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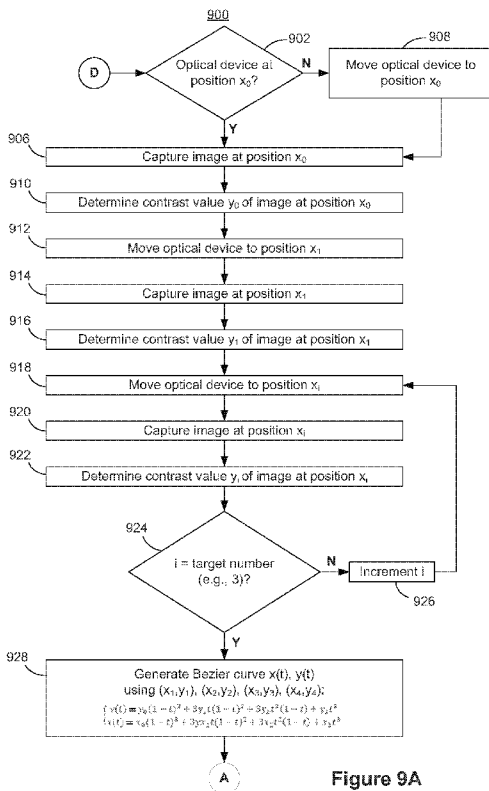
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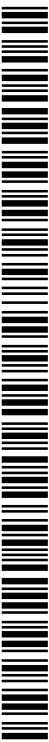
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[Continued on next page]

(54) Title: CONTRAST DETECTION AUTOFOCUS USING ADAPTIVE STEP



(57) Abstract: Systems, methods and/or devices are used for moving an optical device relative to an image sensor to focus an image. The image sensor acquires a first image. A first contrast variation rate is obtained. In accordance with a determination that the contrast variation rate meets a first threshold criterion, the optical device is moved by a first step size that is greater than a previous step size, to a second position. In accordance with a determination that the first contrast variation rate does not meet the first threshold criterion, the optical device is moved by a second step size that is smaller than the previous step size to the second position. The aforementioned operations are repeated until a second contrast variation rate determined for a second image that is acquired when the optical device is at the second position meets a second threshold criterion.



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CONTRAST DETECTION AUTOFOCUS USING ADAPTIVE STEP

TECHNICAL FIELD

[0001] The disclosed embodiments relate generally to focusing an image and more particularly, but not exclusively, to a contrast detection focusing operation that iteratively adjusts the amount by which a distance between an optical device and an image sensor is increased.

BACKGROUND

[0002] Contrast detection autofocus techniques typically rely on adjusting camera focus until an optimal focus point is passed in order to home in on the optical focus point. When a camera is a component of a UAV, adjusting camera focus presents unique challenges, particularly if the adjustment is to be made while the UAV is in flight. Reducing the movement of an optical component of a UAV is beneficial for image stability and flight control.

SUMMARY

[0003] There is a need for systems and methods for moving an optical device relative to an image sensor to focus an image. Such systems and methods optionally complement or replace conventional methods for moving an optical device relative to an image sensor to focus an image.

[0004] In accordance with some embodiments, a method for moving an optical device relative to an image sensor to focus an image comprises: acquiring, by the image sensor, a first image when the optical device is at a first position relative to the image sensor; obtaining a first contrast value of the first image and a first contrast variation rate at the first position; and determining whether the first contrast variation rate meets a first threshold criterion. In accordance with a determination that the contrast variation rate meets the first threshold criterion: a first step size is determined, wherein the first step size is greater than a previous step size used for moving the optical device to the first position, and the optical device is moved from the first position to a second position according to the first step size. In accordance with a determination that the first contrast variation rate does not meet the first threshold criterion: a second step size is determined, wherein the second step size is smaller than the previous step size used for

moving the optical device to the first position, and the optical device is moved from the first position to the second position according to the second step size. The aforementioned operations are repeated until a second contrast variation rate for a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the second position.

[0005] In accordance with some embodiments, a system for moving an optical device relative to an image sensor to focus an image comprises one or more processors and an imaging device comprising an image sensor and an optical device. The one or more processors are configured for: acquiring, by the image sensor, a first image when the optical device is at a first position relative to the image sensor; obtaining a first contrast value of the first image and a first contrast variation rate at the first position; and determining whether the first contrast variation rate meets a first threshold criterion. The one or more processors are further configured for, in accordance with a determination that the contrast variation rate meets the first threshold criterion: determining a first step size, wherein the first step size is greater than a previous step size used for moving the optical device to the first position, and moving the optical device from the first position to a second position according to the first step size. The one or more processors are further configured for, in accordance with a determination that the first contrast variation rate does not meet the first threshold criterion: determining a second step size, wherein the second step size is smaller than the previous step size used for moving the optical device to the first position, and moving the optical device from the first position to the second position according to the second step size. The one or more processors are further configured for repeating the aforementioned operations until a second contrast variation rate for a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the second position.

[0006] In accordance with some embodiments, an unmanned aerial vehicle (UAV) comprises a propulsion system, an imaging device comprising an image sensor and an optical device, and one or more processors. The one or more processors are configured for: acquiring, by the image sensor, a first image when the optical device is at a first position relative to the image sensor; obtaining a first contrast value of the first image and a first contrast variation rate at the first position; and determining whether the first contrast variation rate meets a first

threshold criterion. The one or more processors are further configured for, in accordance with a determination that the contrast variation rate meets the first threshold criterion: determining a first step size, wherein the first step size is greater than a previous step size used for moving the optical device to the first position, and moving the optical device from the first position to a second position according to the first step size. The one or more processors are further configured for, in accordance with a determination that the first contrast variation rate does not meet the first threshold criterion: determining a second step size, wherein the second step size is smaller than the previous step size used for moving the optical device to the first position, and moving the optical device from the first position to the second position according to the second step size. The one or more processors are further configured for repeating the aforementioned operations until a second contrast variation rate for a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the second position.

[0007] In accordance with some embodiments, a computer readable storage medium stores one or more programs, the one or more programs comprising instructions, which when executed, cause an imaging device to: acquire, by an image sensor, a first image when an optical device is at a first position relative to the image sensor; obtain a first contrast value of the first image and a first contrast variation rate at the first position; and determine whether the first contrast variation rate meets a first threshold criterion. The one or more programs further cause the imaging device to, in accordance with a determination that the contrast variation rate meets the first threshold criterion: determine a first step size, wherein the first step size is greater than a previous step size used for moving the optical device to the first position, and move the optical device from the first position to a second position according to the first step size. The one or more programs further cause the imaging device to, in accordance with a determination that the first contrast variation rate does not meet the first threshold criterion: determine a second step size, wherein the second step size is smaller than the previous step size used for moving the optical device to the first position, and move the optical device from the first position to the second position according to the second step size. The one or more programs further cause the imaging device to repeat the aforementioned operations until a second contrast variation rate for

a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the second position.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Figure 1A-1B illustrate movable object environments, in accordance with some embodiments.

[0009] Figure 2A illustrates a movable object in the movable object environment of Figure 1A, in accordance with some embodiments.

[0010] Figure 2B illustrates a movable object in the movable object environment of Figure 1B, in accordance with some embodiments.

[0011] Figure 3 illustrates an exemplary movable object sensing system, in accordance with some embodiments.

[0012] Figure 4 is a cross sectional view of an exemplary imaging device, in accordance with some embodiments.

[0013] Figure 5 illustrates contrast variation determination for an exemplary image captured by an image sensor, in accordance with some embodiments.

[0014] Figures 6A-6C illustrate a simplified representation of locations at which light rays corresponding to an object converge based on various separation distances between an optical device and an image sensor, in accordance with some embodiments.

[0015] Figures 6D-6F illustrate contrast distributions corresponding to the respective separation distances illustrated in Figures 6A-6C, in accordance with some embodiments.

[0016] Figure 6G-6I illustrate pixel arrays corresponding to the respective separation distances illustrated in Figures 6A-6C, in accordance with some embodiments.

[0017] Figure 7 illustrates exemplary contrast values obtained for images captured at various distances between an optical device and an image sensor, in accordance with some embodiments.

[0018] Figure 8A illustrates a cubic Bézier curve determined for obtained contrast values, in accordance with some embodiments.

[0019] Figure 8B illustrates determined values corresponding to an estimated distance between an optical device and an image sensor at which an image captured by image sensor will be focused, in accordance with some embodiments.

[0020] Figure 8C illustrates a contrast value determined after the distance between an optical device and an image sensor has been increased by a determined step size, in accordance with some embodiments.

[0021] Figure 8D illustrates various threshold values to which determined contrast variation rates are compared, in accordance with various embodiments.

