

METHOD AND SYSTEM FOR A SINGLE FRAME CAMERA MODULE ACTIVE ALIGNMENT TILT CORRECTION

BACKGROUND

Technical Field

[0001] This disclosure relates generally to camera module components and more specifically to adjusting the optical alignment of camera components.

Description of the Related Art

[0002] The advent of small, mobile multipurpose devices such as smartphones and tablet or pad devices has resulted in a need for the mass production of high-resolution, small form factor cameras, capable of generating high levels of image quality, for integration in the devices. Mass production creates pressure to maximize throughput of the machines used for assembling these cameras.

[0003] Camera module active alignment is thought of in terms of an image quality driven process that aligns a camera module lens to the image sensor, taking into consideration the optical properties of the combined lens/sensor system rather than only considering the mechanical alignment in physically assembling and bonding these two components together, as typically done in a high-throughput, non-image quality driven conventional camera module lens holder attachment process. The intention of active alignment is to align the optical axis of the lens to the center of the image sensor, which itself has been placed orthogonal to the principal axis of the lens. While camera modules active alignment is a key process in assembling a high resolution compact camera with high levels of image quality, conventional active alignment methods have low throughput compared with the conventional mechanical alignment process, making it difficult and expensive to meet mass production demands. There is a need for a faster method to realize camera module active alignment for high throughput mass production.

[0004] Manufacturing tolerances of the lens elements placed into the lens barrel, as well as tolerances in component placement, result in tilt and decenter between the lens and sensor, which can degrade image quality in the finished camera, especially on the periphery of images taken by the camera, which may exhibit noticeable blur at the edges and sharpness at the center.

SUMMARY OF EMBODIMENTS

[0005] Some embodiments include methods for correcting optical alignment of components in a camera module for a multifunction device. In some embodiments, components of a camera module for use in a multifunction device are assembled on a test station. Some embodiments include a method that includes capturing a single test image, calculating from spatial frequency response data derived from the test image an optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module, and mechanically adjusting an alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt. In some embodiments, the capturing is performed using the components of the camera module, and the single test image contains visually encoded spatial frequency response data for characterizing the components of the camera module.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. 1 illustrates a block diagram of a portable multifunction device with a camera in accordance with some embodiments.

[0007] FIG. 2 depicts a portable multifunction device having a camera in accordance with some embodiments.

[0008] FIG. 3 depicts a side view of an example embodiment of actuator module components assembled on a test station for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0009] FIG. 4 illustrates a processed test pattern chart for generating spatial frequency response data that may be used for imaging for single frame camera active optical tilt alignment correction, according to at least some embodiments, marked up with feature detection results.

[0010] FIG. 5 depicts a graph of low spatial frequency spatial frequency response sensitivity to lens-to-sensor tilt in the presence of large defocus for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0011] FIG. 6 depicts charts of rotation values for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0012] FIG. 7A illustrates a graph of angle sign adjustments along axes for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0013] FIG. 7B illustrates a graph of angle sign adjustments within quadrants for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0014] FIG. 8 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0015] FIG. 9 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0016] FIG. 10 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0017] FIG. 11 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0018] FIG. 12 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0019] FIG. 13 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0020] FIG. 14 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments.

[0021] FIG. 15 illustrates an example computer system configured to implement aspects of the system and method for camera control, according to some embodiments.

[0022] This specification includes references to “one embodiment” or “an embodiment.” The appearances of the phrases “in one embodiment” or “in an embodiment” do not necessarily refer to the same embodiment. Particular features, structures, or characteristics may be combined in any suitable manner consistent with this disclosure.

[0023] “Comprising.” This term is open-ended. As used in the appended claims, this term does not foreclose additional structure or steps. Consider a claim that recites: “An apparatus

comprising one or more processor units ...” Such a claim does not foreclose the apparatus from including additional components (e.g., a network interface unit, graphics circuitry, etc.).

[0024] “Configured To.” Various units, circuits, or other components may be described or claimed as “configured to” perform a task or tasks. In such contexts, “configured to” is used to connote structure by indicating that the units/circuits/components include structure (e.g., circuitry) that performs those task or tasks during operation. As such, the unit/circuit/component can be said to be configured to perform the task even when the specified unit/circuit/component is not currently operational (e.g., is not on). The units/circuits/components used with the “configured to” language include hardware—for example, circuits, memory storing program instructions executable to implement the operation, etc. Reciting that a unit/circuit/component is “configured to” perform one or more tasks is expressly intended not to invoke 35 U.S.C. § 112, sixth paragraph, for that unit/circuit/component. Additionally, “configured to” can include generic structure (e.g., generic circuitry) that is manipulated by software and/or firmware (e.g., an FPGA or a general-purpose processor executing software) to operate in manner that is capable of performing the task(s) at issue. “Configure to” may also include adapting a manufacturing process (e.g., a semiconductor fabrication facility) to fabricate devices (e.g., integrated circuits) that are adapted to implement or perform one or more tasks.

[0025] “First,” “Second,” etc. As used herein, these terms are used as labels for nouns that they precede, and do not imply any type of ordering (e.g., spatial, temporal, logical, etc.). For example, a buffer circuit may be described herein as performing write operations for “first” and “second” values. The terms “first” and “second” do not necessarily imply that the first value must be written before the second value.

[0026] “Based On.” As used herein, this term is used to describe one or more factors that affect a determination. This term does not foreclose additional factors that may affect a determination. That is, a determination may be solely based on those factors or based, at least in part, on those factors. Consider the phrase “determine A based on B.” While in this case, B is a

factor that affects the determination of A, such a phrase does not foreclose the determination of A from also being based on C. In other instances, A may be determined based solely on B.

DETAILED DESCRIPTION

Introduction to motion compensation for camera modules

[0027] Some embodiments include methods for correcting optical alignment of components in a camera module for a multifunction device. In some embodiments, components of a camera module for use in a multifunction device are assembled on a test station. Some embodiments include a method that includes capturing a single test image, calculating from spatial frequency response data an optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module, and mechanically adjusting an alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt. In some embodiments, the capturing is performed using the components of the camera module, and the single test image contains visually encoded spatial frequency response data for characterizing the components of the camera module.

[0028] In some embodiments, the calculating from the spatial frequency response data the optical tilt between the optical axis of the lens and the optical axis of the image sensor of the camera module further includes calculating the optical tilt between the optical axis of the lens and the optical axis of the image sensor of the camera module from not more than one test image. The ability to perform calculating the optical tilt between the optical axis of the lens and the optical axis of the image sensor of the camera module with only one test image from the camera module is an advantage towards achieving high throughput camera module active alignment presented by some embodiments.

[0029] In some embodiments, the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a two-dimensional surface model to the spatial frequency response data. While examples are provided with the use of a linear plane for the purpose of clarity in illustrating embodiments, one of skill in the art will readily realize from having read the attached disclosure that other embodiments take into account higher order effects such as lens

field curvature without departing from the scope and intent of the disclosed embodiments. Embodiments use various models for fitting a generalized two dimensional surface model to the spatial frequency response data. From the fitted surface, the optical tilt can be determined via comparison between the ideal, non-tilted two-dimensional surface model. In some embodiments, the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a plane to the spatial frequency response data using a tilted linear plane model from low frequency spatial frequency response data. In some embodiments, the method further includes estimating correction angles from the plane, and applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

[0030] In some embodiments, the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a plane to the spatial frequency response data using a weighted-least squares calculation on a tilted linear plane model with low frequency spatial frequency response data. In some embodiments, the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting (generally any) two-dimensional surface to the spatial frequency response data using an optimization procedure such as nelder mead. Linear plane fitting with weighted least squares is only one possible example embodiment, chosen for ready clarity of illustration herein, or specific implementation of the general concept.

[0031] In some embodiments, the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a two dimensional surface to the spatial frequency response data. In some embodiments, the method further includes estimating correction angles from the fitted two-dimensional surface (or a model of the two-dimensional surface) via an optimization procedure, which in some embodiments takes the form of applying linear

calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

[0032] Some embodiments further include bonding a lens barrel assembly including the lens to a connection for the optical axis of the image sensor of the camera module to make permanent the alignment in the position resulting from the mechanically adjusting.

[0033] In some embodiments, the mechanically adjusting the alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt further includes mechanically adjusting an alignment of a lens barrel assembly including the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

[0034] Some embodiments include a camera module of a multifunction device. The camera module includes an image sensor, and a lens assembly moveably fixed to the image sensor. In some embodiments, an optical axis of the lens assembly is fixed relative to an optical axis of the image sensor using a process or method that includes assembling on a test station one or more components of the camera module for use in a multifunction device, capturing a single test image with the one or more components of the camera module, calculating from the single test image an optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module, and based at least in part upon the optical tilt, mechanically adjusting an alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

[0035] In some embodiments, capturing the single test image further includes capturing exactly one test image from the camera module, and calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module from the exactly one test image.

[0036] In some embodiments, the calculating from the single test image the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a plane two-dimensional surface to low spatial frequency response data derived from the single test image using a tilted linear plane two-dimensional surface model. In some embodiments, correction angles are estimated from the fitted surface, and linear calibration is applied to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

[0037] In some embodiments, the calculating from the single test image the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a two-dimensional surface to spatial frequency response data in the single test image using a mathematical optimization procedure. Examples include fitting a plane to the low spatial frequency response data and weighted-least squares calculation on a tilted linear plane model with low frequency spatial frequency response data.

