SINGLE-LENS EXTENDED DEPTH-OF-FIELD IMAGING SYSTEMS

CLAIM OF PRIORITY

[0001] This application claims the benefit of priority of PCT Patent Application Serial Number PCT/IB2008/001304, filed on February 29, 2008, and which is incorporated by reference herein, and European Patent Application Serial No. EP08305927, filed on December 12, 2008, and which is incorporated by reference herein.

BACKGROUND ART

Field of the Invention

[0002] The present invention relates generally to extended depth-of-field imaging systems, and particularly relates to such a system that utilizes a single lens element in the imaging optical system.

Technical Background

[0003] Extended depth-of-field ("EDOF") imaging systems (also referred to as "extended depth-of-focus" imaging systems) have seen increased use in various applications such as biometrics (e.g., iris recognition), bar-code scanners and closed-circuit television (CCTV) systems.

[0004] The optical systems of EDOF imaging systems typically include either more than one lens element or include a non-circularly symmetric "wavefront coding" plate arranged in the entrance pupil to impart a complex wavefront shape.

[0005] Since EDOF imaging systems are desirable for use in an increasingly greater number of imaging applications that call for small form factors (e.g., cell phones and other hand-held image-capturing devices), there is a need for EDOF imaging systems that are extremely simple and compact but that can still provide EDOF imaging capability.

SUMMARY OF THE INVENTION

[0006] The present invention is directed to an extended depth-of-focus (EDOF) imaging system that has an optical system consisting of only one lens element and an aperture stop located objectwise of the lens element. The lens element is configured so that the optical system has substantially constant spherical aberration over the entire image field while having substantially no coma or astigmatism, and perhaps some chromatic aberration, depending on the spectral bandwidth used to form the image. The

single-lens configuration makes for a very compact and simple EDOF imaging system useful for a wide range of imaging applications.

[0007] Accordingly, a first aspect of the invention is an imaging system for imaging an object within an EDOF and at an imaging wavelength λ. The system includes an optical system having an optical axis and consisting of a single lens element and an aperture stop arranged objectwise of the single lens element. The optical system has an amount of spherical aberration SA wherein $0.2\lambda \leq SA \leq 2\lambda$ when forming an image of the object. The imaging system also includes an image sensor arranged to receive the image and form therefrom a digitized electronic raw image.

[0008] A second aspect of the invention is the above-described imaging system that further includes an image processor electrically connected to the image sensor and adapted to receive and process the digitized electronic raw image using digital filtering to form a digitized contrast-enhanced image.

[0009] A third aspect of the invention is a method of forming an image of an object over an EDOF and at an imaging wavelength λ. The method includes forming a raw image of an object with an optical system that consists of a single lens element and an aperture stop arranged objectwise of the single lens element. The optical system has an amount of spherical aberration SA such that $0.2\lambda \leq SA \leq 2\lambda$. The method further includes using an image sensor to electronically capturing the raw image to form a digitized raw image. In one example embodiment, this digitized raw image is used directly for the given application. In another example embodiment, the method further includes digitally filtering the digitized raw image to form a contrast-enhanced image.

[0010] A fourth aspect of the invention is an EDOF imaging system for forming a contrast-enhanced image of an object at an imaging wavelength λ. The imaging system includes an optical system consisting of a single lens element and an objectwise aperture stop, wherein the optical system has an amount of spherical aberration SA wherein $0.5\lambda \leq SA \leq 2\lambda$, and wherein the optical system forms a raw image. The system further includes an image sensor arranged to receive the raw image and form a raw image electrical signal, wherein the raw image has an associated raw modulation transfer function (MTF). The imaging system also includes an image processor electrically connected to the image sensor. The image processor is adapted to receive the raw image electrical signal and perform image processing thereon to form the contrast-enhanced

image using an enhanced MTF formed from the raw MTF using a rotationally symmetric gain function.

[0011] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention and together with the description serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] **FIG. 1** is a schematic diagram of an example embodiment of a single-lens EDOF imaging system according to the present invention;

[0013] **FIG. 2** is a schematic diagram of an example hand-held device that includes the EDOF imaging system of **FIG. 1**, and illustrates an example controller;

[0014] **FIG. 3** is a plot of the measured (raw) MTF for various defocus positions for an example single-lens EDOF imaging system of **FIG. 1**;

[0015] **FIG. 4A** plots through focus the typical gain in the output MTF' as compared to the raw MTF for various defocus positions D0 through D10;

[0016] **FIG. 4B** plots through focus the typical gain in the output MTF' as compared to the raw MTF as obtained using a constant gain function process for various defocus positions when the object distance is unknown;

[0017] **FIG. 5A** plots the typical output (enhanced) MTF' for the different focus positions D0 through D10 based on the MTF gain of **FIG. 4A**;

[0018] **FIG. 5B** plots the typical output (enhanced) MTF' for the different focus positions **D0** through **D10** based on the MTF gain of **FIG. 4B**;

[0019] **FIG. 6** is a plot of the intensity I versus position for the image of an edge, showing the overshoot Δos caused by ringing in the image;

[0020] **FIG. 7** plots the raw MTF and the output (enhanced) MTF at best focus to illustrate the recovery of image resolution (contrast) via image processing;

[0021] **FIG. 8A** is a plot of the diffraction-limited modulation transfer function (MTF) for an ideal imaging system for varying amounts of defocus as indicated by curves a through g;

[0022] **FIG. 8B** is a gray-scale plot of the MTF distribution through focus (horizontal axis) for an idealized imaging optical system, with the dashed ellipse indicating an approximate depth of focus and the vertical axis indicating spatial frequency;

[0023] **FIG. 9A** is a plot of the modulation transfer function (MTF) for varying amounts of defocus for an imaging optical system having an amount of spherical aberration SA = 0.75λ, along with the zero-focus diffraction limited MTF for comparison, as indicated by curves a through h;

[0024] **FIG. 9B** is the same type of gray-scale through-focus MTF plot as **FIG. 8B**, but for the MTF of **FIG. 9A**, illustrating how the depth of focus (dashed line) is axially extended as compared to the diffraction-limited case of **FIG. 8B** by virtue of the presence of spherical aberration;

[0025] **FIG. 9C** plots the through-focus MTF at 3 line-pairs per millimeter (lp/mm) in object space for NA = 0.0063 for the raw MTF, the enhanced MTF and the diffraction-limited MTF;

[0026] **FIGS. 10A-10D** are plots of the optical path difference (OPD) for various image heights (0 mm, 20 mm, 30 mm and 60 mm, respectively) for an optical system with SA = 0.7λ;

[0027] **FIG. 11** is a schematic diagram of an example embodiment of the single-lens optical system of the EDOF imaging system of **FIG. 1**, wherein the single lens is a plano-convex lens with an objectwise plano surface;

[0028] **FIG. 12** is a plot of coma (Z_8) versus aperture stop position (mm) relative to the single lens element for an example optical system with varying amounts of spherical aberration SA (including SA = 0), illustrating the formation of a zero-coma axial position when the optical system has spherical aberration;

[0029] **FIG. 13** is a schematic diagram of an example single lens element illustrating the radii of curvatures R1 and R2 of respective surfaces **S1** and **S2** and showing how the lens shape or "curvature" *C* changes as a function of R1 and R2;

[0030] **FIG. 14** plots the amount of spherical aberration SA (waves) versus the lens curvature *C* for a single lens element;

[0031] **FIG. 15** shows a series of lens elements and aperture stop positions illustrating the variation of F/# from F/4 to F/11 and the corresponding change in curvature *C* needed to maintain an amount of spherical aberration SA = 0.75λ for a single lens element made of borosilicate glass BK7 with a focal length f = 50 mm;

[0032] **FIG. 16** plots an example range of the F/# as a function of focal length f, wherein the maximum F# is twice the minimum F/#;

[0033] **FIG. 17** is a schematic diagram of a single lens element for the single-lens EDOF imaging system of **FIG. 1**, wherein the objectwise surface includes a diffractive feature;

[0034] **FIG. 18** is an example plot of the axial focal shift (μm) versus wavelength (μm) for an achromatized single lens element having a diffractive feature, where the achromatization is centered at λ = 590 nm;

[0035] **FIG. 19A** is a close-up view of a single lens elements showing the refractive chromatic deviation angle;

[0036] **FIG. 19B** is a close-up view of a portion of a single lens element having a diffractive feature and showing the diffractive chromatic deviation angle;

[0037] **FIG. 20** is a close-up view of an objectwise lens surface of a single lens element having a Fresnel-like diffractive feature designed to reduce chromatic aberration;

[0038] **FIG. 21A** is a ray-trace plot of a single lens element having an objectwise diffractive feature (not shown) and aspherical surfaces;

[0039] **FIG. 21B** is the plot of the thickness of optical material that forms the diffractive feature formed by the configuration of **FIG. 21C** and that corrects chromatic aberration by using the first diffraction order;

[0040] **FIG. 21C** shows virtual coherent source points **P1** and **P2** that produce Newton's fringe pattern and define the rings for the diffractive feature on the objectwise lens surface of the single lens element of **FIG. 21A**;

[0041] **FIG. 22A** is a schematic diagram of a single-lens imaging optical system and a corresponding plot of the field curvature; and

[0042] **FIG. 22B** is a schematic diagram of the single-lens imaging optical system that includes a field lens immediately adjacent the image sensor (not shown), and a corresponding plot of the field curvature showing a substantially flat field at the image sensor.