[0022] Figures 9A-9C are a flow diagram illustrating a method for moving an optical device relative to an image sensor to focus an image, in accordance with some embodiments.

[0023] Figures 10A and 10B illustrate exemplary contrast distributions over a range from a minimum distance between an optical device and an image sensor to a maximum distance between the optical device and the image sensor.

[0024] Figures 11A-11D are a flow diagram illustrating a method for moving an optical device relative to an image sensor to focus an image, in accordance with some embodiments.

DETAILED DESCRIPTION

[0025] 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 various described embodiments. However, it will be apparent to one of ordinary skill in the art that the various described 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.

[0026] The following description uses an unmanned aerial vehicle (UAV) as an example of a movable object. UAVs include, e.g., fixed-wing aircrafts and rotary-wing aircrafts such as helicopters, quadcopters, and aircraft having other numbers and/or configurations of rotors. It

will be apparent to those skilled in the art that other types of movable objects may be substituted for UAVs as described below.

[0027] Techniques related to optical adjustments for movable objects such as UAVs are described herein.

[0028] Figure 1A illustrates a movable object environment 100, in accordance with some embodiments. The movable object environment 100 includes a movable object 102. In some embodiments, the movable object 102 includes a carrier 104 and/or a payload 106.

[0029] In some embodiments, the carrier 104 is used to couple a payload 106 to movable object 102. In some embodiments, the carrier 104 includes an element (e.g., a gimbal and/or damping element) to isolate the payload 106 from movement of the movable object 102 and/or the movement mechanism 114. In some embodiments, the carrier 104 includes an element for controlling movement of the payload 106 relative to the movable object 102.

[0030] In some embodiments, the payload 106 is coupled (e.g., rigidly coupled) to the movable object 102 (e.g., coupled via carrier 104) such that the payload 106 remains substantially stationary relative to movable object 102. For example, the carrier 104 is coupled to the payload 106 such that the payload is not movable relative to the movable object 102. In some embodiments, the payload 106 is mounted directly to the movable object 102 without requiring the carrier 104. In some embodiments, the payload 106 is located partially or fully within the movable object 102.

[0031] In some embodiments, the control unit 108 communicates with the movable object 102, e.g., to provide control instructions to the movable object 102 and/or to display information received from the movable object 102. Although the control unit 108 is typically a portable (e.g., handheld) device, control unit 108 need not be portable. In some embodiments, the control unit 108 is a dedicated control device (e.g., for the movable object 102), a laptop computer, a desktop computer, a tablet computer, a gaming system, a wearable device (e.g., glasses, a glove, and/or a helmet), a microphone, a portable communication device (e.g., a mobile telephone) and/or a combination thereof.

[0032] In some embodiments, an input device of the control unit 108 receives user input to control aspects of the movable object 102, the carrier 104, the payload 106, and/or a component thereof. Such aspects include, e.g., attitude, position, orientation, velocity, acceleration, navigation, and/or tracking. For example, a position of an input device of the control unit 108 (e.g., a position of a component of input device) is manually set by a user to a position corresponding to an input (e.g., a predetermined input) for controlling the movable object 102. In some embodiments, the input device is manipulated by a user to input control instructions for controlling the navigation of the movable object 102. In some embodiments, an input device of control unit 108 is used to input a flight mode for the movable object 102, such as auto pilot or navigation according to a predetermined navigation path.

[0033] In some embodiments, a display of the control unit 108 displays information generated by the movable object sensing system 210, the memory 204, and/or another system of the movable object 102. For example, the display displays information about the movable object 102, the carrier 104, and/or the payload 106, such as position, attitude, orientation, movement characteristics of the movable object 102, and/or distance between the movable object 102 and another object (e.g., a target and/or an obstacle). In some embodiments, information displayed by a display of control unit 108 includes images captured by the imaging device 302, tracking data (e.g., a graphical tracking indicator applied to a representation of a target), and/or indications of control data transmitted to the movable object 102. In some embodiments, information displayed by the display of the control unit 108 is displayed in substantially real-time as information is received from the movable object 102 and/or as image data is acquired. In some embodiments, the display of the control unit 108 is a touchscreen display.

[0034] In some embodiments, the computing device 110 is, e.g., a server computer, desktop computer, a laptop computer, a tablet, or another portable electronic device (e.g., a mobile telephone). In some embodiments, the computing device 110 is a base station that communicates (e.g., wirelessly) with the movable object 102 and/or the control unit 108. In some embodiments, the computing device 110 provides data storage, data retrieval, and/or data processing operations, e.g., to reduce the processing power and/or data storage requirements of the movable object 102 and/or the control unit 108. For example, the computing device 110 is

communicatively connected to a database and/or the computing device 110 includes a database. In some embodiments, the computing device 110 is used in lieu of or in addition to the control unit 108 to perform any of the operations described with regard to the control unit 108.

[0035] In some embodiments, the movable object 102 communicates with a control unit 108 and/or a computing device 110, e.g., via wireless communications 112. In some embodiments, the movable object 102 receives information from the control unit 108 and/or the computing device 110. For example, information received by the movable object 102 includes, e.g., control instructions for controlling parameters of movable object 102. In some embodiments, the movable object 102 transmits information to the control unit 108 and/or the computing device 110. For example, information transmitted by the movable object 102 includes, e.g., images and/or video captured by the movable object 102.

[0036] In some embodiments, communications between the computing device 110, the control unit 108 and/or the movable object 102 are transmitted via a network (e.g., Internet 116) and/or a wireless signal transmitter (e.g., a long range wireless signal transmitter) such as a cellular tower 118. In some embodiments, a satellite (not shown) is a component of Internet 116 and/or is used in addition to or in lieu of the cellular tower 118.

[0037] In some embodiments, information communicated between the computing device 110, the control unit 108 and/or the movable object 102 include control instructions. Control instructions include, e.g., navigation instructions for controlling navigational parameters of the movable object 102 such as position, orientation, attitude, and/or one or more movement characteristics of the movable object 102, the carrier 104, and/or the payload 106. In some embodiments, control instructions include instructions directing movement of one or more of the movement mechanisms 114. For example, control instructions are used to control flight of a UAV.

[0038] In some embodiments, control instructions include information for controlling operations (e.g., movement) of the carrier 104. For example, control instructions are used to control an actuation mechanism of the carrier 104 so as to cause angular and/or linear movement

of the payload 106 relative to the movable object 102. In some embodiments, control instructions adjust movement of the movable object 102 with up to six degrees of freedom.

[0039] In some embodiments, control instructions are used to adjust one or more operational parameters for the payload 106. For example, control instructions include instructions for adjusting an optical parameter (e.g., an optical parameter of an imaging device 302). In some embodiments, control instructions include instructions for adjusting imaging properties and/or image device functions, such as adjusting a distance between an image sensor 304 and an optical device 306, instructions for capturing an image, initiating/ceasing video capture, powering an imaging device 302 on or off, adjusting an imaging mode (e.g., capturing still images or capturing video), adjusting a distance between left and right components of a stereographic imaging system, and/or adjusting a position, orientation, and/or movement (e.g., pan rate, pan distance) of a carrier 104, a payload 106 and/or an imaging device 302.

[0040] In some embodiments, when control instructions are received by movable object 102, the control instructions change parameters of and/or are stored by the memory 204.

[0041] Figure 1B illustrates a movable environment 150, in accordance with some embodiments. In the movable object environment 150, the movable object 102 is moved by a movement mechanism 114 that is remote from the movable object 102, e.g., a person, animal, vehicle, dolly, and/or other moving device. For example, the movable object 102 is a device that is handheld and/or wearable. In some embodiments, movable object is coupled (e.g., via the carrier 104) to a support structure 152 that is handheld and/or wearable.

[0042] In some embodiments, a carrier 104 is coupled to the movable object 102. In some embodiments, the carrier 104 includes one or more mechanisms that allow the movable object 102 to move relative to a movement mechanism 114 and/or relative to the support structure 152. In some embodiments, the movable object 102 is coupled to the support structure 152 via a carrier 104 that includes a gimbal.

[0043] In some embodiments, the movable object 102 is communicatively coupled to the control unit 108 via a wired and/or wireless connection. In some embodiments, information transmitted from the control unit 108 to movable object includes, e.g., control instructions for

altering one or more operating parameters of the movable object 102. For example, the movable object 102 receives control instructions for altering an optical parameter of an imaging device 302 of the movable object 102. In some embodiments, information transmitted from the movable object 102 to the control unit 108 includes, e.g., image and/or video data captured by movable object 102.

[0044] Figure 2A illustrates an exemplary movable object 102 in a movable object environment 100, in accordance with some embodiments. The movable object 102 typically includes one or more processing units 202, a memory 204, a communication system 206, a movable object sensing system 210, and a communication bus 208 for interconnecting these components.

