for arbitrary combinations of the optical system and the image pickup element will be described.

**EMBODIMENT 1**

First of all, referring to FIG. 1, an image processing method in Embodiment 1 of the present invention will be described. FIG. 1 is a flowchart of the image processing method in this embodiment. Each step in FIG. 1 is performed by each unit of an image processing apparatus.

First, at step S101, the image processing apparatus of this embodiment acquires an image (captured image) on which image restoration processing is to be performed. Subsequently, at step S102, the image processing apparatus acquires image capturing condition (image capturing condition information) to start the image restoration processing on the image acquired at step S101. In this embodiment, the image processing apparatus acquires the image capturing condition from information such as an Exif (Exchangeable image file format) added to the image acquired at step S101, or it directly acquires the image capturing condition. In this embodiment, the image capturing condition contains, as the image capturing condition of the optical system (image pickup optical system), a lens identification number (lens ID) to specify a lens used for capturing the image, a focal length at the time of capturing the image, an F number, and an object distance. The image processing apparatus can specify the optical transfer function of the optical system based on the image capturing condition which is a combination of the lens ID, the focal length, the F number, and the object distance.
[0028] As the image capturing condition, information indicating a situation at the time of capturing the image, such as information relating to an array of color filters and information relating to an optical low-pass filter, may be contained. The optical transfer function of the optical system is data discretized with a sampling pitch where a folding signal does not occur. It is preferred that the optical transfer function is for example calculated by simulation on a computer based on design data of a lens (optical system), or alternatively it may be measured by using an image pickup element having a small pixel pitch. It is preferred that the pixel pitch in this case is a pixel pitch where the folding signal does not occur as described above. When generating the optical transfer function of the optical system by using the computer simulation, it is preferred that the optical transfer function calculated, for each wavelength, by using a spectral characteristic of an assumed light source and a spectral characteristic of the color filter of the image pickup element is generated according to each of colors R, G, and B.

[0029] The number of the optical transfer functions of the optical system corresponds to the number of the combinations of the position on the image pickup element and mainly the spectral characteristic of the color filters of R, G, and B when the focal length, the F number, and the object distance are determined as described above. In other words, the plurality of optical transfer functions are necessary for each image capturing condition. For example, the number of the combinations of one-hundred (100) representative points on the image pickup element and the color filters of the three colors R, G, and B is 300. Accordingly, specifying the optical transfer functions of the optical system described above means specifying the 300 points.

[0030] Subsequently, at step S103, the image processing apparatus acquires the optical transfer function of the optical system based on the image capturing condition acquired at step S102. In this case, it is preferred that an acquisition range of the optical transfer function varies depending on a size of the image pickup element which is to be used. The acquisition range of the optical transfer function is for example determined based on a ratio of a range determined depending on the optical system and a range in which the image pickup element can acquire an optical image. The range determined depending on the optical system is for example a range in which an aberration correction is performed at the time of designing the optical system.

[0031] Subsequently, at step S104, the image processing apparatus revises (i.e., corrects) the optical transfer function acquired at step S103. The acquired optical transfer function of the optical system as it is cannot be applied to the image restoration processing. The image processing apparatus of this embodiment revises the optical transfer function of the optical system, with respect to various image pickup elements, depending on characteristics (frequency characteristics) of a band of each image pickup element and a shape of the pixel. In order to revise the optical transfer function of the optical system
depending on the characteristics of the image pickup element, the following characteristics are considered.

[0032] First, as the characteristics of the image pickup element, there are information relating to a size of the image pickup element, a pixel pitch, an array of color filters, and the like. The size of the image pickup element is information which specifies an image circle to cut out an optical aerial image. The pixel pitch is information relating to a folding signal of the optical transfer function. In addition to the information described above, a characteristic of an optical low-pass filter may be considered. The characteristic of the optical low-pass filter is information relating to the presence or absence of the optical low-pass filter and information relating to a characteristic affected by the optical transfer function according to the optical low-pass filter. For example, the information contains information relating to a separation width, a separation direction, a separation method, and the like of the point spread function by the optical low-pass filter. When a single plate sensor is used, array information of the R, G, and B pixels can be used as information on the folding signal for a sampling interval of the Bayer array. When the image pickup element has the Bayer array, the sampling pitch of each of the R, G, and B pixels may be different from each other and the image pickup element may have a special arrangement. Accordingly, the information can be considered as well. The information can be acquired as the image capturing condition (image capturing condition information) at step S102.