[0038] In some embodiments, the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a two-dimensional surface to the spatial frequency response data. In some embodiments, the process further includes estimating correction angles from the fitted surface and applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt. In some embodiments, a lens barrel assembly includes the lens and is bonded to a connection for the optical axis of the image sensor of the camera module to make permanent the alignment in the position resulting from the mechanically adjusting.

[0039] In some embodiments, the mechanically adjusting the alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt further includes mechanically adjusting an alignment of a lens barrel assembly comprising the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

[0040] Some embodiments include a non-transitory computer-readable medium storing program instructions. In some embodiments the program instructions are computer-executable to implement capturing a single test image, calculating from the spatial frequency response data an optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module, estimating correction angles from the fitted two-dimensional surface and applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt. In some embodiments, the single test image contains visually encoded spatial frequency response data for characterizing the components of the camera module, and the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a two-dimensional surface model to the spatial frequency response data. One example is using a tilted linear plane model from low frequency spatial frequency response data.

[0041] In some embodiments, the program instructions computer-executable to implement the capturing the single test image further include program instructions computer-executable to implement capturing exactly one test and not more than one image from the camera module. In some embodiments, the program instructions computer-executable to implement calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further include program instructions computer-executable to implement calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module from the exactly one and not more than one test image.

[0042] In some embodiments, the program instructions computer-executable to implement calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further include program instructions computer-executable to implement fitting a two-dimensional surface to the low spatial frequency response data using a mathematical optimization procedure (e.g., nelder mead or weighted-least squares calculation on a tilted linear plane mode)l.

[0043] In some embodiments, the program instructions computer-executable to implement calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further include program instructions computer-executable to implement fitting a two-dimensional surface to the spatial frequency response data. In some embodiments, the computer-readable medium storing program instructions further includes program instructions computer-executable to implement estimating correction angles from the plane and program instructions computer-executable to implement applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

[0044] Some embodiments further include program instructions computer-executable to implement bonding a lens barrel assembly comprising the lens to a connection for the optical axis of the image sensor of the camera module to make permanent the alignment in the position resulting from the mechanically adjusting. In some embodiments, the program instructions computer-executable to implement mechanically adjusting the alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt further include program instructions computer-executable to implement mechanically adjusting an alignment of a lens barrel assembly comprising the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

Multifunction device examples

[0045] Reference will now be made in detail to embodiments, examples of which are illustrated in the accompanying drawings. In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be apparent to one of ordinary skill in the art that some embodiments may be practiced without these specific details. In other instances, well-known methods, procedures, components, circuits, and networks have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

[0046] It will also be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first contact could be termed a second contact, and, similarly, a second contact could be termed a first contact, without departing from the intended scope. The first contact and the second contact are both contacts, but they are not the same contact.

[0047] The terminology used in the description herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used in the description and the appended claims, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms "includes," "including," "comprises," and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0048] As used herein, the term "if" may be construed to mean "when" or "upon" or "in response to determining" or "in response to detecting," depending on the context. Similarly, the phrase "if it is determined" or "if [a stated condition or event] is detected" may be construed to mean "upon determining" or "in response to determining" or "upon detecting [the stated condition or event]" or "in response to detecting [the stated condition or event]," depending on the context.

[0049] Embodiments of electronic devices, user interfaces for such devices, and associated processes for using such devices are described. In some embodiments, the device is a portable communications device, such as a mobile telephone, that also contains other functions, such as PDA and/or music player functions. Other portable electronic devices, such as laptops, cameras, cell phones, or tablet computers, may also be used. It should also be understood that, in some

embodiments, the device is not a portable communications device, but is a desktop computer with a camera. In some embodiments, the device is a gaming computer with orientation sensors (e.g., orientation sensors in a gaming controller). In other embodiments, the device is not a portable communications device, but is a camera.

[0050] In the discussion that follows, an electronic device that includes a display and a touch-sensitive surface is described. It should be understood, however, that the electronic device may include one or more other physical user-interface devices, such as a physical keyboard, a mouse and/or a joystick.

[0051] The device typically supports a variety of applications, such as one or more of the following: a drawing application, a presentation application, a word processing application, a website creation application, a disk authoring application, a spreadsheet application, a gaming application, a telephone application, a video conferencing application, an e-mail application, an instant messaging application, a workout support application, a photo management application, a digital camera application, a digital video camera application, a web browsing application, a digital music player application, and/or a digital video player application.

[0052] The various applications that may be executed on the device may use at least one common physical user-interface device, such as the touch-sensitive surface. One or more functions of the touch-sensitive surface as well as corresponding information displayed on the device may be adjusted and/or varied from one application to the next and/or within a respective application. In this way, a common physical architecture (such as the touch-sensitive surface) of the device may support the variety of applications with user interfaces that are intuitive and transparent to the user.

[0053] Attention is now directed toward embodiments of portable devices with cameras. FIG. 1 is a block diagram illustrating portable multifunction device 100 with camera 164 in accordance with some embodiments. Camera 164 is sometimes called an "optical sensor" for convenience, and may also be known as or called an optical sensor system. Device 100 may include memory

102 (which may include one or more computer readable storage mediums), memory controller 122, one or more processing units (CPU's) 120, peripherals interface 118, RF circuitry 108, audio circuitry 110, speaker 111, touch-sensitive display system 112, microphone 113, input/output (I/O) subsystem 106, other input or control devices 116, and external port 124. Device 100 may include one or more optical sensors 164. These components may communicate over one or more communication buses or signal lines 103.

[0054] It should be appreciated that device 100 is only one example of a portable multifunction device, and that device 100 may have more or fewer components than shown, may combine two or more components, or may have a different configuration or arrangement of the components. The various components shown in various of the figures may be implemented in hardware, software, or a combination of hardware and software, including one or more signal processing and/or application specific integrated circuits.

[0055] Memory 102 may include high-speed random access memory and may also include non-volatile memory, such as one or more magnetic disk storage devices, flash memory devices, or other non-volatile solid-state memory devices. Access to memory 102 by other components of device 100, such as CPU 120 and the peripherals interface 118, may be controlled by memory controller 122.

[0056] Peripherals interface 118 can be used to couple input and output peripherals of the device to CPU 120 and memory 102. The one or more processors 120 run or execute various software programs and/or sets of instructions stored in memory 102 to perform various functions for device 100 and to process data.

[0057] In some embodiments, peripherals interface 118, CPU 120, and memory controller 122 may be implemented on a single chip, such as chip 104. In some other embodiments, they may be implemented on separate chips.

[0058] RF (radio frequency) circuitry 108 receives and sends RF signals, also called electromagnetic signals. RF circuitry 108 converts electrical signals to/from electromagnetic signals and communicates with communications networks and other communications devices via the electromagnetic signals. RF circuitry 108 may include well-known circuitry for performing these functions, including but not limited to an antenna system, an RF transceiver, one or more amplifiers, a tuner, one or more oscillators, a digital signal processor, a CODEC chipset, a subscriber identity module (SIM) card, memory, and so forth. RF circuitry 108 may communicate with networks, such as the Internet, also referred to as the World Wide Web (WWW), an intranet and/or a wireless network, such as a cellular telephone network, a wireless local area network (LAN) and/or a metropolitan area network (MAN), and other devices by wireless communication. The wireless communication may use any of a variety of communications standards, protocols and technologies, including but not limited to Global System for Mobile Communications (GSM), Enhanced Data GSM Environment (EDGE), high-speed downlink packet access (HSDPA), high-speed uplink packet access (HSUPA), wideband code division multiple access (W-CDMA), code division multiple access (CDMA), time division multiple access (TDMA), Bluetooth, Wireless Fidelity (Wi-Fi) (e.g., IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and/or IEEE 802.11n), voice over Internet Protocol (VoIP), Wi-MAX, a protocol for e-mail (e.g., Internet message access protocol (IMAP) and/or post office protocol (POP)), instant messaging (e.g., extensible messaging and presence protocol (XMPP), Session Initiation Protocol for Instant Messaging and Presence Leveraging Extensions (SIMPLE), Instant Messaging and Presence Service (IMPS)), and/or Short Message Service (SMS), or any other suitable communication protocol, including communication protocols not yet developed as of the filing date of this document.

[0059] Audio circuitry 110, speaker 111, and microphone 113 provide an audio interface between a user and device 100. Audio circuitry 110 receives audio data from peripherals interface 118, converts the audio data to an electrical signal, and transmits the electrical signal to speaker 111. Speaker 111 converts the electrical signal to human-audible sound waves. Audio circuitry 110 also receives electrical signals converted by microphone 113 from sound waves. Audio circuitry 110 converts the electrical signal to audio data and transmits the audio data to

peripherals interface 118 for processing. Audio data may be retrieved from and/or transmitted to memory 102 and/or RF circuitry 108 by peripherals interface 118. In some embodiments, audio circuitry 110 also includes a headset jack (e.g., 212, FIG. 2). The headset jack provides an interface between audio circuitry 110 and removable audio input/output peripherals, such as output-only headphones or a headset with both output (e.g., a headphone for one or both ears) and input (e.g., a microphone).

[0060] I/O subsystem 106 couples input/output peripherals on device 100, such as touch screen 112 and other input control devices 116, to peripherals interface 118. I/O subsystem 106 may include display controller 156 and one or more input controllers 160 for other input or control devices. The one or more input controllers 160 receive/send electrical signals from/to other input or control devices 116. The other input control devices 116 may include physical buttons (e.g., push buttons, rocker buttons, etc.), dials, slider switches, joysticks, click wheels, and so forth. In some alternate embodiments, input controller(s) 160 may be coupled to any (or none) of the following: a keyboard, infrared port, USB port, and a pointer device such as a mouse. The one or more buttons (e.g., 208, FIG. 2) may include an up/down button for volume control of speaker 111 and/or microphone 113. The one or more buttons may include a push button (e.g., 206, FIG. 2).