[0045] In some embodiments, the movable object 102 is a UAV and includes components to enable flight and/or flight control. In some embodiments, the movable object 102 includes the communication system 206 with one or more network or other communications interfaces, the movement mechanisms 114, and/or the movable object actuators 212, which are optionally interconnected with one or more other components of the movable object 102 via the communication bus 208. Although the movable object 102 is depicted as an aircraft, this depiction is not intended to be limiting, and any suitable type of movable object can be used.

[0046] In some embodiments, the movable object 102 includes movement mechanisms 114 (e.g., propulsion mechanisms). Although the plural term “movement mechanisms” is used herein for convenience of reference, “movement mechanisms 114” refers to a single movement mechanism (e.g., a single propeller) or multiple movement mechanisms (e.g., multiple rotors). The movement mechanisms 114 include one or more movement mechanism types such as rotors, propellers, blades, engines, motors, wheels, axles, magnets, nozzles, and so on. The movement mechanisms 114 are coupled to movable object 102 at, e.g., the top, bottom, front, back, and/or sides. In some embodiments, the movement mechanisms 114 of a single movable object 102 include multiple movement mechanisms of the same type. In some embodiments, the movement mechanisms 114 of a single movable object 102 include multiple movement mechanisms with different movement mechanism types. The movement mechanisms 114 are coupled to movable object 102 (or vice-versa) using any suitable means, such as support elements (e.g., drive shafts)

and/or other actuating elements (e.g., the movable object actuators 212). For example, a movable object actuator 212 receives control signals from the processor(s) 202 (e.g., via the control bus 208) that activates the movable object actuator 212 to cause movement of a movement mechanism 114. For example, the processor(s) 202 include an electronic speed controller that provides control signals to a movable object actuator 212.

[0047] In some embodiments, the movement mechanisms 114 enable the movable object 102 to take off vertically from a surface or land vertically on a surface without requiring any horizontal movement of the movable object 102 (e.g., without traveling down a runway). In some embodiments, the movement mechanisms 114 are operable to permit the movable object 102 to hover in the air at a specified position and/or orientation. In some embodiments, one or more of the movement mechanisms 114 are controllable independently of one or more of the other movement mechanisms 114. For example, when the movable object 102 is a quadcopter, each rotor of the quadcopter is controllable independently of the other rotors of the quadcopter. In some embodiments, multiple movement mechanisms 114 are configured for simultaneous movement.

[0048] In some embodiments, the movement mechanisms 114 include multiple rotors that provide lift and/or thrust to the movable object 102. The multiple rotors are actuated to provide, e.g., vertical takeoff, vertical landing, and hovering capabilities to the movable object 102. In some embodiments, one or more of the rotors spin in a clockwise direction, while one or more of the rotors spin in a counterclockwise direction. For example, the number of clockwise rotors is equal to the number of counterclockwise rotors. In some embodiments, the rotation rate of each of the rotors is independently variable, e.g., for controlling the lift and/or thrust produced by each rotor, and thereby adjusting the spatial disposition, velocity, and/or acceleration of the movable object 102 (e.g., with respect to up to three degrees of translation and/or up to three degrees of rotation).

[0049] In some embodiments, the memory 204 stores one or more programs (e.g., sets of instructions), modules, and/or data structures. One or more elements described with regard to the memory 204 are optionally stored by the control unit 108, the computing device 110, and/or

another device. In some embodiments, imaging device 302 includes memory that stores one or more parameters described with regard to the memory 204.

[0050] In some embodiments, the memory 204 stores a system configuration that includes one or more system settings (e.g., as configured by a manufacturer, administrator, and/or user). For example, identifying information for the movable object 102 is stored as a system setting of the system configuration. In some embodiments, the system configuration includes an imaging device configuration. The imaging device configuration stores parameters for the optical device 306 such as initial position, initial step size, zoom level and/or focus parameters (e.g., amount of focus, selecting autofocus or manual focus, and/or adjusting an autofocus target in an image). Imaging property parameters stored by the imaging device configuration include, e.g., image resolution, image size (e.g., image width and/or height), aspect ratio, pixel count, quality, focus distance, depth of field, exposure time, shutter speed, and/or white balance. In some embodiments, parameters stored by the imaging device configuration are updated in response to control instructions (e.g., received by the movable object 102 from control unit 108 and/or the computing device 110). In some embodiments, parameters stored by the imaging device configuration are updated in response to information received from the movable object sensing system 210 and/or the imaging device 302.

[0051] In some embodiments, the memory 204 includes an imaging device adjustment module. The imaging device adjustment module stores, e.g., instructions for adjusting a distance between an image sensor 304 and an optical device 306 of an imaging device 302.

[0052] The above identified modules or programs (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 re-arranged in various embodiments. In some embodiments, the memory 204 may store a subset of the modules and data structures identified above. Furthermore, the memory 204 may store additional modules and data structures not described above. In some embodiments, the programs, modules, and data structures stored in the memory 204, or a non-transitory computer readable storage medium of memory 204, provide instructions for implementing respective operations in the methods described below. In some embodiments, some or all of these modules may be implemented with specialized hardware

circuits that subsume part or all of the module functionality. One or more of the above identified elements may be executed by one or more processors 202 of the movable object 102. In some embodiments, one or more of the above identified elements is executed by one or more processors of a device remote from the movable object 102, such as processor(s) of control unit 108 and/or processor(s) of computing device 110.

[0053] The communication system 206 enables communication with the control unit 108 and/or the computing device 110, e.g., via wireless signals 112. The communication system 206 includes, e.g., transmitters, receivers, and/or transceivers for wireless communication. In some embodiments, the communication is one-way communication, such that data is only received by the movable object 102 from the control unit 108 and/or the computing device 110, or vice-versa. In some embodiments, communication is two-way communication, such that data is transmitted in both directions between the movable object 102 and the control unit 108 and/or the computing device 110. In some embodiments, the movable object 102, the control unit 108, and/or the computing device 110 are connected to the Internet 116 or other telecommunications network, e.g., such that data generated by the movable object 102, the control unit 108, and/or the computing device 110 is transmitted to a server for data storage and/or data retrieval (e.g., for display by a website).

[0054] In some embodiments, the sensing system 210 of the movable object 102 includes one or more sensors. In some embodiments, one or more sensors of the movable object sensing system 210 are mounted to the exterior, located within, or otherwise coupled to the movable object 102. In some embodiments, one or more sensors of the movable object sensing system 210 are components of the carrier 104, the payload 106, and or the imaging device 302. Where sensing operations are described herein as being performed by the movable object sensing system 210, it will be recognized that such operations are optionally performed by one or more sensors of the carrier 104, the payload 106, and or the imaging device 302 in addition to or in lieu of one or more sensors of the movable object sensing system 210.

[0055] The movable object sensing system 210 generates static sensing data (e.g., a single image captured in response to a received instruction) and/or dynamic sensing data (e.g., a series of images captured at a periodic rate, such as a video).

[0056] In some embodiments, the movable object sensing system 210 includes an image sensor 304. For example, the movable object sensing system 210 includes an image sensor 304 that is a component of an imaging device 302, such as a camera (Figure 3). In some embodiments, the movable object sensing system 210 includes multiple image sensors, such as a pair of image sensors for stereographic imaging (e.g., a left stereographic image sensor and a right stereographic image sensor).

[0057] In some embodiments, the movable object sensing system 210 includes one or more audio transducers. For example, an audio detection system includes an audio output transducer (e.g., a speaker) and/or an audio input transducer (e.g., a microphone, such as a parabolic microphone). In some embodiments, microphone and a speaker are used as components of a sonar system. A sonar system is used, for example, to provide a three-dimensional map of the surroundings of the movable object 102.

[0058] In some embodiments, the movable object sensing system 210 includes one or more infrared sensors. In some embodiments, a distance measurement system for measuring a distance from the movable object 102 to an object or surface includes one or more infrared sensors, such a left infrared sensor and a right infrared sensor for stereoscopic imaging and/or distance determination.

[0059] In some embodiments, the movable object sensing system 210 includes one or more global positioning system (GPS) sensors, motion sensors (e.g., accelerometers), rotation sensors (e.g., gyroscopes), inertial sensors, proximity sensors (e.g., infrared sensors) and/or weather sensors (e.g., pressure sensor, temperature sensor, moisture sensor, and/or wind sensor).

[0060] In some embodiments, sensing data generated by one or more sensors of the movable object sensing system 210 and/or information determined using sensing data from one or more sensors of the movable object sensing system 210 is used as a depth sensor for depth detection, e.g., the image sensor, the audio sensor, and/or the infrared sensor are used to determine a distance from the movable object 102 to another object, such as a target, an obstacle, and/or terrain.