[0033] The optical transfer function revised depending on the characteristics of the image pickup element at step S104 is represented by a model as the following expression (3).

\[
H_s(u, v) = \mathbf{H}(u, v) \cdot \text{OLPF}(u, v) \cdot \text{PIX}(u, v)\]

\[\text{S} \quad \text{... (3)}\]

[0034] In expression (3), symbol \(H_s(u,v)\) is an optical transfer function revised depending on the characteristics of the image pickup element. Symbol \(H(u,v)\) is an optical transfer function of the optical system, symbol \(\text{OLPF}(u,v)\) is a frequency characteristic of the optical low-pass filter, and symbol \(\text{PIX}(u,v)\) is a frequency characteristic depending on a pixel shape of the image pickup element. Symbol \(\text{S}\) denotes acquisition of the frequency characteristic within a band of the image pickup element.

[0035] Subsequently, at step S105, the image processing apparatus performs a frequency conversion on each of the plurality of optical transfer functions revised at step S104 to convert them into data on a real space, and thus it generates point spread functions (PSFs) containing the characteristic of the image pickup element. Then, at step S106, the image processing apparatus determines the number of repetition times (the number of repetition times of calculation) in the image restoration processing based on the PSF generated at step S105. The number of repetition times of calculation is determined for
each position or each region in the image. In this case, the image processing apparatus divides the image into a plurality of regions for example based on a pixel position of the image pickup element.

Subsequently, at step S107, the image processing apparatus performs the image restoration processing by using the PSF generated at step S105 and expression (2), and then it performs development processing on the restored image. With respect to expression (2), a deformation including various regularizations can be also adopted. It is preferred that the image processing method of this embodiment is provided as a program which operates by software or on a hard ware.

**EMBODIMENT 2**

Next, referring to FIGs. 2A, 2B, 3A, and 3B, Embodiment 2 of this embodiment will be described. FIGs. 2A and 2B are explanatory diagrams of an image processing method which corrects a shift-variant deterioration characteristic, and they illustrate an example of image restoration processing using a PSF which varies depending on the characteristic of the image pickup element.

This embodiment will describe an image processing method in which a satisfactory result can be obtained in a case where a characteristic of the PSF significantly varies depending on a position in an image. When the PSF greatly changes depending on the position such as an image height in the image, ideally, the image processing is performed by using an appropriate (i.e., precise) PSF for each position in the image. However, storing data of the precise PSFs for all pixels of the image pickup element in a memory is not ideal. In this embodiment, with respect to each predetermined position in an image, an optical transfer function of the optical system corresponding to each position is revised (i.e., corrected) depending on the characteristic of the image pickup element. Then, the revised optical transfer function is converted into a PSF by frequency conversion to be used.

In this embodiment, as illustrated in FIG. 2A, the numbers of vertical and horizontal data of the R, G, and B of the image are denoted by V and H, respectively. When the R, G, and B are processed as the Bayer array, the numbers V and H may be different from each other. PSFs at M and N points are coordinated for the vertical and horizontal directions, respectively, and the respective intervals of the arrangement are defined as A and B, and a plurality of ((M-1)x(N-1)) rectangular regions are considered. It is preferred that A=V/(M-1) and B=H/(N-1) are satisfied for the purpose of calculation. In this case, by performing the integer division of i/A and j/B for each target pixel (i,j) to be processed, the rectangular region to which the PSF (target pixel) belongs among the plurality of rectangular regions can be calculated immediately without using processing such as conditional branching.

Accordingly, using m=i/A and n=j/B, four PSFs of PSF[m,n], PSF[m,n+1],
PSF[m+l,n], and PSF[m+l,n+l] are selected. In this embodiment, a rectangle region (vertical length A and horizontal length B) having grid point positions of the selected four PSFs as vertexes is represented by a region <m,n>.

FIG. 2B illustrates the region <m,n> in FIG. 2A. The number of repetition times of calculation (the number of repetition times) for the region <m,n> is calculated based on four PSF kernels of the PSF[m,n], PSF[m,n+1], PSF[m+1,n], and PSF[m+1,n+1] corresponding to the grid point positions. X and Y coordinates in the PSF kernels are as illustrated in FIG. 2B.