DETAILED DESCRIPTION OF THE INVENTION

[0043] Reference is now made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, like or similar reference numerals are used throughout the drawings to refer to like or similar parts. Various modifications and alterations may be made to the following examples within the scope of the present invention, and aspects of the different examples may be mixed in different ways to achieve yet further examples. Accordingly, the true scope of the invention is to be understood from the entirety of the present disclosure, in view of but not limited to the embodiments described herein.

[0044] The present invention is directed to single-lens EDOF imaging systems that cover a wide range of focal lengths. Potential applications include compact imaging systems such as mobile image capture devices (e.g., cell phone cameras), iris recognition systems, facial image capture for facial recognition systems, and CCTV systems.

[0045] The term "lens element" as used herein is defined as a single, rotationally symmetric optical component, and does not include so-called "phase plates" or "phase-encoding" elements that typically reside in the entrance pupil of an optical system and that are not rotationally symmetric.

[0046] The phrase "extended depth-of-field" as used herein means a depth-of-field that is larger than what is normally associated with the corresponding diffraction-limited optical system. The phrase "extended depth-of-focus" is similarly defined.

[0047] The phrase "contrast-enhanced image" means an image having improved contrast as compared to the contrast of an initial or "raw" image formed by the optical system.

[0048] Unless otherwise noted, the values of F/# and numerical aperture (NA) are for the image space.

[0049] A generalized single-lens EDOF optical imaging system is first discussed, followed by example embodiments of single-lens imaging optical systems for use in the generalized EDOF imaging system.

Generalized EDOF system

[0050] **FIG. 1** is a schematic diagram of a generalized embodiment of a generalized single-lens EDOF optical system ("system") **10** according to the present invention. System **10** includes an optical axis **A1** along which is arranged an imaging optical system **20** that consists of a single lens element **22** and an aperture stop **AS** located objectwise of the lens element. Aperture stop **AS** is "clear" or "open," meaning that it does not include any phase-altering elements, such as phase plates, phase-encoding optical elements or other types of phase-altering means.

[0051] Optical system **20** has a lateral magnification M_L, an axial magnification $M_A = (M_L)^2$, an object plane **OP** in an object space **OS** and an image plane **IP** in an image space **IS**. An object **OB** is shown in object plane **OP** and the corresponding image **IM** formed by optical system **20** is shown in image plane **IP**. Object **OB** is at an axial object distance $\mathbf{D_{OB}}$ from lens element **22**.

[0052] Optical system **20** has a depth of field **DOF** in object space **OS** over which the object can be imaged and remain in focus. Likewise, optical system **20** has a corresponding depth of focus **DOF'** in image space **IS** over which image **IM** of object **OB** remains in focus. Object and image planes **OS** and **IS** are thus idealizations of the respective positions of object **OB** and the corresponding image **IM** and typically correspond to an optimum object position and a "best focus" position, respectively. In actuality, these planes can actually fall anywhere within their respective depth of field **DOF** and depth of focus **DOF'**, and are typically curved rather than planar. The depth of field **DOF** and depth of focus **DOF'** are defined by the properties of optical system **20**, and their interrelationship and importance in system **10** is discussed more fully below.

[0053] System **10** also includes an image sensor **30** that has a photosensitive surface **32** (e.g., an array of charge-coupled devices) arranged at image plane **IP** so as receive and detect image **IM**, which is also referred to herein as an "initial" or a "raw" image. In an example embodiment, image sensor **30** is or otherwise includes a high-definition CCD camera or CMOS camera. In an example embodiment, photosensitive surface **32** is made up of 3000 x 2208 pixels, with a pixel size of 3.5 microns. The full-

well capacity is reduced to 21,000 electrons for a CMOS camera at this small pixel size, which translates into a minimum of shot noise of 43.2 dB at saturation level. An example image sensor **30** is or includes a camera from Pixelink PL-A781 having 3000 × 2208 pixels linked by IEEE1394 Fire Wire to an image processor (discussed below), and the application calls API provided by a Pixelink library in a DLL to control the camera perform image acquisition.

[0054] In an example embodiment, system **10** further includes a controller **50**, such as a computer or like machine, that is adapted (e.g., via instructions such as software embodied in a computer-readable or machine-readable medium) to control the operation of the various components of the system. Controller **50** is configured to control the operation of system **10** and includes an image processing unit ("image processor") **54** electrically connected to image sensor **30** and adapted to receive and process digitized raw image signals **SRI** therefrom and form processed image signals **SPI**, as described in greater detail below.

[0055] **FIG. 2** is a schematic diagram of an example hand-held device **52** that includes system **10**, and illustrates an example controller **50**. In an example embodiment, controller **50** is or includes a computer with a processor (e.g., image processor **54**) and includes an operating system such as Microsoft WINDOWS or LINUX.

[0056] In an example embodiment, image processor **54** is or includes any processor or device capable of executing a series of software instructions and includes, without limitation, a general- or special-purpose microprocessor, finite state machine, controller, computer, central-processing unit (CPU), field-programmable gate array (FPGA), or digital signal processor. In an example embodiment, the processor is an Intel XEON or PENTIUM processor, or an AMD TURION or other processor in the line of such processors made by AMD Corp., Intel Corp. or other semiconductor processor manufacturer.

[0057] Controller **50** also preferably includes a memory unit ("memory") **110** operably coupled to image processor **54**. As used herein, the term "memory" refers to any processor-readable medium, including but not limited to RAM, ROM, EPROM, PROM, EEPROM, disk, floppy disk, hard disk, CD-ROM, DVD, or the like, on which may be stored a series of instructions executable by image processor **54**. In an example embodiment, controller **50** includes a port or drive **120** adapted to accommodate a

removable processor-readable medium **116**, such as CD-ROM, DVE, memory stick or like storage medium.

[0058] The EDOF methods of the present invention may be implemented in various embodiments in a machine-readable medium (e.g., memory **110**) comprising machine readable instructions (e.g., computer programs and/or software modules) for causing controller **50** to perform the methods and the controlling operations for operating system **10**. In an example embodiment, the computer programs run on image processor **54** out of memory **110**, and may be transferred to main memory from permanent storage via disk drive or port **120** when stored on removable media **116**, or via a network connection or modem connection when stored outside of controller **50**, or via other types of computer or machine-readable media from which it can be read and utilized.

[0059] The computer programs and/or software modules may comprise multiple modules or objects to perform the various methods of the present invention, and control the operation and function of the various components in system **10**. The type of computer programming languages used for the code may vary between procedural code-type languages to object- oriented languages. The files or objects need not have a one to one correspondence to the modules or method steps described depending on the desires of the programmer. Further, the method and apparatus may comprise combinations of software, hardware and firmware. Firmware can be downloaded into image processor **54** for implementing the various example embodiments of the invention.

[0060] Controller **50** also optionally includes a display **130** that can be used to display information using a wide variety of alphanumeric and graphical representations. For example, display **130** is useful for displaying enhanced images. Controller **50** also optionally includes a data-entry device **132**, such as a keyboard, that allows a user of system **10** to input information into controller **50** (e.g., the name of the object being imaged, and to manually control the operation of system **10**. In an example embodiment, controller **50** is made sufficiently compact to fit within a small form-factor housing of a hand-held or portable device, such as device **52** shown in **FIG. 2**.

[0061] System **10** also optionally includes a database unit **90** operably connected to controller **50**. Database unit **90** includes a memory unit **92** that serves as a computer-readable medium adapted to receive processed image signals **SPI** from image processor

54 and store the associated processed digital images of object **OB** as represented by the processed image signals. Memory unit ("memory") **92** may be any computer-readable medium, including but not limited to RAM, ROM, EPROM, PROM, EEPROM, disk, floppy disk, hard disk, CD-ROM, DVD, or the like, on which data may be stored. In an example embodiment, database unit **90** is included within controller **50**.