[0061] In some embodiments, sensing data generated by one or more sensors of the movable object sensing system 210 and/or information determined using sensing data from one or more sensors of the movable object sensing system 210 are transmitted to the control unit 108 and/or the computing device 110 (e.g., via the communication system 206). In some embodiments, data generated by one or more sensors of the movable object sensing system 210 and/or information determined using sensing data from one or more sensors of the movable object sensing system 210 is stored by the memory 204.

[0062] In some embodiments, the movable object 102, the control unit 108, and/or the computing device 110 use sensing data generated by sensors of the sensing system 210 to determine information such as a position of the movable object 102, an orientation of the movable object 102, movement characteristics of the movable object 102 (e.g., angular velocity, angular acceleration, translational velocity, translational acceleration and/or direction of motion along one or more axes), and/or proximity of the movable object 102 to potential obstacles, targets, weather conditions, locations of geographical features and/or locations of manmade structures.

[0063] Figure 2B illustrates an exemplary movable object 102 in a movable object environment 150, in accordance with some embodiments. A movable object 102 in the movable object environment 150 is moved by a movement mechanism 114 that is remote from the movable object 102 (e.g., as described with regard to Figure 1B). The movable object 102 of the movable object environment 150 includes, e.g., one or more processing units 202, a memory 204, a sensing system 210, and/or a communication bus 208 for interconnecting these components. In some embodiments, the movable object 102 is communicatively coupled to a control unit 108, e.g., via a communication system 206.

[0064] Figure 3 illustrates an exemplary sensing system 210 of the movable object 102, in accordance with some embodiments. In some embodiments, the movable object sensing system 210 includes an imaging device 302 (e.g., a camera). In some embodiments, the imaging device 302 is a component of the payload 106. The imaging device 302 includes an image sensor 304 and an optical device 306. In some embodiments, the optical device 306 is moved relative to the imaging device 302 by an imaging device actuator 308.

[0065] The image sensor 304 is, e.g., a sensor that detects light, such as visible light, infrared light, and/or ultraviolet light. In some embodiments, the image sensor 304 includes, e.g., semiconductor charge-coupled devices (CCD), active pixel sensors using complementary metal-oxide-semiconductor (CMOS) and/or N-type metal-oxide-semiconductors (NMOS, Live MOS).

[0066] The optical device 306 affects the focus of light that arrives at the image sensor 304. For example, the optical device 306 is a lens or a device including multiple lenses (e.g., a compound lens). A lens is, e.g., a material having curved surfaces that give rise to lens properties, such as causing light rays to converge (e.g., at a focal length) and/or diverge.

[0067] The imaging device actuator 308 is, e.g., a motor, such as a hydraulic, pneumatic, electric, thermal, magnetic, and/or mechanical motor. In some embodiments, imaging device actuator 308 translates an optical device 306 along one or more axes relative to the image sensor 304 of the imaging device 302. In some embodiments, the imaging device actuator 308 moves the optical device 306 in response to optical control instructions received from a processor (e.g., processor(s) 202). For example, the imaging device actuator 308 moves the optical device 306 in response to optical control instructions generated in response to user input (e.g., user input received via an input device of the control unit 108 to initiate an image capture and/or autofocus process).

[0068] Figure 4 is a cross sectional view of an exemplary imaging device 302, in accordance with some embodiments. In some embodiments, the imaging device 302 includes a camera body 402. The camera body 402 is, e.g., a body of the movable object 102, a body mounted on and/or inside of the movable object 102, a body coupled to the carrier 104 (e.g., as a payload 106), and/or a body coupled to a payload 106. The camera body 402 is, e.g., a structure to which an image sensor 304 is coupled. The camera body 402 includes a camera body opening that admits light into the camera body 402. In some embodiments, the camera body 402 is fabricated from a material that reduces or eliminates light penetration such that the camera body 402 admits light only at the camera body opening (e.g., via the optical device 306 and/or the camera lens 404). In some embodiments, the optical device 306 and/or the camera lens 404 is mounted over an opening of camera body 402.

[0069] In some embodiments, an optical device 306 is coupled (e.g., fixedly, movably, and/or interchangeably mounted) to camera body 402. Although in Figure 4 the optical device 306 is depicted as a single lens that moves relative to the camera body 402, in some embodiments, the optical device 306 is a camera lens 404 (e.g., an optical device that is fixedly and/or detachably mounted to the camera body 402) that includes one or more optical elements (e.g., lenses) that move relative to the image sensor 304. In some embodiments, the optical device 306 is mounted on the interior of the camera body 402.

[0070] The optical device 306 moves relative to the image sensor 304 along an x-axis. In Figure 4, the optical device 306 is shown (with dotted lines indicating past positions of the optical device 306) at a first position x_0 that is at a first separation distance between the optical device 306 and the image sensor 304, a second position x_1 that is at a second separation distance between optical device 306 and the image sensor 304, and a third position x_2 that is at a third separation distance between the optical device 306 and the image sensor 304. Optical device 306 is shown (with solid lines indicating a current position of the optical device 306) at a fourth position x_3 that is at a fourth separation distance between the optical device 306 and the image sensor 304. In some embodiments, during an autofocus operation, a first image is captured at first position x_0 , a second image is captured at second position x_1 , a third image is captured at first position x_2 , a fourth image is captured at first position x_3 , and so on.

[0071] In some embodiments, the optical device 306 is moved relative to the image sensor 304 to focus an image captured by the image sensor 304. For example, the optical device 306 is moved relative to the image sensor 304 during an autofocus operation. In some embodiments, the autofocus operation is a contrast detection autofocus operation. The contrast detection autofocus operation includes, e.g., determining a contrast variation rate for an image captured by the image sensor 304. As the contrast variation rate increases, the focus of the image captured by the image sensor 304 improves. During the autofocus operation, when the optical device 306 is moved relative to the image sensor 304, a contrast variation rate is determined (e.g., based on an image captured by the image sensor 304 and at least one previous captured image). In accordance with some embodiments as described below, the contrast variation rate is used to determine a step size for approaching a separation distance between the image sensor 304 and

the optical device 306 at which the image is focused. In some embodiments, by determining a new step size after capturing a new image during the autofocus process, autofocus can be achieved by gradually approaching a focus separation distance (e.g., an estimated separation distance between the image sensor 304 and the optical device 306 at which focus is achieved, substantially achieved, and/or maximized). The new step size is, e.g., an increased step size (e.g., when the current separation distance is relatively far from the focus separation distance) or a decreased step size (e.g., when the current separation is relatively close to the focus separation distance). In some embodiments, the focus of the image captured by the image sensor 304 is iteratively improved such that the focus separation distance is approached and/or reached without the need to overshoot the focus separation distance. In this way, movement of components of the movable object 102, such as the optical device 306 and/or the image sensor 304, is reduced in comparison with autofocus techniques that rely on less precise movements and/or overshoot of a focus separation distance.

[0072] Figure 5 illustrates contrast variation determination for an exemplary image 502 captured by the image sensor 304, in accordance with some embodiments. In some embodiments, a contrast gradient is captured across one or more portions of the image 502. A portion of the image 502 is, e.g., a subset of pixels of the image 502, such as a 16x16 array of pixels or a 4x4 array of pixels. In some embodiments, an image is divided into four quadrants and subsets of pixels are selected from one or more quadrants of the image. For example, the image 502 includes subsets of pixels 504, 506, 508, and 510 corresponding to quadrants 514, 516, 518 and 520, respectively, of the image 502.

[0073] The pixel array 512 illustrates a 4x4 array of pixels corresponding to the subset of pixels 510. The pixel array 512 includes pixels with a variety of luminance values. For example, the pixel 522 has a low luminance value relative to the pixel 524. A luminance gradient across the pixels of the pixel array 512 is determined based on a variation in luminance across the pixel array 512. For example, a luminance gradient value for the pixel subset 510 is determined as follows:

$$\frac{\text{Highest luminance value for pixel array} - \text{lowest luminance value for pixel array}}{\text{number of pixels in pixel array}} \quad (1)$$

[0074] In some embodiments, determining a contrast value for the image 502 includes determining an average of luminance gradients for the pixel subsets 504, 506, 508, and 510. For example, a contrast value for the image 502 is determined as follows:

$$\frac{\sum \text{luminance gradients for pixel subsets in image}}{\text{number of pixel subsets in image}} \quad (2)$$

[0075] In some embodiments, a contrast value is determined using a pixel subset at a position corresponding to a location in the image 502 designated by a user (e.g., designated by input provided via the control unit 108 and/or the computing device 110). In some embodiments, a contrast value is determined using a pixel subset at a position corresponding to a target or a portion of a target being tracked by the movable object 102 as captured in the image 502 (e.g., a target designated by input provided via the control unit 108 and/or the computing device 110). In some embodiments, a contrast value is determined using luminance values of all pixels of the image 502.