In this embodiment, as an example, a method of calculating the number of repetition times based on a maximum value of the four PSF kernels will be described. First, the four PSF kernels corresponding to the grid point positions as illustrated in FIG. 2B are acquired. Then, the maximum value of the four PSF kernels are obtained and d<m,n> defined as represented by the following expression (4) is acquired.

[Math.3]

d < m , n > = 0.25 \cdot \max_{X,Y} [PSF[m, n](x, y)] + 0.25 \cdot \max_{X,Y} [PSF[m, n + 1](x, y)] + 0.25 \cdot \max_{X,Y} [PSF[m + 1, n](x, y)] + 0.25 \cdot \max_{X,Y} [PSF[m + 1, n + 1](x, y)] \quad (4)

In expression (4), symbol max_{X,Y} denotes a maximum value in an XY space.

Subsequently, using d<m,n> defined by expression (4), the number of repetition times IterNum<m,n> for the region <m,n> is determined as represented by the following expression (5).

[Math.4]

IterNum < m , n > = \text{round} \left[ V \cdot \left[ 1 - \exp\left[ - \frac{1}{d < m , n >} \right] \right] + 1 \right] \quad (5)

In expression (5), symbol round[] denotes a round-off function to an integer, that is, a function of rounding off a value in [] to the nearest integer. Symbol V denotes a parameter to determine the reference number of repetition times, and for example it is input by a user. As described above, in this embodiment, the user determines a single parameter V (the reference number of repetition times) and accordingly the number of repetition times of calculation for each region (the number of repetition times IterNum<m,n>) is automatically set.

FIGs. 3A and 3B are explanatory diagrams of the number of repetition times of calculation. FIGs. 3A and 3B illustrate characteristics of the number of repetition times IterNum<m,n> for d<m,n> where V=5 and V=10 are satisfied, respectively. The number of repetition times IterNum<m,n> for d<m,n> is gently changed, and a
difference of the number of repetition times does not substantially occur for adjacent regions with respect to \(d_{m,n}\). Accordingly, each of the insufficient restoration, the excessive restoration, and the generation of unnatural harmful effects on the restored image is avoided.

[0047] By using the number of repetition times \(\text{IterNum}_{m,n}\) for each region set by this method, the image restoration processing is performed on a target pixel \((i,j)\) in the region \(<m,n>\) illustrated in FIG. 2A. \(\text{PSFs}_y\) corresponding to the target pixel \((i,j)\) are four PSFs of \(\text{PSF}[m,n]\), \(\text{PSF}[m,n+1]\), \(\text{PSF}[m+1,n]\), and \(\text{PSF}[m+1,n+1]\), and they can be calculated as follows.

[0048] In this embodiment, a weight \(W\) (weight coefficient) for each PSF is determined as follows.

\[
W(m,n) = \frac{(A-a)(B-b)}{(A*B)} \\
W(m,n+1) = \frac{(A-a)b}{(A*B)} \\
W(m+1,n) = \frac{a(B-b)}{(A*B)} \\
W(m+1,n+1) = \frac{ab}{(A*B)}
\]

[0049] In the above expressions, \(a=\text{mod}(i,A)\) and \(b=\text{mod}(j,B)\) are satisfied. Symbol \(\text{mod}(x,y)\) denotes a residue of \(x\) by \(y\). As described above, the following expression (6) is obtained.

\[
\text{Math.5} \\
\text{PSF}_{1,1}(x, y) = W(m, n) \cdot \text{PSF}_{jm, n}(x, y) + W(m, n + 1) \cdot \text{PSF}_{jm, n+1}(x, y) + W(m + 1, n) \cdot \text{PSF}_{jm+1, n}(x, y) + W(m + 1, n + 1) \cdot \text{PSF}_{jm+1, n+1}(x, y) \quad \cdots (6)
\]

[0050] Accordingly, in this embodiment, expression (2) is used as represented by the following expression (7) based on expression (6).

\[
\text{Math.6} \\
f_n(x, y) \leftarrow f_{n-1}(x, y) \sum_x \sum_y \sum_s \sum_t \text{PSF}_{1,1}(X - x, Y - y)g(x, y) \text{PSF}_{1,1}(X - s, Y - t)f_{n-1}(s, t) \quad \cdots (7)
\]

[0051] The processing by expression (7) is performed for each of \(R, G,\) and \(B\) of the image and the repeating calculation (repetition processing) is performed by the number of repetition times \(\text{IterNum}_{m,n}\) for each region \(<m,n>\) to obtain a final image.