[0061] Touch-sensitive display 112 provides an input interface and an output interface between the device and a user. Display controller 156 receives and/or sends electrical signals from/to touch screen 112. Touch screen 112 displays visual output to the user. The visual output may include graphics, text, icons, video, and any combination thereof (collectively termed "graphics"). In some embodiments, some or all of the visual output may correspond to user-interface objects.

[0062] Touch screen 112 has a touch-sensitive surface, sensor or set of sensors that accepts input from the user based on haptic and/or tactile contact. Touch screen 112 and display controller 156 (along with any associated modules and/or sets of instructions in memory 102) detect contact (and any movement or breaking of the contact) on touch screen 112 and converts the detected

contact into interaction with user-interface objects (e.g., one or more soft keys, icons, web pages or images) that are displayed on touch screen 112. In an example embodiment, a point of contact between touch screen 112 and the user corresponds to a finger of the user.

[0063] Touch screen 112 may use LCD (liquid crystal display) technology, LPD (light emitting polymer display) technology, or LED (light emitting diode) technology, although other display technologies may be used in other embodiments. Touch screen 112 and display controller 156 may detect contact and any movement or breaking thereof using any of a variety of touch sensing technologies now known or later developed, including but not limited to capacitive, resistive, infrared, and surface acoustic wave technologies, as well as other proximity sensor arrays or other elements for determining one or more points of contact with touch screen 112. In an example embodiment, projected mutual capacitance sensing technology is used, such as that found in the iPhone®, iPod Touch®, and iPad® from Apple Inc. of Cupertino, California.

[0064] Touch screen 112 may have a video resolution in excess of 100 dpi. In some embodiments, the touch screen has a video resolution of approximately 160 dpi. The user may make contact with touch screen 112 using any suitable object or appendage, such as a stylus, a finger, and so forth. In some embodiments, the user interface is designed to work primarily with finger-based contacts and gestures, which can be less precise than stylus-based input due to the larger area of contact of a finger on the touch screen. In some embodiments, the device translates the rough finger-based input into a precise pointer/cursor position or command for performing the actions calculated by the user.

[0065] In some embodiments, in addition to the touch screen, device 100 may include a touchpad (not shown) for activating or deactivating particular functions. In some embodiments, the touchpad is a touch-sensitive area of the device that, unlike the touch screen, does not display visual output. The touchpad may be a touch-sensitive surface that is separate from touch screen 112 or an extension of the touch-sensitive surface formed by the touch screen.

[0066] Device 100 also includes power system 162 for powering the various components. Power system 162 may include a power management system, one or more power sources (e.g., battery, alternating current (AC)), a recharging system, a power failure detection circuit, a power converter or inverter, a power status indicator (e.g., a light-emitting diode (LED)) and any other components associated with the generation, management and distribution of power in portable devices.

[0067] Device 100 may also include one or more optical sensors or cameras 164. FIG. 28 shows an optical sensor coupled to optical sensor controller 158 in I/O subsystem 106. Optical sensor 164 may include charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) phototransistors. Optical sensor 164 receives light from the environment, projected through one or more lens, and converts the light to data representing an image. In conjunction with imaging module 143 (also called a camera module), optical sensor 164 may capture still images or video. In some embodiments, an optical sensor is located on the back of device 100, opposite touch screen display 112 on the front of the device, so that the touch screen display may be used as a viewfinder for still and/or video image acquisition. In some embodiments, another optical sensor is located on the front of the device so that the user's image may be obtained for videoconferencing while the user views the other video conference participants on the touch screen display.

[0068] Device 100 may also include one or more proximity sensors 166. FIG. 28 shows proximity sensor 166 coupled to peripherals interface 118. Alternately, proximity sensor 166 may be coupled to input controller 160 in I/O subsystem 106. In some embodiments, the proximity sensor turns off and disables touch screen 112 when the multifunction device is placed near the user's ear (e.g., when the user is making a phone call).

[0069] Device 100 includes one or more orientation sensors 168. In some embodiments, the one or more orientation sensors include one or more accelerometers (e.g., one or more linear accelerometers and/or one or more rotational accelerometers). In some embodiments, the one or more orientation sensors include one or more gyroscopes. In some embodiments, the one or more

orientation sensors include one or more magnetometers. In some embodiments, the one or more orientation sensors include one or more of global positioning system (GPS), Global Navigation Satellite System (GLONASS), and/or other global navigation system receivers. The GPS, GLONASS, and/or other global navigation system receivers may be used for obtaining information concerning the location and orientation (e.g., portrait or landscape) of device 100. In some embodiments, the one or more orientation sensors include any combination of orientation/rotation sensors. FIG. 1 shows the one or more orientation sensors 168 coupled to peripherals interface 118. Alternately, the one or more orientation sensors 168 may be coupled to an input controller 160 in I/O subsystem 106. In some embodiments, information is displayed on the touch screen display in a portrait view or a landscape view based on an analysis of data received from the one or more orientation sensors.

[0070] In some embodiments, the software components stored in memory 102 include operating system 126, communication module (or set of instructions) 128, contact/motion module (or set of instructions) 130, graphics module (or set of instructions) 132, text input module (or set of instructions) 134, Global Positioning System (GPS) module (or set of instructions) 135, arbiter module 157 and applications (or sets of instructions) 136. Furthermore, in some embodiments memory 102 stores device/global internal state 157, as shown in Figures 1A and 3. Device/global internal state 157 includes one or more of: active application state, indicating which applications, if any, are currently active; display state, indicating what applications, views or other information occupy various regions of touch screen display 112; sensor state, including information obtained from the device's various sensors and input control devices 116; and location information concerning the device's location and/or attitude.

[0071] Operating system 126 (e.g., Darwin, RTXC, LINUX, UNIX, OS X, WINDOWS, or an embedded operating system such as VxWorks) includes various software components and/or drivers for controlling and managing general system tasks (e.g., memory management, storage device control, power management, etc.) and facilitates communication between various hardware and software components.

[0072] Communication module 128 facilitates communication with other devices over one or more external ports 124 and also includes various software components for handling data received by RF circuitry 108 and/or external port 124. External port 124 (e.g., Universal Serial Bus (USB), FIREWIRE, etc.) is adapted for coupling directly to other devices or indirectly over a network (e.g., the Internet, wireless LAN, etc.). In some embodiments, the external port is a multi-pin (e.g., 30-pin) connector that is the same as, or similar to and/or compatible with the 30-pin connector used on iPod (trademark of Apple Inc.) devices.

[0073] Contact/motion module 130 may detect contact with touch screen 112 (in conjunction with display controller 156) and other touch sensitive devices (e.g., a touchpad or physical click wheel). Contact/motion module 130 includes various software components for performing various operations related to detection of contact, such as determining if contact has occurred (e.g., detecting a finger-down event), determining if there is movement of the contact and tracking the movement across the touch-sensitive surface (e.g., detecting one or more finger-dragging events), and determining if the contact has ceased (e.g., detecting a finger-up event or a break in contact). Contact/motion module 130 receives contact data from the touch-sensitive surface. Determining movement of the point of contact, which is represented by a series of contact data, may include determining speed (magnitude), velocity (magnitude and direction), and/or an acceleration (a change in magnitude and/or direction) of the point of contact. These operations may be applied to single contacts (e.g., one finger contacts) or to multiple simultaneous contacts (e.g., "multitouch"/multiple finger contacts). In some embodiments, contact/motion module 130 and display controller 156 detect contact on a touchpad.

[0074] Contact/motion module 130 may detect a gesture input by a user. Different gestures on the touch-sensitive surface have different contact patterns. Thus, a gesture may be detected by detecting a particular contact pattern. For example, detecting a finger tap gesture includes detecting a finger-down event followed by detecting a finger-up (lift off) event at the same position (or substantially the same position) as the finger-down event (e.g., at the position of an icon). As another example, detecting a finger swipe gesture on the touch-sensitive surface

includes detecting a finger-down event followed by detecting one or more finger-dragging events, and subsequently followed by detecting a finger-up (lift off) event.

[0075] Graphics module 132 includes various known software components for rendering and displaying graphics on touch screen 112 or other display, including components for changing the intensity of graphics that are displayed. As used herein, the term “graphics” includes any object that can be displayed to a user, including without limitation text, web pages, icons (such as user-interface objects including soft keys), digital images, videos, animations and the like.

[0076] In some embodiments, graphics module 132 stores data representing graphics to be used. Each graphic may be assigned a corresponding code. Graphics module 132 receives, from applications etc., one or more codes specifying graphics to be displayed along with, if necessary, coordinate data and other graphic property data, and then generates screen image data to output to display controller 156.

[0077] Text input module 134, which may be a component of graphics module 132, provides soft keyboards for entering text in various applications (e.g., contacts 137, e-mail 140, IM 141, browser 147, and any other application that needs text input).

[0078] GPS module 135 determines the location of the device and provides this information for use in various applications (e.g., to telephone 138 for use in location-based dialing, to camera 143 as picture/video metadata, and to applications that provide location-based services such as weather widgets, local yellow page widgets, and map/navigation widgets).