[0076] Figures 6A-6C illustrate a simplified representation of locations at which light rays corresponding to the object 602 converge based on various separation distances between the optical device 306 and the image sensor 304, in accordance with some embodiments. Figures 6D-6F illustrate contrast distributions corresponding to the respective separation distances illustrated in Figures 6A-6C, in accordance with some embodiments. Figures 6G-6I illustrate pixel arrays corresponding to the respective separation distances illustrated in Figures 6A-6C, in accordance with some embodiments.

[0077] Typically, an image is in focus when the contrast value in the image is maximized. In some embodiments, an autofocus operation that uses contrast value determination includes iteratively adjusting a separation distance between the optical device 306 and the image sensor 304 as a contrast value reaches a maximum value.

[0078] In Figures 6A and 6C, an image 502 of an object 602 captured by the image sensor 304 is out of focus. In Figure 6A, light rays 604 corresponding to the object 602 converge at a position 606 in front of the image sensor 304 (e.g., to the right of the image sensor 304 as illustrated in Figure 6A). In Figure 6C, light rays 602 converge at a position 608 behind the image sensor 304 (e.g., to the left of the image sensor 304 as illustrated in Figure 6C). In Figure

6B, an image 502 captured by the image sensor 304 is in focus because light rays 604 converge at a position corresponding to the position of the image sensor 304.

[0079] Figure 6D illustrates a contrast distribution 612 across a portion of an image 502 (e.g., at a pixel array 512). The contrast distribution 612 of Figure 6D corresponds to the separation distance of the optical device 306 and the image sensor 304 shown in Figure 6A. Figure 6E illustrates a contrast distribution 614 across a portion of an image 502 captured when the separation distance of the optical device 306 and the image sensor 304 are as shown in Figure 6B. Figure 6F illustrates a contrast distribution 616 across a portion of an image 502 captured when the separation distance of the optical device 306 and the image sensor 304 is as shown in Figure 6C.

[0080] Figure 6G illustrates a subset of pixels 618 from an image 502 captured by the image sensor 304, corresponding to the separation distance of the optical device 306 and the image sensor 304 shown in Figure 6A. Figure 6H illustrates a subset of pixels 620 from an image captured by the image sensor 304, corresponding to the separation distance of the optical device 306 and the image sensor 304 shown in Figure 6B. Figure 6I illustrates a subset of pixels 622 from an image captured by the image sensor 304, corresponding to the separation distance of the optical device 306 and the image sensor 304 shown in Figure 6C. Compared with contrast values of the pixel array 622 and the pixel array 618, the contrast value of the pixel array 620 is high, demonstrating that the difference between the highest-luminance pixels and lowest-luminance pixels increases as focus improves. This is also demonstrated by the steepness of the slope of the contrast distribution 614 relative to contrast distributions 612 and 616.

[0081] Figure 7 illustrates contrast values y_0 , y_1 , y_2 , and y_3 obtained from images captured at separation distances x_0 , x_1 , x_2 , and x_3 , respectively, between the optical device 306 and the image sensor 304. For example, separation distances x_0 , x_1 , x_2 , and x_3 of Figure 7 are separation distances x_0 , x_1 , x_2 , and x_3 , described with regard to Figure 4.

[0082] In some embodiments, a curve is generated based on determined contrast values y_0 , y_1 , y_2 , and y_3 . For example, a generated curve is used to estimate a peak contrast value (e.g., an estimated contrast value y_{peak} corresponding to a focus separation distance x_{peak} between the

optical device 306 and the image sensor 304. In some embodiments, the generated curve is a Bézier curve, such as a cubic Bézier curve. For example, a generated cubic Bézier curve is determined for (x_0, y_0) , (x_1, y_1) , (x_2, y_2) , (x_3, y_3) as follows:

$$\text{Cubic Bézier curve: } \begin{cases} y(t) = y_0(1-t)^3 + 3y_1t(1-t)^2 + 3y_2t^2(1-t) + y_3t^3 \\ x(t) = x_0(1-t)^3 + 3x_1t(1-t)^2 + 3x_2t^2(1-t) + x_3t^3 \end{cases} \quad (3)$$

[0083] In some embodiments, e.g., after the separation distance between the optical device 306 and the image sensor 304 is increased by a next step value s_n such that a contrast value y_n is determined at a separation distance x_n between the optical device 306 and the image sensor 304, a nonlinear least squares analysis is used to find a best fit curve to (x_0, y_0) , (x_1, y_1) , (x_2, y_2) , (x_3, y_3) . . . (x_n, y_n) .

[0084] Figure 8A illustrates a cubic Bézier curve 802 determined for (x_0, y_0) , (x_1, y_1) , (x_2, y_2) , (x_3, y_3) . An estimated point at which the contrast value is at a maximum y_{peak} (the peak of the curve) corresponds to a point at which the derivative of the curve 802 is equal to zero. To obtain y_{peak} , the value t_{peak} (e.g., the value of t when $y'(t)$ of the cubic Bézier curve is equal to zero) is determined:

$$-3t_{\text{peak}}^2(y_0 - 3y_1 + 3y_2 - y_3) + 6t_{\text{peak}}(y_0 - 2y_1 + y_2) - 3(y_0 - y_1) = 0 \quad (4)$$

[0085] To obtain x_{peak} , the determined value of t from (4) is used in (5):

$$x(t_{\text{peak}}) = x_0(1 - t_{\text{peak}})^3 + 3x_1t_{\text{peak}}(1 - t_{\text{peak}})^2 + 3x_2t_{\text{peak}}^2(1 - t_{\text{peak}}) + x_3t_{\text{peak}}^3 \quad (5)$$

[0086] Figure 8B illustrates determined values $(x_{\text{peak}}, y_{\text{peak}})$ corresponding to an estimated focus separation distance between the optical device 306 and the image sensor 304, in accordance with some embodiments.

[0087] In some embodiments, the determined x_{peak} value is used for determining an increased next step value s_n , as indicated below:

$$\text{Increased step size: } s_n = \frac{1+(x_{\text{peak}}-x_c)}{\text{total length}}(x_3 - x_2) \quad (6)$$

The value of “total length” in equation (6) is, for example, a maximum separation distance between the optical device 306 and the image sensor 304 (e.g., as constrained by the camera

body 402 and/or the camera lens 404) A current separation distance between the optical device 306 and the image sensor 304 is indicated by x_c .

[0088] In some embodiments, when next step value s_n has been determined, the separation distance between the optical device 306 and the image sensor 304 is increased from x_c by the value s_n , such that the distance between the optical device 306 and the image sensor 304 is increased to x_n (e.g., as shown in Figure 8C). In some embodiments, when the separation distance between the optical device 306 and the image sensor 304 has been increased to a next distance x_n , an image 502 is captured and a next contrast value y_n is determined.

[0089] Figure 8C illustrates a contrast value y_n determined after the distance between the optical device 306 and the image sensor 304 has been increased to a distance x_n .

[0090] In some embodiments, when a contrast value y_n has been determined, a contrast variation rate 804 (e.g., dy/dx) is determined at the point x_n . For example, the contrast variation rate 804 is determined as follows:

$$\frac{dy}{dx} = \frac{y_n - y_{previous}}{x_n - x_{previous}} \quad (7)$$

[0091] In the illustrative example of Figure 8C, $x_{previous}$ is x_3 and $y_{previous}$ is y_3 .

[0092] In some embodiments, when a contrast variation rate has been determined, the contrast variation rate is compared with one or more threshold values. For example, a contrast variation rate is compared with a first threshold value (e.g., threshold A) to determine whether a next step size will be an increased step size or a decreased step size. In accordance with a determination that the contrast variation rate meets a first threshold criterion (e.g., the contrast variation rate is greater than threshold A), the next step size will be an increased step size. In accordance with a determination that the contrast variation rate does not meet the first threshold criterion (e.g., the contrast variation rate is less than or equal to threshold A), if a next step will be taken, the next step size will be a decreased step size determined as follows:

$$\text{Decreased step size: } s_n = \frac{1 - (x_{peak} - x_c)}{\text{total length}} (x_3 - x_2) \quad (8)$$

[0093] Figure 8D illustrates various threshold values to which determined contrast variation rates are compared, in accordance with various embodiments. A first threshold 806

(e.g., threshold A) has a first gradient (e.g., slope value), a second threshold 808 (e.g., threshold B) has a second gradient, and a third threshold 810 has a third gradient. In some embodiments, the absolute value of the gradient of threshold B is lower than the absolute value of the gradient of threshold A and the absolute value of the gradient of threshold C is lower than the absolute value of the gradient of threshold B.