General method of operation

[0062] With reference to **FIG. 1**, in the general operation of system **10**, image **IM** of object **OB** is formed on photosensitive surface **32** of sensor **30** by optical system **20**. Controller **50** sends a control signal **S30** to activate image sensor **30** for a given exposure time so that image **IM** is captured by photosensitive surface **32**. Image sensor **30** digitizes this "raw" image **IM** and creates the electronic raw image signal **SRI** representative of the raw captured image.

[0063] At this point, in one example embodiment, the raw image **IM** can be used directly, i.e., without any image processing, or with only minor image processing that does not involve MTF-enhancement, as discussed below. This approach can be used for certain types of imaging applications, such as character recognition and for imaging binary objects (e.g., bar-code objects) where, for example, determining edge location is more important than image contrast. The raw image **IM** is associated with an EDOF provided by optical system **20** even without additional contrast-enhancing image processing, so that in some example embodiments, system **10** need not utilize the image-processing portion of the system. In an example embodiment, a number N of raw images are collected and averaged (e.g., using image processor **54**) in order to form a (digitized) raw image **IM'** that has reduced noise as compared to any one of the N raw images.

[0064] In other example embodiments where the raw image **IM** is not directly usable, image processor **54** receives and digitally processes the electronic raw image signal **SRI** to form a corresponding contrast-enhanced image embodied in an electronic processed image signal **SPI**, which is optionally stored in database unit **90**. For example, when system **10** is used for iris recognition, controller **50** accesses the stored processed images in database unit **90** and compares them to other stored iris images or to recently obtained processed iris images to perform personnel identification.

Image processing

[0065] Image processor **54** is adapted to receive from image sensor **30** digitized electrical raw image signals **SRI** and process the corresponding raw images to form processed, contrast-enhanced images. This is accomplished by filtering the raw images in a manner that restores the MTF as a smooth function that decreases continuously with spatial frequency and that preferably avoids overshoots, ringing and other image artifacts.

[0066] Noise amplification is often a problem in any filtering process that seeks to sharpen a signal (e.g., enhance contrast in a digital optical image). Accordingly, in an example embodiment, an optimized gain function (similar to Wiener's filter) that takes in account the power spectrum of noise is applied to reduce noise amplification during the contrast-enhancement process.

[0067] In an example embodiment, the gain function applied to the "raw" MTF to form the "output" or "enhanced" MTF depends on the object distance $\mathbf{D_{OB}}$. The MTF versus distance $\mathbf{D_{OB}}$ is acquired by a calibration process wherein the MTF is measured in the expected depth of field **DOF** by sampling using defocus steps $\delta_F \leq (1/8)(\lambda/(NA^2)$ to avoid any undersampling and thus the loss of through-focus information for the MTF. In this instance, the enhanced MTF is said to be "focus-dependent."

[0068] **FIG. 3** plots the measured or "raw" MTFs as measured at different defocus distances δ_F of 10 mm from best focus between extremes of −50 mm and +50 mm of defocus. The raw MTF plots for different focus distances illustrate the MTF dispersion that occurs due to defocus. For each step through defocus, a digital filtering function is used to restore the best MTF for the processed image according to the measured MTF. The use of this filter requires knowing the amount of defocus, which can be measured using any one of a number of available techniques known in the art. The filter used between defocus steps δ_F is the linear interpolation of the adjacent focus steps.

MTF restoration

[0069] The above-mentioned MTF gain function used to restore or enhance the raw MTF is a three-dimensional function $G(u, v, d)$, wherein u is the spatial frequency along the X axis, v is the spatial frequency along the Y axis, and d is the distance of the object in the allowed extended depth of field **DOF** (d thus corresponds to the object distance

$\mathbf{D_{OB}}$). The rotational symmetry of the PSF and MTF results in a simplified definition of the gain function, namely:

$$G'(\omega, d) \text{ with } \omega^2 = u^2 + v^2$$

The rotational symmetry also makes $G'(\omega, d)$ a real function instead of a complex function in the general case.

[0070] The "enhanced" or "restored" OTF is denoted OTF' and is defined as:

$$OTF'(u, v, d) = G(u, v, d)\, OTF(u, v, d)$$

where *OTF* is the Optical Transfer Function of the optical system for incoherent light, *OTF'* is the equivalent *OTF* of the imaging system including the digital processing, and *G* is the aforementioned MTF gain function. The relationship for the restored or "output" or "enhanced" MTF (i.e., *MTF'*) based on the original or unrestored MTF is given by:

$$MTF'(\omega, d) = G'(\omega, d)\, MTF(\omega, d)$$

[0071] When the object distance is unknown, an optimized average gain function *G'* can be used, as shown in **FIG. 4B**. The resulting MTF is enhanced, but is not a function of the object distance.

[0072] The after-digital process is preferably optimized to deliver substantially the same MTF at any distance in the range of the working depth of field **DOF**. This provides a substantially constant image quality, independent of object distance $\mathbf{D_{OB}}$, so long as $\mathbf{D_{OB}}$ is within the depth of field **DOF** of optical system **20**. Because optical system **20** has an extended depth of field **DOF** due to the presence of spherical aberration as described below, system **10** can accommodate a relatively large variation in object distance $\mathbf{D_{OB}}$ and still be able to capture suitable images.

[0073] **FIG. 4A** plots through focus the typical gain in the output MTF' obtained using the above-described process. **FIG. 5A** plots the typical output MTF' for the different focus positions. The shape of the output MTF' is close as possible of the hypergaussian function, namely:

$$MTF'(\omega,d)=\exp\left(-\left(\frac{\omega}{\omega_c}\right)^{2n}\right)$$

wherein n is the hypergaussian order, ω_c is the cutoff frequency, which is set at the highest frequency where the raw MTF is higher that 5% on the whole range of the extended depth of field **DOF**.

[0074] If $n = 1$, the output MTF' is Gaussian. This provides a PSF, LSF (line-spread function) and ESF (edge-spread function) without any ringing or overshoot. If $n > 1$, the output MTF' is a hypergaussian. For higher values of n, the contrast in high spatial frequencies is also high, but the occurrence of ringing and overshoot increases. A good compromise is $n = 2$, wherein the output MTF' is well enhanced at low and medium spatial frequencies, while the ringing and overshoot are limited to about 3%, which is acceptable for most imaging applications.

[0075] The real output MTF' is as close as possible to a hypergaussian, and is determined by an optimization process that involves a merit function M, which is defined as:

$$M = A_0 \cdot \int_0^{Fc}\left(MTF'(\omega,d)-\exp\left(-\left(\frac{\omega}{\omega_c}\right)^{2n}\right)\right)^2 d\omega + A_1 \cdot \int G'(\omega,d)^2\, d\omega + A_2 \cdot \Delta os^2$$

Merit function M is minimized by using, for example, a Newton optimization algorithm. The first term with the coefficient A_0 minimizes the deviation from the hypergaussain output MTF'. The second term with the coefficient A_1 controls the power noise amplification. The third term with the coefficient A_2 controls the overshoot amplification.

[0076] It is important to control the power noise amplification. At distances where the gain on the raw MTF is higher in order to achieve the output MTF', a good compromise between the MTF level and the signal-to-noise ratio on the image can be determined, while controlling the slope of the output MTF' at high special frequencies avoids significant overshoot. The third term in the merit function M is the square of the relative overshoot on an edge spread, which is illustrated in **FIG. 6**, wherein the overshoot is given by Δos.

[0077] **FIG. 7** is a plot of the raw MTF (dashed line) along with an output MTF' (solid line) formed using the process described above. The output MTF' has a smooth shape that avoids overshoots and other imaging artifacts. The applied gain of the digital filter is optimized or enhanced to obtain the maximum output MTF' while controlling the gain or noise.

[0078] In an example embodiment, the raw MTF is measured for calibration at different sampled distances that overlap the extended depth of field **DOF** by using a slanted edge with a uniform incoherent backlighting at the same spectrum used during image capture.

Image noise reduction by averaging sequential images

[0079] There are two distinct sources of noise associated with the image acquisition and image processing steps. The first source of noise is called "fixed-pattern noise" or FP noise for short. The FP noise is reduced by a specific calibration of image sensor **30** at the given operating conditions. In an example embodiment, FP noise is reduced via a multi-level mapping of the fixed pattern noise wherein each pixel is corrected by a calibration table, e.g., a lookup table that has the correction values. This requires an individual calibration of each image sensor and calibration data storage in a calibration file. The mapping of the fixed pattern noise for a given image sensor is performed, for example, by imaging a pure white image (e.g., from an integrating sphere) and measuring the variation in the acquired raw digital image.