[0052] When the numbers of repetition times \(\text{IterNum}_{m,n}\) for adjacent regions \(<m,n>\) are significantly different from each other, there is a possibility that a block noise or the like occurs at the boundary of the adjacent regions. Accordingly, limiting the
difference of the numbers of repetition times IterNum<sub>m,n</sub> between the adjacent regions in advance is effective. A dispersion value of the PSF may be calculated and considered. In this embodiment, it is preferred that processing to match centroid positions of respective PSFs each other is performed in advance in order to perform the calculation of expression (6) with high accuracy by using small M and N. Maximum values can be matched each other, in addition to the centroid positions, and the PSFs can be corrected so that an evaluation value for evaluating both of them is satisfied. It is preferred that the image processing apparatus decreases the number of repetition times with increasing the maximum value of the point spread function (PSF).

**EMBODIMENT 3**

[0053] Next, referring to FIG. 4, an image processing system (image processing apparatus) in Embodiment 3 of the present invention will be described. FIG. 4 is a configuration diagram of an image processing system 400 in this embodiment. The image processing system 400 includes an image processing apparatus 401 (hardware as an information processing apparatus), a display device 402 (monitor), and an input device 403 (input unit such as a keyboard). This embodiment will describe a case in which the image processing method of Embodiment 1 or 2 operates on the image processing system 400 (software in a personal computer).

[0054] First, in order to cause the image processing apparatus 401 to operate the image processing method of Embodiment 1 or 2, the software (image processing program) which executes the image processing method is installed in the image processing apparatus 401 (personal computer). The software can be installed from a medium 404 (storage medium) such as a CD-ROM or a DVD-ROM. Alternatively, the software may be installed through download via a network (internet). The image processing apparatus 401 stores a plurality of optical transfer functions (optical transfer function data) of the optical system (image pickup optical system). The plurality of optical transfer functions stored in the image processing apparatus 401 are for example all the optical transfer functions for each of various image capturing conditions (image capturing condition information) of the optical system. The optical transfer functions are also downloaded via the medium 404 or the network to be stored in the image processing apparatus 401. In this embodiment, software (image processing program), and data such as optical transfer function information and image capturing condition information are stored in a storage such as a hard disk and a memory in the image processing apparatus 401. The image processing apparatus 401 can be configured to acquire at least part of data from an external server via the network.

[0055] The image processing apparatus 401 runs the installed software to perform the image restoration processing on the captured image. On the software, various settings (settings of parameters), such as the number of repetition times for determining the
intensity of the image restoration processing and the application of the image restoration processing only in a predetermined region (region where the image restoration processing is to be performed) of an image, are possible. It is preferred that a user can change these parameters while confirming the restored image on the display device 402.

EMBODIMENT 4

[0056] Next, referring to FIG. 5, an image processing apparatus in Embodiment 4 of the present invention will be described. FIG. 5 is a block diagram of an image processing apparatus 500 in this embodiment. The image processing apparatus 500 includes a captured image acquirer 501, an image capturing condition acquirer 502, an optical transfer function memory 503, an optical transfer function acquirer 504, an optical transfer function reviser 505, a frequency converter 506, a number of repetition times setter 507, and an image restorer 508.

[0057] The captured image acquirer 501 (image acquisition unit) acquires an image (captured image) to which information relating to an image capturing condition (image capturing condition information) is added (step S101 in FIG. 1). The image capturing condition acquirer 502 (condition acquisition unit) acquires, as the image capturing condition, information relating an optical system (image pickup optical system) and information relating to an image pickup element (step S102 in FIG. 1). The information relating to the optical system contains information relating to a focal length, an F number, an object distance, or the like, but it is not limited thereto, and it may contain information relating to a diameter of an image circle of the optical system. The diameter of the image circle of the optical system is a radius or a diameter of a unit circle which is predetermined for correcting aberrations at the time of designing the optical system. The information relating to the image pickup element is information relating to a size of the image pickup element (image height), a pixel pitch of the image pickup element, a shape or a size of a pixel, or the like. In this embodiment, various elements (optical members) such as an optical low-pass filter may be provided in the image pickup element. In this case, information relating to characteristics of the various elements can be contained in the information relating to the image pickup element.