[0094] In some embodiments, the contrast variation rate 804 as shown in Figure 8C is compared with the first threshold 806 as shown in Figure 8D. In accordance with a determination that the contrast variation rate 804 (e.g., the dy/dx value of 804) is greater than (steeper than) the first threshold 806 (threshold A) slope value, the next step size will be an increased step size determined using (6). In accordance with a determination that the contrast variation rate 804 (e.g., the dy/dx value of 804) is less than or equal to (e.g., as steep or less steep than) the first threshold 806 (threshold A) slope value, the contrast variation rate 804 is compared with the second threshold 808 (threshold B) slope value. In accordance with a determination that the contrast variation rate 804 (e.g., the dy/dx value of 804) is greater than (steeper than) the second threshold 808 (threshold B) slope value, the next step size will be a decreased step size determined using (8).

[0095] In accordance with a determination that the contrast variation rate 804 (e.g., the dy/dx value of 804) is less than or equal to (e.g., as steep or less steep than) the second threshold 808 (threshold B) slope value, a low pass filter is applied to $(x_0, y_0), (x_1, y_1), (x_2, y_2), (x_3, y_3) \dots (x_n, y_n)$ to obtain a filtered contrast distribution, and a gradient of the filtered contrast distribution is determined at the point x_n as follows:

$$\frac{dy}{dx} = \frac{y_n - y_{previous}}{x_n - x_{previous}} \quad (9)$$

[0096] In some embodiments, the gradient of the filtered contrast distribution is compared with the third threshold 810 (threshold C) slope value. In accordance with a determination that the gradient of the filtered contrast distribution is greater than (steeper than) the third threshold 810 (threshold C) slope value, one or more of the operations described with regard to Figures 4-8D are repeated. In accordance with a determination that the gradient of the filtered contrast distribution is less than or equal to (e.g., as steep or less steep than) the third

threshold 810 (threshold C) slope value, it is determined that the focus separation distance has been achieved.

[0097] Figures 9A-9C are a flow diagram illustrating a method 900 for moving an optical device relative to an image sensor to focus an image, in accordance with some embodiments. The method 900 is performed at a device, such as the movable object 102, the imaging device 302, the control unit 108 and/or the computing device 110. For example, instructions for performing the method 900 are stored in the memory 204 and executed by processor(s) 202.

[0098] In some embodiments, the device determines (902) whether the optical device 306 is at an initial position (e.g., a position x_0 at which a separation distance between the optical device 306 and the image sensor 304 is x_0). In accordance with a determination that optical device 306 is at an initial position, the device captures (906) an image 502 via the image sensor 304. In accordance with a determination that the optical device 306 is not at the initial position, the device provides instructions to the imaging device actuator 308 to move (908) the optical device 306 to the initial position. The device determines (910) an initial contrast value (e.g., y_0) at the initial position. For example, initial contrast value y_0 is determined in accordance with equations (1)-(2) above.

[0099] The device provides instructions to the imaging device actuator 308 to move (912) the optical device 306 to a second position (e.g., a position x_1 at which a separation distance between the optical device 306 and the image sensor 304 is x_1). The device captures (914) a second image 502 via image sensor 304 when optical device 306 is at the second position. The device determines (916) a contrast value (e.g., y_1) at the second position. For example, second contrast value y_1 is determined in accordance with equations (1)-(2) above.

[00100] In some embodiments, the device provides instructions to imaging device actuator 308 to move (918) the optical device 306 to a next position (e.g., a position x_i at which a separation distance between the optical device 306 and the image sensor 304 is x_i). For example, in a first iteration, $i=2$, and the position x_i is x_2 . The device captures (920) a next image 502 via image sensor 304 when optical device 306 is at the next position x_i . The device determines (922)

a next contrast value (e.g., y_i) at the next position. For example, contrast value y_i is determined in accordance with equations (1)-(2) above.

[00101] In some embodiments, the device determines (924) whether the number of positions (i) has reached a target number positions (e.g., a predefined target number of positions). For example, when four contrast values y_0, y_1, y_2, y_3 are needed to perform the calculation indicated at equation (3), $i = 3$. In some embodiments, in accordance with a determination that i has not reached 3, the device (926) increments i (e.g., the device sets the value of i to be $i+1$). Operations 918, 920, 922, 924, and/or 926 are repeated until the device determines that the number of positions (i) has reached a target number positions (e.g. $i=3$). In accordance with a determination that the number of positions has reached the target number of positions (e.g., contrast values y_0, y_1, y_2, y_3 have been obtained), the device generates (928) a curve. For example, the device generates a cubic Bézier curve (e.g., 802) as indicated at equation (3).

[00102] As indicated at A, the device proceeds from operation 928 of Figure 9A to operation 930 of Figure 9B.

[00103] To determine a separation distance x_{peak} between the image sensor 304 and the optical device 306 at which an estimated peak contrast value y_{peak} occurs (e.g., as described with reference to Figures 8A-8B), the device determines (930) a peak value t_{peak} e.g., using equation (4). The device determines (932) a distance x_{peak} based on t_{peak} , e.g., using equation (5). The device determines (934) a next step size s_n , e.g., using equation (6) for an increased next step size or, (e.g., in later iterations and/or in accordance with a determination to use a decreased step size), using equation (8) for a decreased next step size. The device provides instructions to the imaging device actuator 308 to move (936) the optical device 306 from a current position x_c to a next position (e.g., a position x_n at which a separation distance between the optical device 306 and the image sensor 304 is $x_n = x_c + s_n$).

[00104] The device captures (938) a next image 502 when the separation distance between the optical device 306 and the image sensor 304 is x_n . The device determines (940) a next contrast value (e.g., y_n) at the next position. For example, contrast value y_n is determined in accordance with equations (1)-(2) above. The device determines (942) a contrast variation rate

(e.g., as indicated at 804) at position x_n . For example, a contrast variation rate dy/dx is determined in accordance with equation (7) above. The device compares (944) the contrast variation rate determined at (942) with a threshold A (806).

[00105] As indicated at B, the device proceeds from operation 944 of Figure 9B to decision diamond 946 of Figure 9C.

[00106] The device determines (946) whether the contrast variation rate (e.g., 804) exceeds the threshold A 806 gradient value. In accordance with a determination that the contrast variation rate exceeds the threshold A gradient value, the device (948) will determine the next step size s_n (e.g., at an next iteration of the operation 934) using increased next step size equation (6). In accordance with a determination that the contrast variation rate does not exceed the threshold A slope value, the device determines (950) whether the contrast variation rate (e.g., 804) exceeds the gradient of the threshold B 808. In accordance with a determination that the contrast variation rate exceeds the threshold B gradient value, the device (952) will determine the next step size s_n (e.g., at an next iteration of the operation 934) using decreased next step size equation (8).

[00107] As indicated at C, the device proceeds from operations 948 and/or 952 of Figure 9C to the operation 954 of Figure 9B. At the operation 954, the device generates a new curve using $(x_0, y_0), (x_1, y_1), (x_2, y_2), (x_3, y_3) \dots (x_n, y_n)$. For example, a nonlinear least squares analysis is used to find a best fit curve to $(x_0, y_0), (x_1, y_1), (x_2, y_2), (x_3, y_3) \dots (x_n, y_n)$. Operations 930, 932, 934, 936, 938, 940, 942, 944, 946, 948, 950, 952, and/or 954 repeat until the device determines that the contrast variation rate does not exceed the gradient of threshold B slope value.

[00108] In accordance with a determination that the contrast variation rate does not exceed the threshold B slope value, the device applies (956) a low pass filter to $(x_0, y_0), (x_1, y_1), (x_2, y_2), (x_3, y_3) \dots (x_n, y_n)$ to obtain a filtered contrast distribution. The device determines (958) a gradient value dy/dx of the filtered contrast distribution, e.g., using equation (9) at the most recent position of the optical device 306 relative to the image sensor 304 (e.g., at x_n). The device compares (960) the determined gradient value dy/dx of the filtered contrast distribution at the

position x_n to threshold C (810). In some embodiments, in accordance with a determination that the determined gradient value dy/dx of the filtered contrast distribution exceeds the threshold C gradient value, the device proceeds to operation 902 of Figure 9A, as indicated at D. In some embodiments, in accordance with a determination that the determined gradient value dy/dx of the filtered contrast distribution does not exceed the threshold C gradient value, the focus separation distance is determined to have been reached and the flow ends.

[00109] Figures 10A and 10B illustrate exemplary contrast distributions over a range from a minimum separation distance x_{\min} between the optical device 306 and the image sensor 304 to a maximum separation distance x_{\max} between the optical device 306 and the image sensor 304. Figure 10A illustrates an example of a contrast distribution obtained in a high contrast setting and Figure 10B illustrates an example of a contrast distribution obtained in a low contrast setting (e.g., a low light setting). The presence of noise in a contrast distribution (e.g., as demonstrated in Figure 10B, particularly in comparison with Figure 10A) due to, e.g., low light conditions, light flicker, and/or movement of the imaging device during the autofocus process, has the potential to reduce the accuracy with which a focus separation distance is determined. Applying a low pass filter to determined contrast values $(x_0, y_0), (x_1, y_1), (x_2, y_2), (x_3, y_3) \dots (x_n, y_n)$ reduces the probability of inaccuracy in the determination of the focus separation distance due to noise.