[0079] Applications 136 may include the following modules (or sets of instructions), or a subset or superset thereof:

- contacts module 137 (sometimes called an address book or contact list);
- telephone module 138;
- video conferencing module 139;
- e-mail client module 140;

- instant messaging (IM) module 141;
- workout support module 142;
- camera module 143 for still and/or video images;
- image management module 144;
- browser module 147;
- calendar module 148;
- widget modules 149, which may include one or more of: weather widget 149-1, stocks widget 149-2, calculator widget 149-3, alarm clock widget 149-4, dictionary widget 149-5, and other widgets obtained by the user, as well as user-created widgets 149-6;
- widget creator module 150 for making user-created widgets 149-6;
- search module 151;
- video and music player module 152, which may be made up of a video player module and a music player module;
- notes module 153;
- map module 154; and/or
- online video module 155.

[0080] Examples of other applications 136 that may be stored in memory 102 include other word processing applications, other image editing applications, drawing applications, presentation applications, JAVA-enabled applications, encryption, digital rights management, voice recognition, and voice replication.

[0081] In conjunction with touch screen 112, display controller 156, contact module 130, graphics module 132, and text input module 134, contacts module 137 may be used to manage an address book or contact list (e.g., stored in application internal state 192 of contacts module 137 in memory 102 or memory 370), including: adding name(s) to the address book; deleting name(s) from the address book; associating telephone number(s), e-mail address(es), physical address(es) or other information with a name; associating an image with a name; categorizing and sorting names; providing telephone numbers or e-mail addresses to initiate and/or facilitate communications by telephone 138, video conference 139, e-mail 140, or IM 141; and so forth.

[0082] In conjunction with RF circuitry 108, audio circuitry 110, speaker 111, microphone 113, touch screen 112, display controller 156, contact module 130, graphics module 132, and text input module 134, telephone module 138 may be used to enter a sequence of characters corresponding to a telephone number, access one or more telephone numbers in address book 137, modify a telephone number that has been entered, dial a respective telephone number, conduct a conversation and disconnect or hang up when the conversation is completed. As noted above, the wireless communication may use any of a variety of communications standards, protocols and technologies.

[0083] In conjunction with RF circuitry 108, audio circuitry 110, speaker 111, microphone 113, touch screen 112, display controller 156, optical sensor 164, optical sensor controller 158, contact module 130, graphics module 132, text input module 134, contact list 137, and telephone module 138, videoconferencing module 139 includes executable instructions to initiate, conduct, and terminate a video conference between a user and one or more other participants in accordance with user instructions.

[0084] In conjunction with RF circuitry 108, touch screen 112, display controller 156, contact module 130, graphics module 132, and text input module 134, e-mail client module 140 includes executable instructions to create, send, receive, and manage e-mail in response to user instructions. In conjunction with image management module 144, e-mail client module 140 makes it very easy to create and send e-mails with still or video images taken with camera module 143.

[0085] In conjunction with RF circuitry 108, touch screen 112, display controller 156, contact module 130, graphics module 132, and text input module 134, the instant messaging module 141 includes executable instructions to enter a sequence of characters corresponding to an instant message, to modify previously entered characters, to transmit a respective instant message (for example, using a Short Message Service (SMS) or Multimedia Message Service (MMS) protocol for telephony-based instant messages or using XMPP, SIMPLE, or IMPS for Internet-based

instant messages), to receive instant messages and to view received instant messages. In some embodiments, transmitted and/or received instant messages may include graphics, photos, audio files, video files and/or other attachments as are supported in a MMS and/or an Enhanced Messaging Service (EMS). As used herein, “instant messaging” refers to both telephony-based messages (e.g., messages sent using SMS or MMS) and Internet-based messages (e.g., messages sent using XMPP, SIMPLE, or IMPS).

[0086] In conjunction with RF circuitry 108, touch screen 112, display controller 156, contact module 130, graphics module 132, text input module 134, GPS module 135, map module 154, and music player module 146, workout support module 142 includes executable instructions to create workouts (e.g., with time, distance, and/or calorie burning goals); communicate with workout sensors (sports devices); receive workout sensor data; calibrate sensors used to monitor a workout; select and play music for a workout; and display, store and transmit workout data.

[0087] In conjunction with touch screen 112, display controller 156, optical sensor(s) 164, optical sensor controller 158, contact module 130, graphics module 132, and image management module 144, camera module 143 includes executable instructions to capture still images or video (including a video stream) and store them into memory 102, modify characteristics of a still image or video, or delete a still image or video from memory 102.

[0088] In conjunction with touch screen 112, display controller 156, contact module 130, graphics module 132, text input module 134, and camera module 143, image management module 144 includes executable instructions to arrange, modify (e.g., edit), or otherwise manipulate, label, delete, present (e.g., in a digital slide show or album), and store still and/or video images.

[0089] In conjunction with RF circuitry 108, touch screen 112, display system controller 156, contact module 130, graphics module 132, and text input module 134, browser module 147 includes executable instructions to browse the Internet in accordance with user instructions,

including searching, linking to, receiving, and displaying web pages or portions thereof, as well as attachments and other files linked to web pages.

[0090] In conjunction with RF circuitry 108, touch screen 112, display system controller 156, contact module 130, graphics module 132, text input module 134, e-mail client module 140, and browser module 147, calendar module 148 includes executable instructions to create, display, modify, and store calendars and data associated with calendars (e.g., calendar entries, to do lists, etc.) in accordance with user instructions.

[0091] In conjunction with RF circuitry 108, touch screen 112, display system controller 156, contact module 130, graphics module 132, text input module 134, and browser module 147, widget modules 149 are mini-applications that may be downloaded and used by a user (e.g., weather widget 149-1, stocks widget 149-2, calculator widget 149-3, alarm clock widget 149-4, and dictionary widget 149-5) or created by the user (e.g., user-created widget 149-6). In some embodiments, a widget includes an HTML (Hypertext Markup Language) file, a CSS (Cascading Style Sheets) file, and a JavaScript file. In some embodiments, a widget includes an XML (Extensible Markup Language) file and a JavaScript file (e.g., Yahoo! Widgets).

[0092] In conjunction with RF circuitry 108, touch screen 112, display system controller 156, contact module 130, graphics module 132, text input module 134, and browser module 147, the widget creator module 150 may be used by a user to create widgets (e.g., turning a user-specified portion of a web page into a widget).

[0093] In conjunction with touch screen 112, display system controller 156, contact module 130, graphics module 132, and text input module 134, search module 151 includes executable instructions to search for text, music, sound, image, video, and/or other files in memory 102 that match one or more search criteria (e.g., one or more user-specified search terms) in accordance with user instructions.

[0094] In conjunction with touch screen 112, display system controller 156, contact module 130, graphics module 132, audio circuitry 110, speaker 111, RF circuitry 108, and browser module 147, video and music player module 152 includes executable instructions that allow the user to download and play back recorded music and other sound files stored in one or more file formats, such as MP3 or AAC files, and executable instructions to display, present or otherwise play back videos (e.g., on touch screen 112 or on an external, connected display via external port 124). In some embodiments, device 100 may include the functionality of an MP3 player, such as an iPod (trademark of Apple Inc.).

[0095] In conjunction with touch screen 112, display controller 156, contact module 130, graphics module 132, and text input module 134, notes module 153 includes executable instructions to create and manage notes, to do lists, and the like in accordance with user instructions.

[0096] In conjunction with RF circuitry 108, touch screen 112, display system controller 156, contact module 130, graphics module 132, text input module 134, GPS module 135, and browser module 147, map module 154 may be used to receive, display, modify, and store maps and data associated with maps (e.g., driving directions; data on stores and other points of interest at or near a particular location; and other location-based data) in accordance with user instructions.

[0097] In conjunction with touch screen 112, display system controller 156, contact module 130, graphics module 132, audio circuitry 110, speaker 111, RF circuitry 108, text input module 134, e-mail client module 140, and browser module 147, online video module 155 includes instructions that allow the user to access, browse, receive (e.g., by streaming and/or download), play back (e.g., on the touch screen or on an external, connected display via external port 124), send an e-mail with a link to a particular online video, and otherwise manage online videos in one or more file formats, such as H.264. In some embodiments, instant messaging module 141, rather than e-mail client module 140, is used to send a link to a particular online video.

[0098] Each of the above identified modules and applications correspond to a set of executable instructions for performing one or more functions described above and the methods described in this application (e.g., the computer-implemented methods and other information processing methods described herein). These modules (i.e., sets of instructions) need not be implemented as separate software programs, procedures or modules, and thus various subsets of these modules may be combined or otherwise rearranged in various embodiments. In some embodiments, memory 102 may store a subset of the modules and data structures identified above. Furthermore, memory 102 may store additional modules and data structures not described above.

[0099] In some embodiments, device 100 is a device where operation of a predefined set of functions on the device is performed exclusively through a touch screen and/or a touchpad. By using a touch screen and/or a touchpad as the primary input control device for operation of device 100, the number of physical input control devices (such as push buttons, dials, and the like) on device 100 may be reduced.

[00100] The predefined set of functions that may be performed exclusively through a touch screen and/or a touchpad include navigation between user interfaces. In some embodiments, the touchpad, when touched by the user, navigates device 100 to a main, home, or root menu from any user interface that may be displayed on device 100. In such embodiments, the touchpad may be referred to as a “menu button.” In some other embodiments, the menu button may be a physical push button or other physical input control device instead of a touchpad.

[00101] FIG. 2 illustrates a portable multifunction device 100 having a touch screen 112 in accordance with some embodiments. The touch screen may display one or more graphics within user interface (UI) 200. In this embodiment, as well as others described below, a user may select one or more of the graphics by making a gesture on the graphics, for example, with one or more fingers 202 (not drawn to scale in the figure) or one or more styluses 203 (not drawn to scale in the figure).