[0058] The optical transfer function memory 503 (memory) previously stores an optical transfer function (optical transfer function data) of the optical system. The optical transfer function acquirer 504 (function acquisition unit) acquires a plurality of optical transfer functions from the optical transfer function data stored in the optical transfer function memory 503 based on the information relating to the optical system acquired by the image capturing condition acquirer 502 (step S103 in FIG. 1). The optical transfer function reviser 505 (function revision unit) revises (i.e., corrects), based on
the information relating to the image pickup element, the plurality of optical transfer functions acquired based on the information relating to the optical system (step S104 in FIG. 1). This revision contains providing a characteristic of the optical low-pass filter or the pixel, or processing of conversion into an optical transfer function up to a frequency band according to the pixel pitch of the image pickup element.

[0059] The frequency converter 506 (PSF acquisition unit) performs the inverse Fourier transform of all the optical transfer functions revised by the optical transfer function reviser 505, and it generates a point spread function (PSF) depending on characteristics of the optical system and the image pickup element (step S105 in FIG. 1). The number of repetition times setter 507 (number setting unit) sets the number of repetition times for each region corresponding to the point spread function based on the point spread function generated by the frequency converter 506 (step S106 in FIG. 1). In other words, the number of repetition times setter 507 sets the number of repetition times for each of a plurality of regions in an image based on the point spread function (degree of blur) corresponding to each of the regions.

[0060] The image restorer 508 (image restoration unit) performs image restoration processing by using the image acquired by the captured image acquirer 501 and the point spread function generated by the frequency converter 506, based on the number of repetition times for each region corresponding to the point spread function (step S107 in FIG. 1). In other words, the image restorer 508 performs repetition processing by the number of repetition times on each of the plurality of regions by using the point spread function to perform the restoration processing on the image.

[0061] The captured image acquirer 501 acquires the image (captured image), and the image capturing condition information may not be added to the captured image in some cases. Accordingly, in this embodiment, the image processing apparatus 500 can be configured such that the captured image and the image capturing condition are acquired separately. In this case, the image capturing condition acquirer 502 can acquire the image capturing condition information separately from the captured image (for example, via an image pickup optical system controller 606 or a state detector 607 of an image pickup apparatus 600 illustrated in FIG. 6).

**EMBODIMENT 5**

[0062] Next, referring to FIG. 6, an image pickup apparatus in Embodiment 5 of the present invention will be described. FIG. 6 is a block diagram of an image pickup apparatus 600 in this embodiment. The image pickup apparatus 600 includes an image processor 604 (image processing apparatus) capable of performing the image processing method of each embodiment described above.

[0063] In the image pickup apparatus 600, an object (not illustrated) is imaged on an image pickup element 602 via an image pickup optical system 601 (optical system) including
an aperture stop 601a (or light shielding member) and a focus lens 601b. In this embodiment, the image pickup optical system 601 is an interchangeable lens (lens apparatus) removably mounted on an image pickup apparatus body including the image pickup element 602. This embodiment, however, is not limited to this, and can be applied also to an image pickup apparatus including an image pickup apparatus body and an image pickup optical system 601 integrated with each other.

[0064] An aperture value (F number) is determined by the aperture stop 601a or the light shielding member. The image pickup element 602 photoelectrically converts an object image (optical image) formed via the image pickup optical system 601 to output an image signal (captured image data). An electric signal output from the image pickup element 602 is output to an A/D converter 603. The A/D converter 603 converts the electric signal (analog signal) input from the image pickup element 602 to a digital signal (captured image) and then outputs the digital signal to the image processor 604. The image pickup element 602 and the A/D converter 603 constitute an image pickup unit configured to photoelectrically convert the optical image (object image) formed via the image pickup optical system 601 to output the captured image.