[00110] Figures 11A-11D are a flow diagram illustrating a method 1100 for moving an optical device 306 relative to an image sensor 304 to focus an image 502, in accordance with some embodiments. The method 1100 is performed at a device, such as the movable object 102, the imaging device 302, the control unit 108 and/or the computing device 110. For example, instructions for performing the method 1100 are stored in the memory 204 and executed by the processor(s) 202.

[00111] The device acquires (1102), by the image sensor 304, a first image 502 when the optical device 306 is at a first position relative to the image sensor 304 (e.g., at a separation distance x_n between the optical device 306 and the image sensor 304). The device obtains (1104) a first contrast value y_n of the first image 502 (e.g., a contrast value determined in accordance with equations (1) and/or (2)) and a first contrast variation rate dy/dx at the first position x_n (e.g.,

a contrast variation rate determined in accordance with equation (7), such as the contrast variation rate illustrated at 804).

[00112] The device determines (1106) whether the first contrast variation rate dy/dx meets a first threshold criterion. For example, the device determines whether the first contrast variation rate dy/dx is greater than a first threshold gradient value (e.g., a threshold A gradient value as illustrated at 806 of Figure 8D).

[00113] In accordance with a determination that the contrast variation rate meets the first threshold criterion, the device (1108): determines a first step size s_n , the first step size greater than a previous step size used for moving the optical device to the first position (e.g., equation (6) for determining an increased step size is used to determine the first step size s_n); and the device moves the optical device 306 from the first position to a second position according to the first step size s_n (e.g., the optical device 306 is moved to a separation distance x_n from the image sensor 304).

[00114] In accordance with a determination that the first contrast variation rate does not meet the first threshold criterion (e.g., the first contrast variation rate is less than (or equal to) the first threshold gradient value, such as a gradient value of threshold A as illustrated at 806 of Figure 8D), the device (1110): determines a second step size s_n , the second step size smaller than the previous step size used for moving the optical device 306 to the first position (e.g., equation (8) for determining an decreased step size is used to determine the second step size s_n); and the device moves the optical device 306 from the first position to the second position according to the second step size s_n (e.g., the optical device 306 is moved to a separation distance x_n from the image sensor 304).

[00115] The device repeats (1112) the aforementioned operations (e.g., 1102, 1104, 1106, 1108, and/or 1110) until a second contrast variation rate dy/dx meets a second threshold criterion (e.g., the second contrast variation dy/dx is less than (or equal to) a second threshold gradient value such as threshold B (808)). The second image 502 is acquired when the optical device 306 is at the second position (separation distance) x_{n+1} .

[00116] In some embodiments, determining that the first contrast variation rate meets the first threshold criterion includes (1114) comparing the first contrast variation rate to a first threshold gradient value. For example, the first threshold gradient value is a gradient value indicating the slope of the line corresponding to threshold A, as shown at 806 of Figure 8D.

[00117] In some embodiments, the first contrast variation rate meets the first threshold criterion when (1116) the first contrast variation rate exceeds a first threshold gradient value. For example, the first contrast variation rate meets the first threshold criterion when contrast variation rate dy/dx as determined in accordance with equation (7) exceeds a gradient value indicating the threshold A gradient value, as shown at 806 of Figure 8D.

[00118] In some embodiments, determining that the second contrast variation rate meets the second threshold criterion includes (1118) comparing the second contrast variation rate to a second threshold gradient value, wherein the second threshold gradient value is less than (e.g., less steep than) the first threshold gradient value. For example, the second contrast variation rate meets the second threshold criterion when contrast variation rate dy/dx as determined in accordance with equation (7) exceeds a threshold B gradient value, as shown at 808 of Figure 8D.

[00119] In some embodiments, determining at least one of the first step size and the second step size includes (1120): generating a curve based on a plurality of contrast values including the first contrast value (e.g., generating a curve based on y_0, y_1, y_2, y_3, y_n as described with regard to 954 of Figure 9B), determining a position (e.g., separation distance) of the optical device 306 relative to the image sensor 304 at which the curve has a peak value (e.g., determining a position x_{peak} , as described with regard to 932) and determining the first step size s_n using the determined position (e.g., x_{peak}) of the optical device 306 relative to the image sensor 304 at which the curve has a peak value. For example, the determined x_{peak} value is used to determine an increased step size s_n as indicated in equation (6).

[00120] In some embodiments, in at least one iteration of the repeating operation, the curve is a Bézier curve (1122). For example, the Bézier curve is a quadratic or higher-order Bézier curve.

[00121] In some embodiments, the Bézier curve is a cubic Bézier curve (1124), e.g., the Bézier curve as defined at (3).

[00122] In some embodiments, in at least one iteration of the repeating operation, the curve is determined (1126) using a non-linear least squares analysis. For example, a non-linear least squares analysis is applied to find a best fit curve to $(x_0, y_0), (x_1, y_1), (x_2, y_2), (x_3, y_3) \dots (x_n, y_n)$.

[00123] In some embodiments, the device determines (1128) the first contrast value using at least one luminance gradient value from the first image 502, wherein a respective luminance gradient value is a luminance gradient across a portion (e.g., a 4 pixel x 4 pixel array 512, or a 16 pixel x 16 pixel array) of the first image 502. For example, a contrast value is determined in accordance with equations (1) and/or (2) above.

[00124] In some embodiments, the device determines (1130) the first contrast value using an average of a plurality of luminance gradient values from the first image 502 (e.g., four luminance gradient values corresponding to pixel arrays 504, 506, 508, 510 from quadrants 514, 516, 518, 520, respectively, of first image 502), as described with regard to equation (2).

[00125] In some embodiments, in response to determining that the second contrast variation rate meets a second threshold criterion (e.g., the second contrast variation rate is less than (or equal to) the slope of second threshold B gradient value, as indicated at 808), the device applies (1132) a filter to a plurality of obtained contrast values $(x_0, y_0), (x_1, y_1), (x_2, y_2), (x_3, y_3) \dots (x_n, y_n)$ to generate a filtered curve.

[00126] In some embodiments, the filter (1134) is a low pass filter. In some embodiments, the low pass filter is (1136) a one-dimensional Gaussian filter.

[00127] In some embodiments, the device determines (1138) whether the filtered curve at the current position of the optical device 306 relative to the image sensor 304 satisfies an end criterion, and, in response to determining that the filtered curve does not satisfy the end criterion, the device initializes the optical device 306 at an initial position (e.g., x_0) relative to the image sensor 304 and repeats the aforementioned operations (e.g. repeats operations 1102-1112). In other words, the current autofocus attempt is aborted and the autofocus process is restarted from

the initial position of the optical device 306 relative to the image sensor 304 (e.g., separation distance x_0). For example, in a target tracking or other video capture context, various aspects of the captured images, such as the composition and/or light level of captured images, may change rapidly over time, such that if a current autofocus attempt fails it is more efficient to restart the autofocus process by collecting new contrast values rather than continuing to try to achieve focus based on previously collected contrast values.

[00128] In some embodiments, determining whether the filtered curve at the current position of the optical device 306 relative to the image sensor 304 satisfies the end criterion includes (1140) determining whether a gradient of the filtered curve at the current position of the optical device (e.g., as determined using equation 9) relative to the image sensor meets a third threshold criterion. In some embodiments, the gradient of the filtered curve at the current position of the optical device meets a third threshold criterion when the gradient of the filtered curve at the current position of the optical device is less than (or equal to) a threshold C gradient value (e.g., as indicated at 810).

[00129] In some embodiments, the second contrast variation rate dy/dx is determined (1142) using a second contrast value y_{n+1} obtained for a second image 502.

[00130] In some embodiments, the first contrast variation rate dy/dx is a gradient value indicating (1144) a rate of change of a contrast value from a previous image to a current image.

[00131] In some embodiments, a contrast variation rate difference is a difference (1146) between the first contrast value y_n of the first image and a contrast value y_{previous} of a previous image; a distance difference is a difference between a first distance x_n between the optical device and the image sensor at which the first image is captured and a second distance x_{previous} between the optical device and the image sensor at which the second image is captured; and the rate of change of the contrast value is the contrast variation rate difference divided by the distance difference, e.g., as indicated in equation (7).