[0080] The other source of noise is shot noise, which is random noise. The shot noise is produced in electronic devices by the Poisson statistics associated with the movement of electrons. Shot noise also arises when converting photons to electrons via the photo-electric effect.

[0081] Some imaging applications, such as iris recognition, require a high-definition image sensor **30**. To this end, in an example embodiment, image sensor **30** is or includes a CMOS or CCD camera having an array of 3000 × 2208 pixels with a pixel size of 3.5 μm. The full well capacity is reduced to 21,000 electrons for a CMOS camera at this small pixel size, and the associated minimum of shot noise is about 43.2 dB at the saturation level.

[0082] An example embodiment of system **10** has reduced noise so that the MTF quality is improved, which leads to improved images. The random nature of the shot

noise is such that averaging N captured images is the only available approach to reducing the noise (i.e., improving the SNR). The noise decreases (i.e., the SNR increases) in proportion to $N^{1/2}$. This averaging process can be applied to raw images as well as to processed (i.e., contrast-enhanced) images.

[0083] Averaging N captured images is a suitable noise reduction approach so long as the images being averaged are of a fixed object or scene. However, such averaging is problematic when the object moves. In an example embodiment, the movement of object **OB** is tracked and accurately measured, and the averaging process for reducing noise is employed by accounting for and compensating for the objection motion prior to averaging the raw images.

[0084] In an example embodiment, the image averaging process of the present invention uses a correlation function between the sequential images at a common region of interest. The relative two-dimensional image shifts are determined by the location of the correlation peak. The correlation function is processed in the Fourier domain to speed the calculation by using a fast-Fourier transform (FFT) algorithm. The correlation function provided is sampled at the same sampling intervals as the initial images. The detection of the correlation maximum is accurate to the size of one pixel.

[0085] An improvement of this measurement technique is to use a 3×3 kernel of pixels centered on the pixel associated with the maximum correlation peak. The sub-pixel location is determined by fitting to two-dimensional parabolic functions to establish a maximum. The (X,Y) image shift is then determined. The images are re-sampled at their shifted locations. If the decimal part of the measured (X,Y) shift is not equal to 0, a bi-linear interpolation is performed. It is also possible to use a Shannon interpolation as well because there is no signal in the image at frequencies higher than the Nyquist frequency. All the images are then summed after being re-sampled, taking in account the (X,Y) shift in the measured correlation.

Optical System

[0086] As discussed above, imaging optical system **20** has a depth of field **DOF** in object space **OS** and a depth of focus **DOF'** in image space **IS** as defined by the particular design of the optical system. The depth of field **DOF** and the depth of focus **DOF'** for conventional optical imaging systems can be ascertained by measuring the evolution of the Point Spread Function (PSF) through focus, and can be established by specifying an amount of loss in resolution R that is deemed acceptable for a given

application. The "circle of least confusion" is often taken as the parameter that defines the limit of the depth of focus **DOF'**.

[0087] In the present invention, both the depth of field **DOF** and the depth of focus **DOF'** are extended by providing optical system **20** with an amount of spherical aberration (SA). In an example embodiment, $0.2\lambda \leq SA \leq 5\lambda$, more preferably $0.2\lambda \leq SA \leq 2\lambda$ and even more preferably $0.5\lambda \leq SA \leq 1\lambda$, where λ is an imaging wavelength. In an example embodiment, the amount of spherical aberration SA in the optical system at the imaging wavelength λ is such that the depth of field **DOF** or the depth of focus **DOF'** increases by an amount between 50% and 500% as compared to a diffraction limited optical system. By adding select amounts of spherical aberration SA, the amount of increase in the depth of field **DOF** can be controlled. The example optical system designs set forth below add select amounts of spherical aberration SA to increase the depth of field **DOF** without substantially increasing the adverse impact of other aberrations on image formation.

[0088] Since the depth of field **DOF** and the depth of focus **DOF'** are related by the axial magnification M_A and lateral magnification M_L of optical system **20** via the relationships $DOF' = (M_A)\, DOF = (M_L)^2\, DOF$, system **10** is said to have an "extended depth of field" for the sake of convenience. One skilled in the art will recognize that this expression also implies that system **10** has an "extended depth of focus" as well. Thus, either the depth of field **DOF** or the depth of focus **DOF'** is referred to below, depending on the context of the discussion.

[0089] The MTF can also be used in conjunction with the PSF to characterize the depth of focus **DOF'** by examining the resolution R and image contrast CI of the image through focus. Here, the image contrast is given by

$$CI = (I_{MAX} - I_{MIN}) / (I_{MAX} + I_{MIN})$$

and is measured for an image of a set of sinusoidal line-space pairs having a particular spatial frequency, where I_{MAX} and I_{MIN} are the maximum and minimum image intensities, respectively. The "best focus" is defined as the image position where the MTF is maximized and where the PSF is the narrowest. When an optical system is free from aberrations (i.e., is diffraction limited), the best focus based on the MTF coincides with the best focus based on the PSF. However, when aberrations are present in an optical system, the best focus positions based on the MTF and PSF can differ.

[0090] Conventional lens design principles call for designing an optical system in a manner that seeks to eliminate all aberrations, or to at least balance them to minimize their effect so that the optical system on the whole is substantially free of aberrations.

[0091] However, in the present invention, optical system **20** is intentionally designed to have spherical aberration as a dominant aberration, and optionally has a small amount of chromatic aberration as well. **FIG. 8A** is a plot of the MTF for an F/8 lens without aberrations (curves a through g), while **FIG. 9A** is a plot of an MTF for an F 5.6 lens that has SA = 0.75λ (curves a through h). **FIG. 8B** is a gray-scale plot of the MTF through focus for the diffraction-limited case of the F/8 lens of **FIG. 8A**, and **FIG. 9B** is a similar gray-scale plot of the MTF through focus for the F/5.6 lens with spherical aberration of **FIG. 9A**.

[0092] The spherical aberration reduces the contrast of the image by reducing the overall level of the MTF from the base frequency $f_0 = 0$ to the cutoff frequency f_C. The cut off frequency f_C is not significantly reduced as compared to the ideal (i.e., diffraction-limited) MTF, so nearly all the original spatial-frequency spectrum is available. Thus, the spatial-frequency information is still available in the image, albeit with a lower contrast. The reduced contrast is then restored by the digital filtering process as carried out by image processing unit **54**, as described above.

[0093] The amount of spherical aberration SA increases the depth of focus **DOF'** in the sense that the high spatial frequencies stay available over a greater range of defocus. The digital filtering restores the contrast over the enhanced depth of focus **DOF'**, thereby effectively enhancing the imaging performance of optical system **20**.

[0094] Spherical aberration is an "even" aberration in the sense that the wavefront "error" is given by $W(\rho) = \rho^4$, wherein ρ is the pupil coordinate. Thus, spherical aberration presents a rotationally symmetric wave front so that the phase is zero. This means that the resulting Optical Transfer Function (OTF) (which is the Fourier Transform of the PSF) is a rotationally symmetric, real function. The MTF, which is the magnitude of the OTF, can be obtained where spherical aberration is the dominant aberration by considering a one-dimensional MTF measurement taken on a slanted edge. This measurement provides all the required information to restore the two-dimensional image via digital signal processing. Also, the phase is zero at any defocus position, which allows for digital image processing to enhance the MTF without the need to

consider the phase component (i.e., the phase transfer function, or PFT) of the OTF in the Fourier (i.e., spatial-frequency) space.

[0095] As can be seen from **FIG. 9A**, because the image-wise side of the defocus (as measured from the "best focus" plane) has no zero in the MTF when there is spherical aberration present, there is no contrast inversion. This allows for an image to be formed and detected in this extended depth of focus **DOF'** (see dashed ellipse in **FIG. 9B**) to be restored without having to account for detrimental ringing, overshoot or other image artifacts.

[0096] An amount of spherical aberration SA of about 0.75λ gives a significant DOF enhancement without forming a zero in the MTF on one defocus side. Beyond about $SA = 0.75\lambda$, a zero occurs on both sides of defocus from the best focus position. For a diffraction-limited optical system, the depth of focus **DOF'** is given by the relationship $DOF' = \pm \lambda/(NA^2)$, where NA is the numerical aperture of the optical system. In an example embodiment, optical system **20** has an NA between about 0.033 and 0.125 (i.e., about F/15 to about F/4, where F/# = 1/(2NA) assuming the small-angle approximation).

[0097] By way of example, for F/ 6.6, a center wavelength of $\lambda = 800$ nm and a bandwidth of $\Delta\lambda$, the diffraction-limited depth of focus **DOF'** is about 20mm, with a transverse magnification of 1/1.4. The introduction of an amount of spherical aberration $SA = 0.75\ \lambda$ increases the depth of focus **DOF'** to about 100 mm, an increase of about 5X.