[0065] The image processor 604 performs predetermined image processing on the digital signal output from the A/D converter 603, i.e., image generated based on the image signal output from the image pickup element 602, by using information of a state detector 607 and a memory 608. Especially, the image processor 604 of this embodiment performs image restoration processing on the captured image to output a corrected image (restored image). The image processor 604 includes units having the same functions as the captured image acquirer 501, the image capturing condition acquirer 502, the optical transfer function memory 503, the optical transfer function acquirer 504, the optical transfer function reviser 505, the frequency converter 506, the number of repetition times setter 507, and the image restorer 508.

[0066] The memory 608 (storage unit) stores an optical transfer function (optical transfer function data) of the image pickup optical system 601 for each image capturing condition (image capturing condition information), i.e., for each of combinations of a focal length at the time of capturing an image, an F number, a photographing distance, and an image height. The memory 608 has the same function as the optical transfer function memory 503 illustrated in FIG. 5. The image capturing condition is for example acquired by the image pickup optical controller 606 or the state detector 607. In this embodiment, the image processor 604 and the memory 608 constitute the image processing apparatus. In this embodiment, the optical transfer function memory can be included in the image processor 604, instead of the memory 608 provided outside the image processor 604.

[0067] The image processor 604 acquires the optical transfer function of the optical system
corresponding to the acquired image capturing condition, and it revises the optical
transfer function of the optical system by using the information relating to the image
pickup element. Then, the image processor 604 (frequency converter) performs the
Fourier transform on the revised optical transfer function, and it generates the point
spread function depending on characteristics of the image pickup optical system and
the image pickup element. The image processor 604 (number of repetition times setter)
sets the number of repetition times for each region corresponding to the point spread
function based on the generated point spread function. Then, the image processor 604
(image restorer) reads image data from the memory 608, and it performs the repetition
processing by the number of repetition times set for each region by using the point
spread function depending on the characteristics of the optical system and the image
pickup element to perform the image restoration processing. In the image restoration
processing, various settings (settings of parameters), such as application of the image
restoration processing only in a predetermined region (region where the image
restoration processing is to be performed) of an image, are possible. It is preferred that
a user can change these parameters while confirming the restored image on the display
605.

The output image (restored image) processed by the image processor 604 is recorded
in an image recording medium 609 in a predetermined format. A display 605 displays
an image obtained by performing predetermined processing for display on the
processed image in this embodiment. Alternatively, the display 605 may display a
simply-processed image for high-speed display. The display 605 also displays a GUI to
select an image restoration mode or a normal image capturing mode by a user. When
the image restoration mode is selected by the user via the GUI on the display 605, a
system controller 610 controls the image processor 604 to perform the image
processing method of Embodiment 1 or 2.

The system controller 610 includes a CPU, an MPU, or the like, and it controls a
whole of the image pickup apparatus 600. More specifically, the system controller 610
controls each of the image processor 604, the display 605, the image pickup optical
system controller 606, the state detector 607, and the image recording medium 609.
The image pickup optical system controller 606 controls the motion of the image
pickup optical system 601. The state detector 607 detects a state of the image pickup
optical system 601 based on information of the image pickup optical system controller
606. In the image pickup apparatus 600, software (an image processing program) that
realizes the image processing method described above can be supplied to the system
controller 610 via a network or a storage medium, and then the system controller 610
can read out and execute the image processing program.

As described above, an image processing apparatus includes an image acquisition
unit (captured image acquirer 501), a condition acquisition unit (image capturing condition acquirer 502), a PSF acquisition unit (frequency converter 506), and a number setting unit (number of repetition times setter 507), and an image restoration unit (image restorer 508). The image acquisition unit acquires an image (captured image). The condition acquisition unit acquires image capturing condition information of the image. The PSF acquisition unit acquires point spread functions relating to an optical system. The number setting unit sets the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions. The image restoration unit performs repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image. The PSF acquisition unit acquires the point spread functions based on the image capturing condition information.

[0071] Preferably, the PSF acquisition unit acquires the point spread functions which vary depending on a pixel position of an image pickup element 602. Preferably, the PSF acquisition unit divides the image into the plurality of regions based on the pixel position of the image pickup element.

[0072] Preferably, the image restoration unit specifies a plurality of point spread functions corresponding to a target pixel of the image pickup element from among the point spread functions acquired by the PSF acquisition unit, and performs the restoration processing on the image for each target pixel. More preferably, the image restoration unit determines weight information (weight coefficient) to be applied to the plurality of point spread functions corresponding to the target pixel, and performs the restoration processing on the image for each target pixel based on the weight information.