[00102] Device 100 may also include one or more physical buttons, such as "home" or menu button 204. As described previously, menu button 204 may be used to navigate to any application 136 in a set of applications that may be executed on device 100. Alternatively, in some embodiments, the menu button is implemented as a soft key in a GUI displayed on touch screen 112.

[00103] In one embodiment, device 100 includes touch screen 112, menu button 204, push button 206 for powering the device on/off and locking the device, volume adjustment button(s) 208, Subscriber Identity Module (SIM) card slot 210, head set jack 212, and docking/charging external port 124. Push button 206 may be used to turn the power on/off on the device by depressing the button and holding the button in the depressed state for a predefined time interval; to lock the device by depressing the button and releasing the button before the predefined time interval has elapsed; and/or to unlock the device or initiate an unlock process. In an alternative embodiment, device 100 also may accept verbal input for activation or deactivation of some functions through microphone 113.

[00104] It should be noted that, although many of the examples herein are given with reference to optical sensor / camera 164 (on the front of a device), a rear-facing camera or optical sensor that is pointed opposite from the display may be used instead of or in addition to an optical sensor / camera 164 on the front of a device.

[00105] FIG. 3 depicts a side view of an example embodiment of actuator module components assembled on a test station for single frame camera active optical tilt alignment correction, according to at least some embodiments. A test station 3050 with an optical target 3058 is loaded with an assembly of camera components including an optics module (e.g., a lens barrel) 3002 attached to an optics holder 3003 and a magnet holder 3006. An image sensor 3070, which may or may not be mounted on a substrate that is not shown separately in FIG. 3, is attached to a camera module base 3008. The camera components may further include, in addition to components such as power and remote control connections not shown, a cover 3012 and suspension wires 3020.

[00106] Optics module 3002 may be suspended on the base assembly 3008 by suspension of the upper springs 3030 and the suspension wires 3020. Camera components may include one or more of, but are not limited to, optics 3002, optics holder 3003, magnet holder(s) 3006, upper spring(s) 3030, and lower spring(s) 3032. The upper and lower spring(s) may be collectively referred to herein as optics springs. An optics module (e.g., a lens or lens assembly or lens barrel) 3002 may be screwed, mounted or otherwise held in or by an optics holder 3003. In at least some embodiments, the optics 3002/optics holder 3003 assembly may be suspended from or attached to the magnet holder 3006 by upper spring(s) 3030, and lower spring(s) 3032. Note that upper spring(s) 3030 and lower spring(s) 3032 are flexible to allow the optics assembly 3000 a range of motion along the Z (optical) axis for optical focusing, wires 3020 are flexible to allow a range of motion on the XY plane orthogonal to the optical axis for optical image stabilization.

[00107] Note that, in some embodiments, a camera may not include magnets and magnet holder(s) 3006, but may include a yoke or other structure 3006 that may be used to help support the optics assembly on suspension wires 3020 via upper springs 3030. In general, other embodiments of an optics assembly 3000 may include fewer or more components than the example optics assembly 3000 shown in FIG. 3. Also note that, while embodiments show the optics assembly 3000 suspended on wires 3020, other mechanisms may be used to suspend an optics assembly 3000 in other embodiments.

[00108] The autofocus yoke (e.g., magnet holder(s) 3006) acts as the support chassis structure for the autofocus mechanism of actuator 3000. The lens carrier (optics holder 3003) is suspended on the autofocus yoke by an upper autofocus (AF) spring 3030 and a lower optics spring 3032. In this way when an electric current is applied to the autofocus coil, Lorentz forces are developed due to the presence of the four magnets, and a force substantially parallel to the optical axis is generated to move the lens carrier, and hence lens, along the optical axis, relative to the support structure of the autofocus mechanism of the actuator, so as to focus the lens. In addition to suspending the lens carrier and substantially eliminating parasitic motions, the upper spring 3030 and lower spring 3032 also resist the Lorentz forces, and hence convert the forces to a

displacement of the lens. This basic architecture shown in FIGs 3 is typical of some embodiments, in which optical image stabilization function includes moving the entire autofocus mechanism of the actuator (supported by the autofocus yoke) in linear directions orthogonal to the optical axis, in response to user handshake, as detected by some means, such a two or three axis gyroscope, which senses angular velocity. The handshake of interest is the changing angular tilt of the camera in 'pitch and yaw directions', which can be compensated by said linear movements of the lens relative to the image sensor.

[00109] In at least some embodiments, the suspension of the autofocus mechanism on the actuator 3000 support structure may be achieved by the use of four corner wires 3020, for example wires with a circular cross-section. Each wire 3020 acts as a flexure beams capable of bending with relatively low stiffness, thus allowing motion in both optical image stabilization degrees-of-freedom. However, wire 3020 is in some embodiments relatively stiff in directions parallel to the optical axis, as this would require the wire to stretch or buckle, thus substantially preventing parasitic motions in these directions. In addition, the presence of four such wires, appropriately separated allows them to be stiff in the parasitic tilt directions of pitch and yaw, thus substantially preventing relative dynamic tilt between the lens and image sensor. This may be seen by appreciating that each wire 3020 is stiff in directions that require it to change in length, and hence the fixed points at the ends of each wire (eight points in total) will substantially form the vertices of a parallelepiped for all operational positions of the optical image stabilization mechanism.

[00110] In some embodiments, upon assembly of the aforementioned camera components on test station 3050, an image sensor optical axis 3052 will differ from a lens optical axis 3053 by an angle 3056. The difference or correspondence between an image sensor optical axis 3052 and a lens optical axis 3053 is referred to as optical alignment, and correcting optical alignment of components in a camera module for a multifunction device is defined as reducing absolute value of an angle 3056. Some embodiments provide methods and systems for correcting optical alignment of components in a camera module for a multifunction device by reducing angle 3056.

[00111] Some embodiments include methods for correcting optical alignment of components in a camera module for a multifunction device by reducing angle 3056. In some embodiments, components of a camera module for use in a multifunction device, such as items 3002-3032 and 3070 are assembled on a test station 3050 associated with a target 3058. Some embodiments include a method that includes capturing a single test image of target 3058, calculating from spatial frequency response data derived from target 3058 an optical tilt (e.g., angle 3056) between the optical axis of a lens 3053 and an optical axis of the image sensor 3070 of the camera module, and mechanically adjusting an alignment of the lens 3053 and the optical axis 3052 of the image sensor 3070 of the camera module to reduce the optical tilt (e.g., angle 3056). In some embodiments, the capturing is performed using the components of the camera module, such as items 3002-3032 and 3070, and the single test image contains visually encoded spatial frequency response data captured from target 3058 for characterizing the components of the camera module that includes items 3002-3032 and 3070.

[00112] In some embodiments, the calculating from the spatial frequency response data captured from target 3058 the optical tilt represented by angle 3056 between the optical axis of the lens 3053 and the optical axis of the image sensor 3053 of the camera module further includes calculating the optical tilt represented by angle 3056 between the optical axis of the lens 3053 and the optical axis of the image sensor 3053 of the camera module from not more than one test image of target 3058. The ability to perform calculating the optical tilt between represented by angle 3056 between the optical axis of the lens 3053 and the optical axis of the image sensor 3053 of the camera module with only one test image of target 3058 is a decisive advantage presented by some embodiments.

[00113] In some embodiments, the calculating from the spatial frequency response data acquired from target 3058 the optical tilt represented by angle 3056 between the optical axis of the lens 3053 and the optical axis of the image sensor 3053 of the camera module further includes fitting a two-dimensional surface to the spatial frequency response data acquired from target 3058 using a tilted linear plane model from low frequency spatial frequency response data acquired from target 3058. In some embodiments, the method further includes estimating

correction angles from the plane, and applying linear calibration to convert the correction angles to physical correction angles applicable to the lens of lens of optics module 3002 and the optical axis of the image sensor 3070 of the camera module to reduce the optical tilt represented by angle 3056.

[00114] In some embodiments, the calculating from the spatial frequency response data acquired from target 3058 the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further includes fitting a plane to the spatial frequency response data using a weighted-least squares calculation on a tilted linear plane model with low frequency spatial frequency response data.

[00115] In some embodiments, the calculating from the spatial frequency response data the optical tilt by angle 3056 between the optical axis of the lens 3053 and the optical axis of the image sensor 3053 of the camera module further includes fitting a plane to the spatial frequency response data. In some embodiments, the method further includes estimating correction angles from the plane, and applying linear calibration to convert the correction angles to physical correction angles applicable to the lens of optics module 3002 and the optical axis of the image sensor 3070 of the camera module to reduce the optical tilt represented by angle 3056.

[00116] Some embodiments further include bonding the lens barrel assembly (e.g., optics module 3002 including the lens to a connection (e.g., optics holder 3003) for the optical axis of the image sensor 3070 of the camera module to make permanent the alignment in the position resulting from the mechanically adjusting. In some embodiments, the mechanically adjusting the alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt further includes mechanically adjusting an alignment of a lens barrel assembly comprising the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt. Some embodiments include a camera module of a multifunction device. The camera module 3000 includes an image sensor, and a lens assembly moveably fixed to the image sensor.