[0098] **FIG. 9C** plots the through-focus MTF at 3 lp/mm in object space for NA = 0.0063 for the raw MTF, the enhanced MTF (i.e., MTF') and the diffraction-limited MTF.

[0099] **FIGS. 10A-10D** are plots of the optical path difference (OPD) for various image heights (0 mm, 20 mm, 30 mm and 60 mm, respectively) for an example optical system **20** having an amount of spherical aberration $SA = 0.7\lambda$.

Example single-lens optical systems

[00100] **FIG. 11** is a schematic side view of an example embodiment of a single-lens optical system **20** according to the present invention. As discussed above in connection with the generalized embodiment of system **10** of **FIG. 1**, optical system **20** consists of single lens element **22** arranged along optical axis **A1**, and aperture stop **AS** arranged objectwise of the single lens element. Lens element **20** has a front (i.e., objectwise)

surface **S1** and a rear (i.e., imagewise) surface **S2**, and a center (axial) thickness **TH**. Aperture stop **AS** is arranged along optical axis **A1** a distance D_{AS} away from lens front surface **S1** and defines a pupil **P** having a radial coordinate ρ. Pupil **P** also defines the optical system's entrance and exit pupils as viewed from the object and image spaces, respectively.

[00101] In the example embodiment of optical system **20** of **FIG. 11**, lens element **22** is a plano-convex lens with objectwise surface **S1** as the plano surface. Also in an example embodiment, surface **S2** is an aspheric surface. In an example embodiment, lens element **22** is integrally formed from a single material, such as glass or plastic.

[00102] **Table 1** below sets forth an example design for optical system **20** of **FIG. 11**.

Table 1: Example Optical System 20

Lens Type	Plano-Convex
Material	Fused Silica; $n_d = 1.458464$; $v_d = 67.82$
Radius of curvature of surface S2	23 mm
Center (axial) thickness TH	7 mm
Working diameter	14 mm
Entrance pupil diameter	8 mm
D_{AS}	11 mm
F/#	6.6
Center wavelength λ	800 nm (near IR)
Wavelength bandwidth Δλ	40 nm to 200 nm
Focal length	50 mm
Working Depth of Focus DOF'	0.77 mm ~ 5X (or~ 500%) greater than the diffraction limited DOF'.
Lateral Magnification M_L	(1/11.4)
Clear Aperture CA	12 mm
Depth of Field DOF	100 mm
Resolution R	3 lines/mm at 60% contrast

Spherical aberration SA	0.75 λ
Chromatic aberration	0.4 mm in [735 nm – 890 nm]
Coma	Null
Field Curvature	Radius in image space: -20 mm
Astigmatism	< λ/10

[00103] This single-element design for optical system **20** provides the required spherical aberration at F/6.6 that matches well to the required practical working conditions for performing a number different EDOF applications, such as iris recognition. Other options for lens element **22** include using non-glass materials such as plastic. An advantage of the single-element design for optical system **20** is that it makes the system very compact so that the resultant EDOF optical imaging system **10** is also compact. A wide variety of single lens elements **22** are also readily commercially available as "off the shelf" components.

[00104] In an example embodiment, distance $\mathbf{D_{AS}}$ is that which substantially minimizes comatic aberration. It is noted here that the presence of spherical aberration SA in optical system **20** creates an axial "zero coma" position for aperture stop **AS** that is objectwise of lens element **22**. Thus, in an example embodiment, aperture stop **AS** preferably resides at or near the zero-coma position. Here, the phrase "near" the zero-coma position means within the positioning tolerance, which in an example embodiment is about a few millimeters.

[00105] **FIG. 12** plots as a function of aperture stop axial position (mm) the eighth Zernike coefficient of the Zernike polynomial representation of wavefront aberrations. The eighth Zernike coefficient (denoted herein in non-conventional form as "Z_8" for the sake of simplicity) is representative of the amount of coma in the wavefront and has form given by the equation $(3\rho^2 - 2)\rho \cdot \mathrm{Sin}\, A$, where A is the angular pupil coordinate and ρ is the normalized radial pupil coordinate.

[00106] Values for spherical aberration of SA = 0 (i.e., no spherical aberration), 0.2λ, 0.75λ and 2λ are shown. The plots are based on a single-element lens **22** made of fused Silica with f = 50 mm, F/6.6, and operating at an imaging wavelength λ = 700 nm. In **FIG. 12**, the curve for the SA= 0 case corresponds to a plano-hyperbolic lens element **22**

with an objectwise plano surface and an imagewise aspheric hyperbolic convex surface. The hyperbolic surface is exactly stigmatic (i.e., has no aberrations) on the axis.

[00107] For the curve having SA = 0, there is no zero coma position over the 20 mm distance range. The amount of coma for this case is also too great to achieve acceptable image quality over the entire image field. The region of good image quality is restricted only to a narrow field surrounding the lens axis. This is why a well-corrected single lens element is typically not considered for most imaging applications, and is generally only used for narrow field or on-axis applications, such as fiber optic coupling.

[00108] It is important to note that coma is always present when imaging with a single, positive lens element, and that the sign of such coma is negative. Having positive spherical aberration SA gives rise to a fortuitous variation with coma with aperture stop distance $\mathbf{D_{AS}}$. The slope of the coma amplitude versus the distance $\mathbf{D_{AS}}$ is positive and a zero-coma position arises objectwise of lens element **22**. By disposing aperture stop **AS** at or near this zero-coma position, the coma of the single lens is substantially eliminated across the entire image field. In an example embodiment, $\mathbf{D_{AS}}$ is preferably in the range $1 \text{ mm} \leq \mathbf{D_{AS}} \leq 20 \text{ mm}$, and more preferably in the range $1 \text{ mm} \leq \mathbf{D_{AS}} \leq 15 \text{ mm}$.

[00109] The main aberration that remains in optical system **20** is spherical aberration, which is constant across the entire image field, which is required to achieve the EDOF effect over the entire image field. In conventional optical systems, spherical aberration is deemed undesirable, and either aspherization or the additional of negative lens elements is used to eliminate or make negligible the effects of spherical aberration created by the use of a single lens element.

[00110] From the plot of **FIG. 12**, it can be seen that the single lens element with SA = 0.75λ has a zero-coma axial position at a distance of about 11 mm from lens element **22**. This distance is relatively small and allows for the formation of a compact, small-form-factor EDOF systems and devices, such device **52** shown in **FIG 2**.

[00111] In an example embodiment, astigmatism in optical system **20** is about λ/10 and so does not significantly affect the image quality. In an example embodiment, optical system **20** is not entirely corrected for chromatic aberration, which can be advantageous in that some chromatic aberration can be used to further increase the depth of field **DOF** when used with a relatively large imaging bandwidth Δλ by eliminating some zeroes in the MTF that might otherwise occur. Otherwise, the chromatic aberration is limited by

using an Abbe number V > 60 so as not to diminish the MTF by introducing lateral color in the edge of the field of a relatively large field. The axial chromatic aberration can be set at different values by the choice of glass. Standard optical glass has an Abbe number in the range from 20 to 64.

[00112] Though axial chromatic aberration increases the depth of field **DOF**, it decreases the MTF. This in turn requires increasing the MTF "amplification" in the digital processing, which increases the SNPD (Spectral Noise Power Density). The Abbe number is thus preferably selected to achieve a good compromise between diminishing the MTF while increasing the depth of field **DOF**. In an example embodiment, the glass material is selected such the added increase in the depth of field **DOF** (i.e., added to the increase provided by the spherical aberration) is up to about 20%, while the decrease in the average MTF level is no more than about 25%.

[00113] Fused silica (Abbe number V= 67.8) is a good glass choice when using an imaging wavelength λ having a relatively wide near-IR spectral bandwidth, e.g., $\Delta\lambda$ = 155 nm (e.g., from 735 nm to 890 nm). In an example embodiment, an acceptable amount of axial chromatic aberration is about 0.34 mm. When using a narrow-band imaging spectrum $\Delta\lambda$ such as from a laser or an LED with a near-IR spectral bandwidth $\Delta\lambda$ of about 50 nm FWHM, the axial chromatic aberration is smaller so that more dispersive glasses can be used for lens element **22**. In the optical system **20** set forth in **Table 1**, the lateral chromatic aberration is 10 μm at the field edge.

[00114] In some cases, field curvature needs to take into account to set the best focus plane. The optical system **20** set forth in **Table 1** has a field curvature of 120 mm radius in object space or -60 mm radius in image space. However, since field curvature is simply a form of defocus, adverse effects presented by this amount of field curvature can be overcome in certain cases by the gain in depth of focus **DOF'** due to the presence of spherical aberration.