[0073] Preferably, the image processing apparatus includes a function acquisition unit (optical transfer function acquirer 504) which acquires optical transfer functions relating to the optical system and a function revision unit (optical transfer function reviser 505) which revises the optical transfer functions based on information relating to the image pickup element. The PSF acquisition unit generates the point spread functions from the optical transfer functions revised by the function revision unit.

[0074] Preferably, the number setting unit sets the number of repetition times based on a maximum value of the point spread function. More preferably, the number setting unit decreases the number of repetition times with increasing the maximum value of the point spread function. Preferably, the number setting unit correlates the plurality of point spread functions with each of the regions to set the number of repetition times for each of the regions based on the plurality of point spread functions.

[0075] Preferably, the image restoration unit generates a first updated image by using the image and the point spread functions. Then, the image restoration unit repeatedly
performs processing of generating an (N+1)th updated image by using the image, an Nth updated image, and the point spread functions (N is a natural number). For example, the restoration processing on the image is performed by the LR method.

According to the present invention, an image processing apparatus, an image pickup apparatus, an image processing method, and an image processing program, and a storage medium which are capable of satisfactorily restoring a deterioration of an image depending on a position in the image can be provided.

OTHER EMBODIMENTS

Embodiment(s) of the present invention can also be realized by a computer of a system or apparatus that reads out and executes computer executable instructions (e.g., one or more programs) recorded on a storage medium (which may also be referred to more fully as a 'non-transitory computer-readable storage medium') to perform the functions of one or more of the above-described embodiment(s) and/or that includes one or more circuits (e.g., application specific integrated circuit (ASIC)) for performing the functions of one or more of the above-described embodiment(s), and by a method performed by the computer of the system or apparatus by, for example, reading out and executing the computer executable instructions from the storage medium to perform the functions of one or more of the above-described embodiment(s). The computer may comprise one or more processors (e.g., central processing unit (CPU), micro processing unit (MPU)) and may include a network of separate computers or separate processors to read out and execute the computer executable instructions. The computer executable instructions may be provided to the computer, for example, from a network or the storage medium. The storage medium may include, for example, one or more of a hard disk, a random-access memory (RAM), a read only memory (ROM), a storage of distributed computing systems, an optical disk (such as a compact disc (CD), digital versatile disc (DVD), or Blu-ray Disc (BD™), a flash memory device, a memory card, and the like.

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

Reference Sings List

500 IMAGE PROCESSING APPARATUS
507 NUMBER OF REPETITION TIMES SETTER (NUMBER SETTING UNIT)
508 IMAGE RESTORER (IMAGE RESTORATION UNIT)
Claims

[Claim 1] An image processing apparatus comprising:
   an image acquisition unit configured to acquire an image;
   a condition acquisition unit configured to acquire image capturing condition information of the image;
   a PSF acquisition unit configured to acquire point spread functions relating to an optical system;
   a number setting unit configured to set the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions; and
   an image restoration unit configured to perform repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image,
   wherein the PSF acquisition unit is configured to acquire the point spread functions based on the image capturing condition information.

[Claim 2] The image processing apparatus according to claim 1, wherein the PSF acquisition unit is configured to acquire the point spread functions which vary depending on a pixel position of an image pickup element.

[Claim 3] The image processing apparatus according to claim 1 or 2, wherein the PSF acquisition unit is configured to divide the image into the plurality of regions based on a pixel position of an image pickup element.

[Claim 4] The image processing apparatus according to any one of claims 1 to 3, wherein the image restoration unit is configured to:
   specify a plurality of point spread functions corresponding to a target pixel of an image pickup element from among the point spread functions acquired by the PSF acquisition unit, and
   perform the restoration processing on the image for each target pixel.

[Claim 5] The image processing apparatus according to claim 4, wherein the image restoration unit is configured to:
   determine weight information to be applied to the plurality of point spread functions corresponding to the target pixel, and
   perform the restoration processing on the image for each target pixel based on the weight information.

[Claim 6] The image processing apparatus according to any one of claims 1 to 5, further comprising:
a function acquisition unit configured to acquire optical transfer functions relating to the optical system; and
a function revision unit configured to revise the optical transfer functions based on information relating to an image pickup element, wherein the PSF acquisition unit is configured to generate the point spread functions from the optical transfer functions revised by the function revision unit.