[00117] FIG. 4 illustrates a processed test pattern chart for generating spatial frequency response data that may be used for imaging for single frame camera active optical tilt alignment correction, according to at least some embodiments, marked up with feature detection results. Target 400 includes a test chart with a distribution of large shapes (e.g. 402), small shapes (e.g., 404) and grid lines (e.g. 406) for generating spatial frequency response data. The large shapes 402 are slanted edge SFR squares, the small shapes 404 are used for feature detection, the grid lines are detection results 406 (not really a feature of the chart, but rather of the markup). The spatial frequency response is the frequency response of the camera system based on a specific target input feature such as a slanted edge, siemens star, dead-leaves pattern, superimposed, orthogonal sinusoidal line-pair pattern, and the like, in regions such as a center region 408, a 30% region 410, a 60% region 412 and an 85% region 414. Some embodiments fit a plane to $(x_i, y_i, \text{SFR}@f_{\text{low}})$ (low spatial frequency information)), where (x_i, y_i) locations include multiple center regions 408, 30% regions 410, 60% regions 412, and 85% regions 414. In some embodiments, multiple regions are useful for reducing noise in the surface fit. Some embodiments estimate correction angles θ_x, θ_y from the fitted two-dimensional surface and apply a linear calibration factor to convert estimated correction angles θ_x, θ_y to physical correction angles applicable to the machine.

[00118] FIG. 5 depicts a graph of low spatial frequency spatial frequency response sensitivity to lens-to-sensor tilt in the presence of large defocus for single frame camera active optical tilt alignment correction, according to at least some embodiments. Low spatial frequency tilt sensitivity enables linear calibration of the fitted surface angle and the machine correction angle. A first graph 500 shows spatial frequency response data for a case varying $\theta_x \in [-1^\circ, 1^\circ]$ while keeping $\theta_y = 0^\circ$ with spatial frequency response 502, y location 504 and x location 506 illustrated. A second graph 510 shows spatial frequency response data for a case varying $\theta_y \in [-1^\circ, 1^\circ]$ while keeping $\theta_x = 0^\circ$ with spatial frequency response 512, y location 514 and x location 516 illustrated.

[00119] As discussed with respect to the methods below, some embodiments employ a Tilted Plane Linear Model: $f(x_i, y_i) = (p_{10})x_i + (p_{01})y_i + (p_{00})$, where $f(x_i, y_i)$ are the low spatial frequency

response ($\text{SFR}@f_{\text{low}}$) at image plane field point position of (x_i, y_i) . In some embodiments, coefficients of fit are estimated with weighted least squares, such that:

$$- \mathbf{A} = [x_i \ y_i \ 1], \mathbf{x} = [p_{10} \ p_{01} \ p_{00}], \mathbf{b} = [f(x_i, y_i)],$$

$$- \mathbf{w} = [w_i], \mathbf{W} = \text{diag}(\mathbf{w}), \text{ and}$$

$$- \mathbf{x} = \min \|\mathbf{b} - \mathbf{Ax}\|_{\mathbf{W}}.$$

As noted before, one of skill in the art will readily comprehend in light of having read the present disclosure that the methods discussed herein can be generalized to fitting a general 2d surface model. Linear plane fitting is a specific embodiment. Other embodiments use models include higher order terms which could account for lens field curvature without departing from the scope and intent of the present disclosure.

[00120] In some embodiments, weights, w_i , are selected to give more weight to those fields which are most sensitive to tilt depending on the lens characteristic. In some embodiments, a normal vector to a tilted plane is estimated by evaluating a fitted plane at (x, y) such that $x \in [\min(x_i), \max(x_i)]$ and $y \in [\min(y_i), \max(y_i)]$: $\mathbf{f}_{\text{measured}}(x, y)$. In some embodiments, a determination is made to find a plane normal in positive z-direction using two measured plane vectors ($\mathbf{p}_0$ and $\mathbf{p}_1$) in the $(x > 0) \wedge (y > 0)$ quadrant (QI), such that $\mathbf{n}_{\text{measured}} = (\mathbf{p}_0 \times \mathbf{p}_1) / \|\mathbf{p}_0 \times \mathbf{p}_1\|^2$.

[00121] Some embodiments estimate transformation angles needed to rotate the ideal non-tilted plane ($\mathbf{f}_{\text{ideal}}(x, y)$) to match the measured tilted plane ($\mathbf{f}_{\text{measured}}(x, y)$) by minimizing the squared error between the measured and estimated tilted planes via Nelder-Mead multidimensional, unconstrained nonlinear minimization:

$$(\theta_x^*, \theta_y^*) = \underset{\theta_x, \theta_y}{\text{argmin}} \sum_x \sum_y (\mathbf{f}_{\text{measured}}(x, y) - \mathbf{f}_{\text{estimated}}(x, y; \theta_x, \theta_y))^2 \text{ with}$$

$\mathbf{f}_{\text{measured}}(x, y)$ from fitted data

$$\mathbf{f}_{\text{estimated}}(x,y;\theta_x,\theta_y) = \mathbf{R}_{xy}(\theta_x,\theta_y) \mathbf{f}_{\text{ideal}}(x,y)$$

$$\mathbf{f}_{\text{ideal}}(x,y) = [x; y; 0] \text{ (i.e. } z = 0 \text{ plane)}$$

$$\mathbf{R}_{xy}(\theta_x,\theta_y) = \mathbf{R}_x(\theta_x)\mathbf{R}_y(\theta_y)$$

[00122] An initial condition (θ_x^0, θ_y^0) is estimated as an angle between normal to $\mathbf{f}_{\text{measured}}(x,y)$ and normal to $\mathbf{f}_{\text{ideal}}(x,y)$. Angle sign adjustment is made depending on where $\mathbf{n}_{\text{measured}}$ lies in the (x,y) plane: ($\times$ denotes vector cross-product, $\cdot$ denotes vector dot product), such that $\theta_{\mathbf{n}_{\text{measured}} \times \mathbf{n}_{\text{ideal}}} = (\pi/180^\circ) \text{atan2}(\|\mathbf{n}_{\text{measured}} \times \mathbf{n}_{\text{ideal}}\|_2, \mathbf{n}_{\text{measured}} \cdot \mathbf{n}_{\text{ideal}})$. In some embodiments Alternative initial condition estimated from the fitted plane:

$$\theta_x^0 = \arctan(p_{01}) \quad \theta_y^0 = -\arctan(p_{10}) \quad \theta_z^0 = -\arctan(p_{10}).$$

[00123] FIG. 6 depicts charts of rotation values for single frame camera active optical tilt alignment correction, according to at least some embodiments. An x-rotation (roll) chart 602 and a y-rotation (pitch) chart 604 are included.

[00124] FIG. 7A illustrates a graph of angle sign adjustments along axes for single frame camera active optical tilt alignment correction, according to at least some embodiments. An x-axis 702 and a y-axis 704 are depicted.

Along axis:

- $(x=0, y>0): (n_x = 0) \wedge (n_y > 0)$

$$- \theta_x^0 = -\theta_{\mathbf{n}_{\text{measured}} \times \mathbf{n}_{\text{ideal}}}$$

$$- \theta_y^0 = 0$$

- $(x=0, y<0): (n_x = 0) \wedge (n_y < 0)$

$$- \theta_x^0 = \theta_{\mathbf{n}_{\text{measured}} \times \mathbf{n}_{\text{ideal}}}$$

$$- \theta_y^0 = 0$$

- $(x>0, y=0): (n_x > 0) \wedge (n_y = 0)$

$$- \theta_x^0 = 0$$

$$- \theta_y^0 = \theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- (x < 0, y = 0): (n_x < 0) \wedge (n_y = 0)$$

$$- \theta_x^0 = 0$$

$$- \theta_y^0 = -\theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

[00125] FIG. 7B illustrates a graph of angle sign adjustments along axes for single frame camera active optical tilt alignment correction, according to at least some embodiments. A first quadrant 710, a second quadrant 712, a third quadrant 714 and a fourth quadrant 716 are depicted.

Inside quadrant:

$$- \text{QI: } (n_x > 0) \wedge (n_y > 0)$$

$$- \theta_x^0 = -\theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- \theta_y^0 = \theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- \text{QII: } (n_x > 0) \wedge (n_y < 0)$$

$$- \theta_x^0 = \theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- \theta_y^0 = \theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- \text{QIII: } (n_x < 0) \wedge (n_y > 0)$$

$$- \theta_x^0 = -\theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- \theta_y^0 = -\theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- \text{QIV: } (n_x < 0) \wedge (n_y < 0)$$

$$- \theta_x^0 = \theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

$$- \theta_y^0 = -\theta_{\text{measured}} \angle \mathbf{n}_{\text{ideal}}$$

[00126] Some embodiments assume use of $\mathbf{R}_{xy}$, but due to commutation under small angle approximation (adjustment of $\pm 2^\circ$ w/1 arcmin resolution), $\mathbf{R}_{xy} \approx \mathbf{R}_{yx}$:

$$\begin{aligned}
\mathbf{R}_x(\theta_x, \theta_y) - \mathbf{R}_y(\theta_x, \theta_y) &= \begin{pmatrix} 0 & -\sin(\theta_x)\sin(\theta_y) & \sin(\theta_y) - \cos(\theta_x)\sin(\theta_y) \\ \sin(\theta_x)\sin(\theta_y) & 0 & \sin(\theta_x) - \cos(\theta_y)\sin(\theta_x) \\ \sin(\theta_x) - \cos(\theta_x)\sin(\theta_y) & \sin(\theta_x) - \cos(\theta_y)\sin(\theta_x) & 0 \end{pmatrix} = \begin{pmatrix} 0 & -\theta_x\theta_y & \theta_y - \left(1 - \frac{\theta_x^2}{2}\right)\theta_y \\ \theta_x\theta_y & 0 & \theta_x - \left(1 - \frac{\theta_y^2}{2}\right)\theta_x \\ \theta_y - \left(1 - \frac{\theta_x^2}{2}\right)\theta_y & \theta_x - \left(1 - \frac{\theta_y^2}{2}\right)\theta_x & 0 \end{pmatrix} \\
\mathbf{R}_x(\theta_x, \theta_y) - \mathbf{R}_x(\theta_x, \theta_z) &= \begin{pmatrix} 0 & \sin(\theta_x)\sin(\theta_z) & -\sin(\theta_z) + \cos(\theta_x)\sin(\theta_z) \\ -\sin(\theta_x)\sin(\theta_z) & 0 & -\sin(\theta_x) + \cos(\theta_z)\sin(\theta_x) \\ -\sin(\theta_x) + \cos(\theta_x)\sin(\theta_z) & -\sin(\theta_x) + \cos(\theta_z)\sin(\theta_x) & 0 \end{pmatrix} = \begin{pmatrix} 0 & \theta_x\theta_z & -\theta_z + \left(1 - \frac{\theta_x^2}{2}\right)\theta_z \\ -\theta_x\theta_z & 0 & -\theta_x + \left(1 - \frac{\theta_z^2}{2}\right)\theta_x \\ -\theta_z + \left(1 - \frac{\theta_x^2}{2}\right)\theta_z & -\theta_x + \left(1 - \frac{\theta_z^2}{2}\right)\theta_x & 0 \end{pmatrix} \\
&\quad \text{Small angle approximation: } \cos(\theta) = 1 - \frac{\theta^2}{2} \quad \sin(\theta) = \theta \\
&\quad \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}
\end{aligned}$$

[00127] FIG. 8 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments. A single test image is captured with one or more components of the camera module (block 800). An optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module is calculated from the single test image (block 802).

[00128] FIG. 9 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments. A single test image that contains visually encoded spatial frequency response data for characterizing the components of the camera module is captured (block 900). An optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module is calculated from the spatial frequency data by fitting a plane, though one of skill in the art will readily comprehend from having read the present disclosure that other two-dimensional surfaces may be used without departing from the scope and intent of the present disclosure, to the spatial frequency response data using a tilted linear plane model from low frequency spatial frequency response data (block 902). Correction angles are estimated from the plane (block 904). Linear calibration is applied to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt (block 906).

[00129] FIG. 10 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments. Components of a camera module

for use in a multifunction device are assembled on a test station (block 1000). A single test image is captured, using the components of the camera module, such that the single test image contains visually encoded spatial frequency response data for characterizing the components of the camera module (block 1002). An optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module is calculated from the spatial frequency response data (block 1004). An alignment of the lens and the optical axis of the image sensor of the camera module is mechanically adjusted to reduce the optical tilt (block 1006).

[00130] FIG. 11 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments. Components of a camera module for use in a multifunction device are assembled on a test station (block 1100). A single test image visually encoded spatial frequency response data for characterizing the components of the camera module is captured using the components of the camera module (block 1102). An optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module is calculated by fitting a plane, though one of skill in the art will readily comprehend from having read the present disclosure that other two-dimensional surfaces may be used without departing from the scope and intent of the present disclosure, to the spatial frequency response data using a tilted linear plane model from low frequency spatial frequency response data (block 1104). Correction angles are estimated from the plane (block 1106). Linear calibration is applied to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt (block 1108). An alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt is mechanically adjusted (block 1110).

[00131] FIG. 12 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments. Components of a camera module for use in a multifunction device are assembled on a test station (block 1200). A single test image such that the single test image contains visually encoded spatial frequency response data for characterizing the components of the camera module is captured using the components of the camera module (block 1202). An optical tilt between the optical axis of a lens and an optical

axis of the image sensor of the camera module is calculated from the spatial frequency response data by fitting a plane to the spatial frequency response data (block 1204). Correction angles are estimated from the plane (block 1206). Linear calibration is applied to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt (block 1208). An alignment of the lens and the optical axis of the image sensor of the camera module is mechanically adjusted to reduce the optical tilt (block 1210).

[00132] FIG. 13 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments. Components of a camera module for use in a multifunction device are assembled on a test station (block 1300). A single test image such that the single test image contains visually encoded spatial frequency response data for characterizing the components of the camera module is captured using the components of the camera module (block 1302). An optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module is calculated from the spatial frequency response data (block 1304). An alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt is adjusted (block 1306). A lens barrel assembly comprising the lens is bonded to a connection for the optical axis of the image sensor of the camera module to make permanent the alignment in the position resulting from the mechanically adjusting (block 1308).

[00133] FIG. 14 is a flow chart of a method usable for single frame camera active optical tilt alignment correction, according to at least some embodiments. Components of a camera module for use in a multifunction device are assembled on a test station (block 1400). A single test image is captured using the components of the camera module, such that the single test image contains visually encoded spatial frequency response data for characterizing the components of the camera module (block 1402). An optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module is calculated (block 1404). An alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt by mechanically adjusting an alignment of a lens barrel assembly comprising the lens and the optical

axis of the image sensor of the camera module is adjusted to reduce the optical tilt (block 1406).

Example Computer System

[00134] FIG. 15 illustrates an example computer system 1500 that may be configured to execute any or all of the embodiments described above. In different embodiments, computer system 1500 may be any of various types of devices, including, but not limited to, a personal computer system, desktop computer, laptop, notebook, tablet, slate, pad, or netbook computer, mainframe computer system, handheld computer, workstation, network computer, a camera, a set top box, a mobile device, a consumer device, video game console, handheld video game device, application server, storage device, a television, a video recording device, a peripheral device such as a switch, modem, router, or in general any type of computing or electronic device.

[00135] Various embodiments of a camera component motion control system as described herein, including embodiments of single frame camera active optical tilt alignment correction, as described herein may be executed in one or more computer systems 1500, which may interact with various other devices. Note that any component, action, or functionality described above with respect to Figures 1-20 may be implemented on one or more computers configured as computer system 1500 of FIG. 30, according to various embodiments. In the illustrated embodiment, computer system 1500 includes one or more processors 1510 coupled to a system memory 1520 via an input/output (I/O) interface 1530. Computer system 1500 further includes a network interface 1540 coupled to I/O interface 1530, and one or more input/output devices 1550, such as cursor control device 1560, keyboard 1570, and display(s) 1580. In some cases, it is contemplated that embodiments may be implemented using a single instance of computer system 1500, while in other embodiments multiple such systems, or multiple nodes making up computer system 1500, may be configured to host different portions or instances of embodiments. For example, in one embodiment some elements may be implemented via one or more nodes of computer system 1500 that are distinct from those nodes implementing other elements.

[00136] In various embodiments, computer system 1500 may be a uniprocessor system including one processor 1510, or a multiprocessor system including several processors 1510 (e.g., two, four, eight, or another suitable number). Processors 1510 may be any suitable processor capable of executing instructions. For example, in various embodiments processors 1510 may be general-purpose or embedded processors implementing any of a variety of instruction set architectures (ISAs), such as the x86, PowerPC, SPARC, or MIPS ISAs, or any other suitable ISA. In multiprocessor systems, each of processors 1510 may commonly, but not necessarily, implement the same ISA.

[00137] System memory 1520 may be configured to store camera control program instructions 1522 and/or camera control data accessible by processor 1510. In various embodiments, system memory 1520 may be implemented using any suitable memory technology, such as static random access memory (SRAM), synchronous dynamic RAM (SDRAM), nonvolatile/Flash-type memory, or any other type of memory. In the illustrated embodiment, program instructions 1522 may be configured to implement a lens control application 1524 incorporating any of the functionality described above. Additionally, existing camera control data 1532 of memory 1520 may include any of the information or data structures described above. In some embodiments, program instructions and/or data may be received, sent or stored upon different types of computer-accessible media or on similar media separate from system memory 1520 or computer system 1500. While computer system 1500 is described as implementing the functionality of functional blocks of previous Figures, any of the functionality described herein may be implemented via such a computer system.

[00138] In one embodiment, I/O interface 1530 may be configured to coordinate I/O traffic between processor 1510, system memory 1520, and any peripheral devices in the device, including network interface 1540 or other peripheral interfaces, such as input/output devices 1550. In some embodiments, I/O interface 1530 may perform any necessary protocol, timing or other data transformations to convert data signals from one component (e.g., system memory 1520) into a format suitable for use by another component (e.g., processor 1510). In some embodiments, I/O interface 1530 may include support for devices attached through various types

of peripheral buses, such as a variant of the Peripheral Component Interconnect (PCI) bus standard or the Universal Serial Bus (USB) standard, for example. In some embodiments, the function of I/O interface 1530 may be split into two or more separate components, such as a north bridge and a south bridge, for example. Also, in some embodiments some or all of the functionality of I/O interface 1530, such as an interface to system memory 1520, may be incorporated directly into processor 1510.

[00139] Network interface 1540 may be configured to allow data to be exchanged between computer system 1500 and other devices attached to a network 1585 (e.g., carrier or agent devices) or between nodes of computer system 1500. Network 1585 may in various embodiments include one or more networks including but not limited to Local Area Networks (LANs) (e.g., an Ethernet or corporate network), Wide Area Networks (WANs) (e.g., the Internet), wireless data networks, some other electronic data network, or some combination thereof. In various embodiments, network interface 1540 may support communication via wired or wireless general data networks, such as any suitable type of Ethernet network, for example; via telecommunications/telephony networks such as analog voice networks or digital fiber communications networks; via storage area networks such as Fibre Channel SANs, or via any other suitable type of network and/or protocol.