[00115] The optical system **20** of **Table 1** has a resolution of R = 120 μm in object space, which is more than adequate to resolve details in many objects, including iris patters to perform iris recognition.

Additional single-lens optical system embodiments

[00116] The amount of spherical aberration in optical system **20** is a function of the refractive index, the focal length f, the F/# and the curvature *C* of lens element **22**. With

reference to **FIG. 13**, the lens curvature (also referred to as the "camber" or the "lens shape") C is defined as:

$$C = \frac{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}{\left(\frac{1}{R_1} - \frac{1}{R_2}\right)}$$

where **R1** is the radius of curvature of the most objectwise surface **S1** and **R2** is the radius of curvature of the most imagewise surface **S2**. **FIG. 14** plots a typical variation of spherical aberration SA (in waves) as the function of lens curvature C for a lens element **22** having a focal length of 20 mm, a refractive index of 1.51 at a wavelength of 750 nm, and an F/# of F/5.6. An amount spherical aberration SA = 0.75λ is achieved at C= -1.5. As discussed above, aperture stop **AS** is preferably axially positioned at or near the zero coma position to maximize the available image field.

[00117] If the F/# number of optical system **20** is to be adjusted, then the curvature C of lens element **22** has to be adjusted (i.e., a different lens needs to be selected) in order to maintain a desired amount of spherical aberration SA. **FIG. 15** shows a series of lens elements **22** and aperture stop positions illustrating the variation of F/# from F/4 to F/11. Note the corresponding change in curvature C needed to maintain an amount of spherical aberration SA = 0.75λ for a single lens element made of borosilicate glass BK7 with a focal length f = 50 mm.

[00118] The following **Tables T1** through **T8** set forth the values for radii **R1** and **R2** and curvature C suitable to achieve SA = 0.75λ at λ=750nm for single lens element **22** made of BK7 glass (n_d =1.5168) having different F/#s and focal lengths f. In **Tables T1** through **T8**, all dimensions are in mm, except the curvature C, which is dimensionless.

Table T1 for F/2 Glass BK7 n_d=1.5168				
f	**R1**	**R2**	***C***	**D_{AS}**
2	1.54	-2.382	0.215	0.2
2,5	1.49	-5.1	0.548	0

Table T2 for F/2 Glass N-LASF44 n_d=1.81042				
f	**R1**	**R2**	***C***	**D_{AS}**
2	3.244	-2,688	-0,094	0,7
2,5	3.264	-4.277	0.134	1
3	3.275	-7.55	0.395	1.2
4	3.047	74.193	1.086	0.5

Table T3 for F/3 Glass BK7 n_d=1.5168				
f	R1	R2	*C*	D_{AS}
5	8.24	-3.25	-0.434	0.03
7.5	7.72	-6.63	-0.076	1.29
10	7.715	-13.205	0.262	1.72
12	7.3	-33.08	0.638	0

Table T4 for F/3 Glass N-LASF44 n_d=1.81042				
f	R1	R2	*C*	D_{AS}
5	43.255	-4.24	-0.821	0.66
7.5	18.96	-8.07	-0.403	2.35
10	16.72	-13.91	-0.092	4.07
15	16.7	-38.15	0.391	6.57
20	15.6	815.35	1.039	3.12
25	18.63	287.57	1.139	0

Table T5 for F/4 Glass BK7 n_d=1.5168				
f	R1	R2	*C*	D_{AS}
10	42.91	-5.67	-0.767	1.69
15	24.92	-10.64	-0.402	4.2
20	23.12	-17.56	-0.137	6.51
25	23.1	-27.42	0.086	3.12
30	23.21	-43.36	0.303	8.23
35	21.46	-103.34	0.656	2.48
40	23.89	-136.6	0.702	0

Table T6 for F/4 Glass N-LASF44 n_d=1.81042				
f	R1	R2	*C*	D_{AS}
5	-6.24	-2.94	-2.782	0
7.5	-15.37	-4.66	-1.870	0.96
10	-39.09	-6.82	-1.423	2.22
15	220.81	-12.51	-0.893	5.18
20	71.26	-20.05	-0.561	8.1
30	51.11	-43.45	-0.081	15
35	50.02	-60.87	0.098	18
40	50.01	-84.7	0.258	20.6
50	50.86	-176.15	0.552	23.2
75	55.38	774	1.154	3.3

Table T7 for F/5.6 Glass BK7 n_d=1.5168				
f	R1	R2	*C*	D_{AS}
10	-7.76	-3.49	-2.635	0.24
15	-18.48	-5.72	-1.897	1.82
20	-41.8	-8.42	-1.504	3.7
25	-108.76	-11.55	-1.238	5.8
30	-860.4	-15.1	-1.036	8.03
35	282.01	-19.06	-0.873	10.38
40	155.26	-23.42	-0.738	12.78

50	105.66	-33.45	-0.519	17.7
75	88.03	-67.28	-0.134	29.16
100	88.1	-120.75	0.156	36.2
120	88.39	-199	0.385	33.77
140	83.66	-493.26	0.710	8.77

Table T8 for F/5.6 Glass N-LASF44 nd=1.81042				
f	**R1**	**R2**	***C***	**D_{AS}**
6	-2.76	-2.59	-31.471	0
10	-5.89	-4.14	-5.731	0.54
15	-11.8	-6.59	-3.530	2.12
20	-20.8	-9.58	-2.708	4.06
30	-55.33	-17.05	-1.891	8.67
35	-89.36	-21.51	-1.634	11.25
40	-150.41	-26.45	-1.427	14
50	-759.8	-37.79	-1.105	19.8
75	282.26	-75.11	-0.580	37.7
100	205.5	-128.56	-0.230	52
150	190.9	-314.41	0.244	81
200	196	-831	0.618	92.64

[00119] At each defined value of F/# and focal length f there is a minimum value SA_M for spherical aberration SA. The value of SA_M depends on the F/#, focal length f and refractive index *n* of the optical material making up lens element **22**. In an example embodiment, the value of SA_M preferably is equal to about 0.75λ to provide optimal EDOF results. This condition limits the range of focal length f and aperture of single lens element **22.**

[00120] The center thickness TH of lens element 22 preferably has a tolerance in the range from about $0.25D_L$ to $0.1D_L$, where D_L is the lens element diameter. Generally, manufacturing and mounting issues determine the best thickness TH.

[00121] The domain of F/# and focal length f covered by single lens element **22** with SA = 0.75λ is set forth below in **Table T9**.

TABLE T9 – F/# Domain		
f	**min F/#**	**max F/#**
4	3.2	6.4
5	3.36	6.72
7	3.65	7.3
10	3.95	7.9
15	4.35	8.7
20	4.66	9.32
38	5.5	11

50	5.9	11.8
75	6.5	13
100	7	14
150	7.7	15.4
200	8.3	16.6
300	9.2	18.4
500	10.4	20.8
1000	12.4	24.8
2000	14.7	29.4

[00122] The minimum F/# is set by aperture stop **AS** where the curvature *C* corresponds to a minimum spherical aberration $SA_M = 0.75\lambda$. A greater aperture diameter or lower F/# will produce too much spherical aberration SA and reduce the EDOF effect. The maximum F/# is limited by a value for curvature *C* where the field must be reduced due to an increase in astigmatism. While there is no real threshold for the F/#, good performance is generally easier to obtain when the F/# does not exceed twice the minimum F/#.

[00123] **FIG. 16** plots the range of the F/# as a function of focal length f as set forth in **Table T9**, wherein the maximum F# is twice the minimum F/#. In an example embodiment, the diameter of lens element **22** is at least about 1.2 times the diameter of aperture stop **AS**.

Enhanced aperture single lens

[00124] Single lens element **22** of optical system **20** can be made to have a larger aperture (diameter) by using optical materials with a relatively high refractive index. At a constant focal length f, increasing the refractive index *n* reduces the spherical aberration SA but increases the radius of curvature of the lens surface. Hence, the aperture required to obtain $SA = 0.75\lambda$ increases.

[00125] For an example lens element **22** with a focal length f=10 mm and made of borosilicate glass BK7 with *n*d=1.5168, vd=64, the minimum F/# available that yields $SA = 0.75\lambda$ is F/2.9. Selecting a higher index glass, such as N-LASF41 with nd=1.835 and vd=43.129 reduces the spherical aberration SA, so it is necessary to select a curvature *C* that produces more spherical aberration to compensate for the reduction in SA. The new minimum F/# decreases to F/2.5 and provides $SA = 0.75\lambda$. The search for maximum aperture or minimum F/# requires selecting higher index materials.