[Claim 7] The image processing apparatus according to any one of claims 1 to 6, wherein the number setting unit is configured to set the number of repetition times based on a maximum value of the point spread function.

[Claim 8] The image processing apparatus according to claim 7, wherein the number setting unit is configured to decrease the number of repetition times with increasing the maximum value of the point spread function.

[Claim 9] The image processing apparatus according to any one of claims 1 to 8, wherein the number setting unit is configured to correlate the plurality of point spread functions with each of the regions to set the number of repetition times for each of the regions based on the plurality of point spread functions.

[Claim 10] The image processing apparatus according to any one of claims 1 to 9, wherein the image restoration unit is configured to:
generate a first updated image by using the image and the point spread functions, and
performs repeatedly processing of generating an (N+1)th updated image by using the image, an Nth updated image, and the point spread functions (N is a natural number).

[Claim 11] An image pickup apparatus comprising:
an image pickup element configured to photoelectrically convert an optical image formed via an optical system to output an image signal;
an image acquisition unit configured to acquire an image generated based on the image signal;
a condition acquisition unit configured to acquire image capturing condition information of the image;
a PSF acquisition unit configured to acquire point spread functions relating to the optical system;
a number setting unit configured to set the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions;
and

an image restoration unit configured to perform repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, wherein the PSF acquisition unit is configured to acquire the point spread functions based on the image capturing condition information.

[Claim 12] An image processing method comprising the steps of:
acquiring an image;
acquiring image capturing condition information of the image;
acquiring point spread functions relating to an optical system;
setting the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions; and
performing repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, wherein in the step of acquiring the point spread functions, the point spread functions are acquired based on the image capturing condition information.

[Claim 13] An image processing program causing a computer to execute a process comprising the steps of:
acquiring an image;
acquiring image capturing condition information of the image;
acquiring point spread functions relating to an optical system;
setting the number of repetition times for each of a plurality of regions in the image based on each of the point spread functions corresponding to one of the plurality of regions; and
performing repetition processing by the number of repetition times by using each of the point spread functions respectively on one of the plurality of regions to perform restoration processing on the image, wherein in the step of acquiring the point spread functions, the point spread functions are acquired based on the image capturing condition information.

[Claim 14] A storage medium storing the image processing program according to claim 13.
ACQUIRE CAPTURED IMAGE

ACQUIRE IMAGE CAPTURING CONDITION

ACQUIRE OPTICAL TRANSFER FUNCTION

REVISE OPTICAL TRANSFER FUNCTION

GENERATE POINT SPREAD FUNCTION

DETERMINE NUMBER OF REPLICATION TIMES

IMAGE RESTORATION AND DEVELOPMENT PROCESSING
500

CAPTURED IMAGE ACQUIRER 501
IMAGE CAPTURING CONDITION ACQUIRER 502
OPTICAL TRANSFER FUNCTION MEMORY 503
OPTICAL TRANSFER FUNCTION ACQUIRER 504
OPTICAL TRANSFER FUNCTION REVISER 505
FREQUENCY CONVERTER 506
NUMBER OF REPETITION TIMES SETTER 507
IMAGE RESTORER 508
**INTERNATIONAL SEARCH REPORT**

**International application No.**
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**A. CLASSIFICATION OF SUBJECT MATTER**

- **Int.Cl.** G06T 5/00 (2006.01) & H04N 5/232 (2006.01)

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**According to International Patent Classification (IPC) or to both national classification and IPC**

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**B. FIELDS SEARCHED**

- **Int.Cl.** G06T 5/00, H04N 5/232

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**Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched**

- Published examined utility model applications of Japan 1992-1996
- Published unexamined utility model applications of Japan 1971-2014
- Registered utility model specifications of Japan 1996-2016
- Published registered utility model applications of Japan 1994-2016

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**Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)**

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**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>JP 2009-267523 A (NIKON CORPORATION) 2009.11.12, [0067] - [0096], [0108] - [0113], Fig. 3 (No Family)</td>
<td>1-14</td>
</tr>
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</table>

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* Further documents are listed in the continuation of Box C.

See patent family annex.

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**Date of the actual completion of the international search**

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**Date of mailing of the international search report**

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