[00140] Input/output devices 1550 may, in some embodiments, include one or more display terminals, keyboards, keypads, touchpads, scanning devices, voice or optical recognition devices, or any other devices suitable for entering or accessing data by one or more computer systems 1500. Multiple input/output devices 1550 may be present in computer system 1500 or may be distributed on various nodes of computer system 1500. In some embodiments, similar input/output devices may be separate from computer system 1500 and may interact with one or more nodes of computer system 1500 through a wired or wireless connection, such as over network interface 1540.

[00141] As shown in FIG. 15, memory 1520 may include program instructions 1522, which may be processor-executable to implement any element or action described above. In one

embodiment, the program instructions may implement the methods described above. In other embodiments, different elements and data may be included. Note that data may include any data or information described above.

[00142] Those skilled in the art will appreciate that computer system 1500 is merely illustrative and is not intended to limit the scope of embodiments. In particular, the computer system and devices may include any combination of hardware or software that can perform the indicated functions, including computers, network devices, Internet appliances, PDAs, wireless phones, pagers, etc. Computer system 1500 may also be connected to other devices that are not illustrated, or instead may operate as a stand-alone system. In addition, the functionality provided by the illustrated components may in some embodiments be combined in fewer components or distributed in additional components. Similarly, in some embodiments, the functionality of some of the illustrated components may not be provided and/or other additional functionality may be available.

[00143] Those skilled in the art will also appreciate that, while various items are illustrated as being stored in memory or on storage while being used, these items or portions of them may be transferred between memory and other storage devices for purposes of memory management and data integrity. Alternatively, in other embodiments some or all of the software components may execute in memory on another device and communicate with the illustrated computer system via inter-computer communication. Some or all of the system components or data structures may also be stored (e.g., as instructions or structured data) on a computer-accessible medium or a portable article to be read by an appropriate drive, various examples of which are described above. In some embodiments, instructions stored on a computer-accessible medium separate from computer system 1500 may be transmitted to computer system 1500 via transmission media or signals such as electrical, electromagnetic, or digital signals, conveyed via a communication medium such as a network and/or a wireless link. Various embodiments may further include receiving, sending or storing instructions and/or data implemented in accordance with the foregoing description upon a computer-accessible medium. Generally speaking, a computer-accessible medium may include a non-transitory, computer-readable storage medium or memory

medium such as magnetic or optical media, e.g., disk or DVD/CD-ROM, volatile or non-volatile media such as RAM (e.g. SDRAM, DDR, RDRAM, SRAM, etc.), ROM, etc. In some embodiments, a computer-accessible medium may include transmission media or signals such as electrical, electromagnetic, or digital signals, conveyed via a communication medium such as network and/or a wireless link.

[00144] The methods described herein may be implemented in software, hardware, or a combination thereof, in different embodiments. In addition, the order of the blocks of the methods may be changed, and various elements may be added, reordered, combined, omitted, modified, etc. Various modifications and changes may be made as would be obvious to a person skilled in the art having the benefit of this disclosure. The various embodiments described herein are meant to be illustrative and not limiting. Many variations, modifications, additions, and improvements are possible. Accordingly, plural instances may be provided for components described herein as a single instance. Boundaries between various components, operations and data stores are somewhat arbitrary, and particular operations are illustrated in the context of specific illustrative configurations. Other allocations of functionality are envisioned and may fall within the scope of claims that follow. Finally, structures and functionality presented as discrete components in the example configurations may be implemented as a combined structure or component. These and other variations, modifications, additions, and improvements may fall within the scope of embodiments as defined in the claims that follow.

WHAT IS CLAIMED IS:

1. A method for correcting optical alignment of components in a camera module for a multifunction device, the method comprising,
assembling on a test station components of a camera module for use in a multifunction device;
capturing a single test image, wherein
the capturing is performed using the components of the camera module,
and
the single test image comprises visually encoded spatial frequency response data for characterizing the components of the camera module;
calculating from the spatial frequency response data an optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module; and
mechanically adjusting an alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.
2. The method of claim 1, wherein:
the calculating from the spatial frequency response data the optical tilt between the optical axis of the lens and the optical axis of the image sensor of the camera module further comprises
calculating the optical tilt between the optical axis of the lens and the optical axis of the image sensor of the camera module from not more than one test image.
3. The method of claim 1, wherein

the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises

fitting a two-dimensional surface to the spatial frequency response data using a tilted linear two-dimensional surface model from low frequency spatial frequency response data; and

the method further comprises

estimating correction angles from the two-dimensional surface, and applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

4. The method of claim 1, wherein

the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises

fitting a two-dimensional surface to the spatial frequency response data using a weighted-least squares calculation on a tilted linear two-dimensional surface model with low frequency spatial frequency response data.

5. The method of claim 1, wherein

the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises fitting a two-dimensional surface to the spatial frequency response data; and

the method further comprises

estimating correction angles from the two-dimensional surface,

applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

6. The method of claim 1, further comprising:

bonding a lens barrel assembly comprising the lens to a connection for the optical axis of the image sensor of the camera module to make permanent the alignment in the position resulting from the mechanically adjusting.

7. The method of claim 1, wherein the mechanically adjusting the alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt further comprises:

mechanically adjusting an alignment of a lens barrel assembly comprising the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

8. A camera module of a multifunction device, the camera module comprising,

an image sensor;

a lens assembly moveably fixed to the image sensor, wherein the optical axis of the lens assembly is fixed relative to an optical axis of the image sensor using a process comprising:

assembling on a test station one or more components of the camera module for use in a multifunction device;

capturing a single test image with the one or more components of the camera module;

calculating from the single test image an optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module, and

based at least in part upon the optical tilt, mechanically adjusting an alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

9. The camera module of claim 8, wherein:

capturing the single test image further comprises capturing exactly one test image from the camera module, and
calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module from the exactly one test image.

10. The camera module of claim 8, wherein

the calculating from the single test image the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises
fitting a two-dimensional surface to spatial frequency response data derived from the single test image using a tilted linear two-dimensional surface model from low frequency spatial frequency response data; and
the process further comprises
estimating correction angles from the two-dimensional surface, and
applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

11. The camera module of claim 8, wherein

the calculating from the single test image the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises fitting a two-dimensional surface to spatial frequency response data in the single test image using a weighted-least squares calculation on a tilted linear two-dimensional surface model with low frequency spatial frequency response data.

12. The camera module of claim 8, wherein

the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises fitting a two-dimensional surface to the spatial frequency response data; and

the process further comprises:

estimating correction angles from the two-dimensional surface, applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

13. The camera module of claim 8, the process further comprising:

bonding the a lens barrel assembly comprising the lens to a connection for the optical axis of the image sensor of the camera module to make permanent the alignment in the position resulting from the mechanically adjusting.

14. The camera module of claim 8, wherein the mechanically adjusting the alignment of the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt further comprises:

mechanically adjusting an alignment of a lens barrel assembly comprising the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

15. A non-transitory computer-readable medium storing program instructions, the computer-readable medium storing program instructions, wherein the program instructions are computer-executable to implement:

capturing a single test image, wherein the single test image comprises visually encoded spatial frequency response data for characterizing the components of the camera module;

calculating from the spatial frequency response data an optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module;

the calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprises

fitting a two-dimensional surface to the spatial frequency response data using a tilted linear two-dimensional surface model from low frequency spatial frequency response data;

estimating correction angles from the two-dimensional surface; and

applying linear calibration to convert the correction angles to physical correction angles applicable to the lens and the optical axis of the image sensor of the camera module to reduce the optical tilt.

16. The non-transitory computer-readable medium storing program instructions of claim 15, wherein:

the program instructions computer-executable to implement the capturing the single test image further comprise program instructions computer-

executable to implement capturing exactly one test image from the camera module, and

the program instructions computer-executable to implement calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprise program instructions computer-executable to implement calculating the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module from the exactly one test image.

17. The non-transitory computer-readable medium storing program instructions of claim 15, wherein

the program instructions computer-executable to implement calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprise:

program instructions computer-executable to implement fitting a two-dimensional surface to the spatial frequency response data using a weighted-least squares calculation on a tilted linear two-dimensional surface model with low frequency spatial frequency response data.

18. The non-transitory computer-readable medium storing program instructions of claim 15, wherein

the program instructions computer-executable to implement calculating from the spatial frequency response data the optical tilt between the optical axis of a lens and an optical axis of the image sensor of the camera module further comprise program instructions computer-executable to implement fitting a two-dimensional surface to the spatial frequency response data; and the computer-readable medium storing program instructions further comprises

program instructions computer-executable to implement estimating
correction angles from the two-dimensional surface, and
program instructions computer-executable to implement applying linear
calibration to convert the correction angles to physical correction
angles applicable to the lens and the optical axis of the image
sensor of the camera module to reduce the optical tilt.

19. The non-transitory computer-readable medium storing program instructions of claim 15,
further comprising:

program instructions computer-executable to direct mechanically adjusting, based
at least in part upon the optical tilt, an alignment of the lens and the optical
axis of the image sensor of the camera module to reduce the optical tilt,
wherein mechanically adjusting the alignment of the lens and the optical
axis of the image sensor of the camera module to reduce the optical tilt
further comprises:

mechanically adjusting an alignment of a lens barrel assembly comprising
the lens and the optical axis of the image sensor of the camera
module to reduce the optical tilt.

20. The non-transitory computer-readable medium storing program instructions of claim 19,
further comprising:

program instructions computer-executable to direct bonding the lens barrel
assembly comprising the lens to a connection for the optical axis of the
image sensor of the camera module to make permanent the alignment in
the position resulting from the mechanically adjusting.