[00126] High-refractive-index glasses have more chromatic dispersion (i.e.. a low Abbe number). This usual rule can limit the choice of glass when broad-spectrum light is used for imaging. On the other hand, in some applications the addition of chromatic aberration favorably combines with the spherical aberration to achieve EDOF imaging.

Aspheric surfaces and diffractive features

[00127] In the case where the use of high index glass is followed by a higher chromatic dispersion in a manner that requires compensation for the resultant chromatic aberration, an example embodiment of single lens element **22** includes at least one diffractive feature **23** on at least one side (surface) of the lens, as illustrated in **FIG. 17**. Various technologies can be used to manufacture diffractive feature **23**, such affixing a molded diffractive structure to one of the lens surfaces, molding the entire lens so that the diffractive feature is integrally formed in one of the lens surfaces, or diamond turning the lens to carve the diffractive feature into the lens surface. The resulting aspherisation from diffractive feature **23** allows an increase in the aperture of lens **22** by reducing the amplitude of spherical aberration to SA = 0.75λ.

[00128] The second advantage of aspherization is that is increases the lens aperture without having to choose a glass with a high index of refraction while keeping the same amount of spherical aberration. A high index of refraction is about 1.8 for glass, but this value is generally not achievable in low-cost molded plastics such as Poly(methyl methacrylate), referred to as PMMA (n_d =1.4917 and v_d =57.44).

[00129] In one example embodiment, single lens element **22** is formed from an acrylic material and has a focal length f = 10 mm and F/# = F/4, with one of surfaces **S1** and **S2** including diffractive feature **23**, while the other surface is also aspherical (but not diffractive), thus making the lens "asphero-diffractive." The function of diffractive feature **23** is to provide substantial correction of chromatic axial aberration produced by the dispersion of the optical material making up lens element **22**. The diffraction order is chosen to allow the largest spectral width. In an example embodiment, two aspherical surfaces are optimized to achieve SA = 0.75λ. The use of two aspherical surfaces on lens element **22** allows a significant increase of the aperture that cannot be achieved with spherical surfaces alone.

[00130] The diffractive surface **S1** has full first-order diffraction efficiency at the central wavelength λ_0 of the light spectrum. With reference again to **FIG. 17**, in an

example embodiment diffractive feature **23** has "Fresnel lens" shape with steps of $k\lambda_0$ optical path difference with k=1 for order 1. The number of steps in diffractive feature **23** is calculated to compensate for the chromatic aberration that arises from the choice of optical material. Acrylic (with n_d=1.4917 and v_d=57.44) is an example material for single lens element **22** where such compensation is useful.

[00131] Diffractive feature **23** operates as a rotationally symmetric blazed grating. The local step function of the radial distance from the lens axis is designed to reduce or eliminate chromatic dispersion. There are many methods for calculating the shape of diffractive feature **23**, such as finite element numerical methods that can be readily carried out on a computer.

[00132] The achromatization from diffractive feature **23** is illustrated in the plot of **FIG. 18** of wavelength (μm) versus focal shift (μm), where the achromatization is centered at λ = 590 nm. Note that a second-order ("secondary") chromatic aberration remains. The secondary chromatic aberration reduces the MTF when a relatively broad light spectrum is used. However, this reduction in MTF can be taken into account in the MTF gain function. The secondary chromatic aberration does not necessarily reduces the depth of focus **DOF'** and in certain cases can increase the depth of focus by averaging the diffraction ring on the point spread function (PSF) and removing unwanted contrast inversion that occurs at high spatial frequencies. Thus, in an example embodiment, optical system **20** includes a small amount of chromatic aberration.

[00133] In an example embodiment, the spherical aberration SA is controlled to be about 0.75λ within the imaging bandwidth $\Delta\lambda$ and over the entire image field. Some residual lateral color can occur, and is a function of the distance of the diffractive feature **23** from aperture stop **AS**. This distance can be different from the "zero" coma distance, and in an example embodiment trade-offs are made between amounts of residual coma and lateral color needed to achieve a desired imaging performance.

[00134] **Table T10** below sets forth paraxial data for an example embodiment of single-lens optical system **20**.

TABLE T10 – Paraxial Lens Data	
Effective focal length	20 mm
Aperture	F/4
Image field size diameter	6 mm
Object field size	16°

Material	PMMA

This design is useful for CCTV cameras because it matches well with 1/3'' and ¼'' image sensor sizes.

[00135] The curvature *C* and asphericization of both surfaces **S1** and **S2** of the single lens element **22** associated with **Table T10** provides a controlled amount of spherical aberration close to SA = 0.75λ. The dual aspherization allows for a larger aperture as compared to a purely spherical design with the same lens material, the same focal length and the same amount of spherical aberration SA. The PMMA or acrylic plastic used in the example lens element **22** of **Table T10** is a common plastic used for optics. While other transparent plastics can be used, PMMA has very good index homogeneity and low irregularity, which reduces undesirable wavefront distortion. Use of a diffractive feature **23** is an option and serves to reduce the axial chromatic aberration, thereby avoiding the reduction in MTF when imaging with a broad wavelength spectrum.

[00136] The equation that describes the achromatization provided by diffractive feature **23** is given by:

$$\frac{d\theta_c}{d\lambda} + \frac{d\theta_d}{d\lambda} = 0$$

where θ_c is the refractive deviation angle (**FIG. 19A**), θ_d is the diffractive deviation angle (**FIG. 19B**), and λ is the imaging wavelength. The change in the refractive deviation angle can be expressed as:

$$\frac{d\theta_c}{d\lambda} = -\frac{1}{(n-1)} \cdot \frac{x}{f} \cdot \frac{dn}{d\lambda} \text{ for } \frac{d\theta_d}{d\lambda} = \frac{k}{p}$$

where n is the refractive index of the lens material at the central imaging wavelength λ_0, f is the focal length of the lens, k is the selected diffraction order (usually k=1), and p is the local step of the diffraction grating.

[00137] The achromatization equation thus becomes:

$$\frac{1}{p} = \frac{x}{k \cdot (n-1) \cdot f} \cdot \frac{dn}{d\lambda}$$

[00138] The integration of this expression from the optical axis along the radius in the x-direction yields the diffractive layer thickness as (where "*INT*" = "integer"):

$$e(x) = INT\left(\frac{x^2}{2\cdot(n-1)\cdot f}\cdot\frac{dn}{d\lambda}\right)\cdot\frac{\lambda_0}{(n-1)}$$

[00139] This form for diffractive feature **23** is shown in the close-up view of **FIG. 20**, and gives rise to a modified lens **22** of **Table T10**, as set forth in **Table T11** below.

TABLE T11 – Lens Element with Diffractive Feature	
Effective focal length	20 mm
Aperture	F/4
Image field diameter	6 mm
Object field size	16°

[00140] **FIG. 21A** shows an example optical system **20** with rays **25** traced from the object (not shown) to the image plane **IP**. Lens element **22** includes a diffractive feature **23** (not shown) on objectwise surface **S1** and an aspheric surface **S2**, as set forth in **Table T12**, below. In **Table T12**, the parameter Z defines the aspheric surface coordinate (and thus the aspheric surface shape), r is the radial coordinate, k is the conic constant, and c is the inverse of the radius of curvature. The diffractive layer that makes up diffractive feature **23** is defined separately and is added to the existing lens surface.

[00141]

TABLE T12– Design Parameters for Lens element with Diffractive Feature	
Curvature of surface S1:	$Z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}$ c=0.04067 mm-1 k=7.6 (ellipse)
Curvature of surface S2:	$Z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}$ C=0.0579 k=-5.63 (hyperbola)
Center thickness	4 mm
Aperture diameter	10 mm
Material	PMMA or Acrylic
Object field size	16°

[00142] Best performance across the image field is achieved with two optimized aspheric surfaces **S1** and **S2**. However, acceptable performance can be achieved by using only one aspheric surface. Aspheric surfaces can be developed as a conic section (hyperbolic, parabolic, elliptical, etc.,) or by a more general aspheric surface defined using a polynomial expansion

[00143] The added diffractive feature **23** on surface **S1** (or on surface **S2**) provides achromatisation by reducing the primary axial chromatic aberration. It also reduces the primary lateral color because the diffractive surface is on the refractive component and is separated from aperture stop **AS**. An example shape of diffractive feature **23** is plotted in **FIG. 21B**. There are about 40 concentric rings **202** separated by steps of 1.1 μm depth that produces a 2π phase change at the central imaging wavelength $\lambda_0 = 550$ nm. With reference to **FIG. 21C**, the radius of the rings **202** can be defined by the radius of the Newton rings (fringes) produced by two coherent sources **SC1** and **SC2** located at axial positions **P1** and **P2** respectively at 53 mm and 46 mm from lens surface **S1**.

Field curvature considerations

[00144] In some example optical systems **20**, the available image field is limited by field curvature. Because field curvature is proportional to the lens power, it cannot be corrected when only a single lens element **22** is used to constitute optical system **20**. **FIG. 22A** is a schematic diagram of the single-lens imaging optical system **20** along with a corresponding plot of the field curvature. The plot of **FIG. 22A** shows a 0.2 mm change in the best focus position as a function of field height h. This change in focus position with field height reduces the EDOF effect.

[00145] **FIG. 22B** is similar to **FIG. 22A** and illustrates an example embodiment that includes a field lens **27** immediately adjacent sensor **30**. Field lens **27** is a negative lens that acts as a "field flattener." Field lens **27** can be considered as part of an assembly formed with image sensor **30** since the field lens only affects field curvature at the image sensor. Thus, in an example embodiment, field lens **27** is contacted to image sensor **30**, and the field lens and image sensor form an image sensor assembly. The plot of **FIG. 22B** shows a substantially flat field due to the presence of field lens **27**. The resultant flat field serves to optimize the EDOF effect.

Advantages

[00146] The single-element lens design of optical system **20** of EDOF system **10** has a number of key advantages over prior art EDOF imaging systems. The first is that the design is simple and only uses one optical element to achieve the desired EDOF effect. The second is that the optical element is a standard rotationally symmetric singlet lens, as opposed to a more complicated phase plate. The third advantage is that configuring the optical system to have select amounts of spherical aberration gives rise to an axial "zero coma" position for the aperture stop so that comatic aberration can be substantially eliminated, with the result that the only significant aberration is spherical aberration uniform over the image field—which is what is required for the EDOF imaging. The fourth advantage is the low cost associated with a single-lens optical system—an advantage that cannot be overstated given that many applications of system **10** will be for compact, hand-held devices such as cell phones and the like that need to maintain their cost competitiveness.

[00147] It will thus be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. An imaging system for imaging an object within an extended depth-of-field (EDOF) at an imaging wavelength λ, comprising:

an optical system having an optical axis and consisting of a single lens element and an aperture stop arranged objectwise of the single lens element, the optical system having amount of spherical aberration SA wherein $0.2\lambda \leq SA \leq 2\lambda$ when forming an image of the object; and

an image sensor arranged to receive the image and form therefrom a digitized electronic raw image.

2. The imaging system of claim 1, further comprising;

an image processor electrically connected to the image sensor and adapted to receive digitally filter the digitized electronic raw image to form a digitized contrast-enhanced image.

3. The system of claim 1, wherein $0.5\lambda \leq SA \leq 1\lambda$.

4. The system of claim 1, wherein the aperture stop is located at an axial position that substantially minimizes comatic aberration.

5. The system of claim 4, wherein the single lens element is made of either glass or plastic.

6. The system of claim 1, wherein the single lens element includes at least one diffractive feature configured to reduce or eliminate chromatic aberration.

7. The system of claim 1, wherein the single lens element has first and second surfaces, and wherein at least one of the first and second surfaces is aspheric.

8. The system of claim 1, wherein the optical system has an F/# such that $F/1.4 \leq F/\# \leq F/15$.

9. The system of claim 1, further comprising:

a field lens arranged immediately adjacent the image sensor and configured to reduce an amount of field curvature imparted by the single lens element.

10. The system of claim 1, wherein the single lens element is selected from the group of lens elements comprising: a bi-convex lens element, a positive meniscus lens element arranged so as to have concave surfaces relative to the object, and a plano-convex lens element arranged to have an objectwise planar surface.

11. A method of forming an image of an object over an extended depth of field (EDOF) at an imaging wavelength λ, comprising:

forming a raw image of an object with an optical system consisting of a single lens element and an aperture stop arranged objectwise of the single lens element, wherein the optical system has an amount of spherical aberration SA such that $0.2\lambda \leq SA \leq 2\lambda$; and

using an image sensor, electronically capturing the raw image to form a digitized raw image.

12. The method of claim 11, wherein $0.5\lambda \leq SA \leq 1\lambda$.

13. The method of claim 11, further comprising:

digitally filtering the digitized raw image to form a contrast-enhanced image.

14. The method of claim 13, wherein the raw image has associated therewith a raw modulation transfer function (MTF), and further comprising:

establishing an amount of defocus in the digitized raw image based on a position of the object relative to the optical system;

forming an enhanced MTF from the raw MTF by multiplying the raw MTF by a gain function, wherein the enhanced MTF is a function of the amount of defocus; and

applying the enhanced MTF to the digitized raw image to obtain the contrast-enhanced image.

15. The method of claim 14, including:

measuring a distance between the object and the optical system; and

forming the enhanced MTF by applying a two-dimensional linear digital filter to the raw MTF according to the measured distance.

16. The method of claim 15, including measuring the raw MTF at different distances that overlap the depth of field DOF by using a slanted edge with uniform incoherent backlighting.

17. The method of claim 13, wherein the raw image has an associated raw MTF, and further comprising:

forming an enhanced MTF from the raw MTF by multiplying the raw MTF by a gain function, wherein the enhanced MTF is substantially constant as a function of focus position; and

applying the enhanced MTF to the digitized raw image to obtain the contrast-enhanced image of the object.

18. The method of claim 11, including arranging the aperture stop at an axial position that substantially minimizes comatic aberration.

19. The method of claim 11, including providing at least one diffraction feature on one or more surfaces of the single lens element so as to reduce chromatic aberration.

20. The method of claim 11, including providing at least one aspheric surface to the single lens element.

21. The method of claim 11, further comprising:

capturing N raw images of the object; and

averaging the N raw images to form a reduced-noise raw image.

22. An enhanced depth-of-field (EDOF) imaging system for forming a contrast-enhanced image of an object at an imaging wavelength λ, comprising:

an optical system consisting of a single lens element and an objectwise aperture stop, with the optical system having an amount of spherical aberration SA, wherein $0.5\lambda \leq SA \leq 2\lambda$, and wherein the optical system forms a raw image;

an image sensor arranged to receive the raw image and form a raw image electrical signal, wherein the raw image has an associated raw modulation transfer function (MTF); and

an image processor electrically connected to the image sensor and adapted to receive the raw image electrical signal and perform image-processing thereon to form the contrast- enhanced image using an enhanced MTF formed from the raw MTF using a rotationally symmetric gain function.

23. The EDOF imaging system of claim 22, wherein the image processor is adapted to average N contrast-enhanced images to form a final contrast-enhanced image having reduced noise as compared to any of the N contrast-enhanced images.

24. The EDOF system of claim 22,wherein the single optical element is selected from the group of lens elements comprising: a bi-convex lens, a positive meniscus lens arranged to have concave surfaces facing the object, and a plano-convex lens arranged to have an objectwise planar surface.

25. The EDOF imaging system of claim 22, wherein the aperture stop is arranged axially arranged at a position that substantially reduces or eliminates comatic aberration.

26. The EDOF imaging system of claim 22, wherein the single lens element includes at least one of a diffractive feature and an aspheric surface.

27. The EDOF imaging system of claim 26, wherein the at least one diffractive feature is integrally formed with the single lens.

28. The EDOF imaging system of claim 22, wherein the single lens element includes first and second aspheric surfaces.

29. A method of forming an image of an object over an extended depth of field (EDOF) at an imaging wavelength λ, comprising:

providing an optical system that consists of a single lens element and an aperture stop;

configuring the optical system to have an amount of spherical aberration SA such that $0.5\,\lambda \leq SA \leq 2\lambda$ so as to give rise to an objectwise zero-coma axial position relative to the lens element;

disposing the aperture stop substantially at the zero coma axial position so as to substantially eliminate comatic aberration in the image; and

electronically capturing the image to form a digitized raw image.

30. The method of claim 29, further comprising:

capturing N raw images of the object; and

averaging the N raw images to form a reduced-noise raw image.

31. The method of claim 29, further comprising:

digitally filtering the digitized raw image to form a contrast-enhanced image.

32. The method of claim 31, wherein the digitized raw image has a corresponding raw modulation transfer function (MTF), and further comprising:

forming an enhanced MTF from the raw MTF by multiplying the raw MTF by a gain function; and

applying the enhanced MTF to the digitized raw image to obtain the contrast-enhanced image of the object.

33. The method of claim 32, wherein the gain function is constant.

34. The method of claim 29, wherein the single lens element has a most imagewise surface from which the zero-coma axial position is located at distance D_{AS} therefrom, and wherein $1\text{ mm} \leq D_{AS} \leq 20\text{ mm}$.