[00132] In some embodiments, initializing the optical device 306 at an initial position (e.g., x_0) relative to the image sensor 304 includes using data generated by a depth sensor of the movable object 102 to determine an initialization distance. For example, the initial position is

determined based on output from a depth sensor (e.g., an image sensor, an audio sensor, and/or an infrared sensor) of the movable object sensing system 210.

[00133] Many features of the present invention can be performed in, using, or with the assistance of hardware, software, firmware, or combinations thereof. Consequently, features of the present invention may be implemented using a processing system. Exemplary processing systems (e.g., processor(s) 202) include, without limitation, one or more general purpose microprocessors (for example, single or multi-core processors), application-specific integrated circuits, application-specific instruction-set processors, field-programmable gate arrays, graphics processing units, physics processing units, digital signal processing units, coprocessors, network processing units, audio processing units, encryption processing units, and the like.

[00134] Features of the present invention can be implemented in, using, or with the assistance of a computer program product, such as a storage medium (media) or computer readable storage medium (media) having instructions stored thereon/in which can be used to program a processing system to perform any of the features presented herein. The storage medium (e.g., the memory 204) can include, but is not limited to, any type of disk including floppy disks, optical discs, DVD, CD-ROMs, microdrive, and magneto-optical disks, ROMs, RAMs, EPROMs, EEPROMs, DRAMs, VRAMs, DDR RAMs, flash memory devices, magnetic or optical cards, nanosystems (including molecular memory ICs), or any type of media or device suitable for storing instructions and/or data.

[00135] Stored on any one of the machine readable medium (media), features of the present invention can be incorporated in software and/or firmware for controlling the hardware of a processing system, and for enabling a processing system to interact with other mechanism utilizing the results of the present invention. Such software or firmware may include, but is not limited to, application code, device drivers, operating systems, and execution environments/containers.

[00136] Communication systems as referred to herein (e.g., the communication system 206) optionally communicate via wired and/or wireless communication connections. For example, communication systems optionally receive and send RF signals, also called electromagnetic

signals. RF circuitry of the communication systems convert electrical signals to/from electromagnetic signals and communicate with communications networks and other communications devices via the electromagnetic signals. RF circuitry optionally includes 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. Communication systems optionally 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. Wireless communication connections optionally use any of a plurality 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), Evolution, Data-Only (EV-DO), HSPA, HSPA+, Dual-Cell HSPA (DC-HSPDA), long term evolution (LTE), near field communication (NFC), 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 102.11a, IEEE 102.11ac, IEEE 102.11ax, IEEE 102.11b, IEEE 102.11g and/or IEEE 102.11n), 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.

[00137] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example, and not limitation. It will be apparent to persons skilled in the relevant art that various changes in form and detail can be made therein without departing from the spirit and scope of the invention.

[00138] The present invention has been described above with the aid of functional building blocks illustrating the performance of specified functions and relationships thereof. The boundaries of these functional building blocks have often been arbitrarily defined herein for the convenience of the description. Alternate boundaries can be defined so long as the specified functions and relationships thereof are appropriately performed. Any such alternate boundaries are thus within the scope and spirit of the invention.

[00139] The terminology used in the description of the various described embodiments herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used in the description of the various described embodiments 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.

[00140] As used herein, the term “if” may be construed to mean “when” or “upon” or “in response to determining” or “in accordance with a determination” or “in response to detecting,” that a stated condition precedent is true, depending on the context. Similarly, the phrase “if it is determined [that a stated condition precedent is true]” or “if [a stated condition precedent is true]” or “when [a stated condition precedent is true]” may be construed to mean “upon determining” or “in response to determining” or “in accordance with a determination” or “upon detecting” or “in response to detecting” that the stated condition precedent is true, depending on the context.

[00141] The foregoing description of the present invention has been provided for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. The breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments. Many modifications and variations will be apparent to the practitioner skilled in the art. The modifications and variations

include any relevant combination of the disclosed features. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application, thereby enabling others skilled in the art to understand the invention for various embodiments and with various modifications that are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following claims and their equivalence.

What is claimed is:

1. A method for moving an optical device relative to an image sensor to focus an image, the method comprising:

acquiring, by the image sensor, a first image when the optical device is at a first position relative to the image sensor;

obtaining a first contrast value of the first image and a first contrast variation rate at the first position;

determining whether the first contrast variation rate meets a first threshold criterion;

moving the optical device from the first position to a next position in accordance with the determination result; and

repeating the aforementioned operations until a second contrast variation rate for a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the next position.

2. The method of claim 1, wherein the second contrast variation rate is determined using a second contrast value obtained for the second image.

3. The method of claim 1, wherein moving the optical device from the first position to the next position in accordance with the determination result further comprises:

in accordance with a determination that the first contrast variation rate meets the first threshold criterion:

determining a first step size, wherein the first step size is greater than a previous step size used for moving the optical device to the first position, and

moving the optical device from the first position to the next position according to the first step size; and

in accordance with a determination that the first contrast variation rate does not meet the first threshold criterion:

determining a second step size, wherein the second step size is smaller than the previous step size used for moving the optical device to the first position, and

moving the optical device from the first position to the next position according to the second step size.

4. The method of claim 1, wherein determining that the first contrast variation rate meets the first threshold criterion includes comparing the first contrast variation rate to a first threshold gradient value.
5. The method of claim 4, wherein the first contrast variation rate meets the first threshold criterion when the first contrast variation rate exceeds a first threshold gradient value.
6. The method of claim 1, wherein determining that the second contrast variation rate meets the second threshold criterion includes comparing the second contrast variation rate to a second threshold gradient value, wherein the second threshold gradient value is less than the first threshold gradient value.
7. The method of claim 2, wherein determining at least one of the first step size and the second step size includes:
 - generating a curve based on a plurality of contrast values including the first contrast value;
 - determining a position of the optical device relative to the image sensor at which the curve has a peak value; and
 - determining the first step size using the determined position of the optical device relative to the image sensor at which the curve has a peak value.
8. The method of claim 7, wherein, in at least one iteration of the repeating operation, the curve is a Bézier curve.
9. The method of claim 8, wherein the Bézier curve is a cubic Bézier curve.
10. The method of claim 7, wherein, in at least one iteration of the repeating operation, the curve is determined using a non-linear least squares analysis.

11. The method of claim 1, wherein the first contrast value is determined using at least one luminance gradient value from the first image, wherein a respective luminance gradient value is a luminance gradient across a portion of the first image.
12. The method of claim 11, wherein the first contrast value is determined using an average of a plurality of luminance gradient values from the first image.
13. The method of claim 1, wherein the first contrast variation rate is a gradient value indicating a rate of change of a contrast value from a previous image to a current image.
14. The method of claim 13, wherein:
 - a contrast value difference is a difference between the first contrast value and a contrast value of a previous image;
 - a distance difference is a difference between a first distance between the optical device and the image sensor at which the first image is captured and a previous distance between the optical device and the image sensor at which the previous image was captured; and
 - the rate of change of the contrast value is the contrast value difference divided by the distance difference.
15. The method of claim 1, further comprising: in response to determining that the second contrast variation rate meets the second threshold criterion, applying a filter to a plurality of obtained contrast values to generate a filtered curve.
16. The method of claim 15, wherein the filter is a low pass filter.
17. The method of claim 16, wherein the low pass filter is a one-dimensional Gaussian filter.
18. The method of claim 15, further comprising:
 - determining whether the filtered curve at a current position of the optical device relative to the image sensor satisfies an end criterion, and,
 - in response to determining that the filtered curve does not satisfy the end criterion:
 - initializing the optical device at an initial position relative to the image sensor; and
 - repeating the aforementioned operations.

19. The method of claim 18, wherein determining whether the filtered curve at the current position of the optical device relative to the image sensor satisfies the end criterion includes determining whether a gradient of the filtered curve at the current position of the optical device relative to the image sensor meets a third threshold criterion.

20. An unmanned aerial vehicle (UAV), comprising:

a propulsion system;

an imaging device comprising an image sensor and an optical device; and

one or more processors;

the one or more processors configured for:

acquiring, by the image sensor, a first image when the optical device is at a first position relative to the image sensor;

obtaining a first contrast value of the first image and a first contrast variation rate at the first position;

determining whether the first contrast variation rate meets a first threshold criterion;

moving the optical device from the first position to a next position in accordance with the determination result; and

repeating the aforementioned operations until a second contrast variation rate for a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the next position.

21. The UAV of claim 20, wherein the second contrast variation rate is determined using a second contrast value obtained for the second image.

22. The UAV of claim 20, wherein moving the optical device from the first position to the next position in accordance with the determination result further comprises:

in accordance with a determination that the first contrast variation rate meets the first threshold criterion:

determining a first step size, wherein the first step size is greater than a previous step size used for moving the optical device to the first position, and

moving the optical device from the first position to the next position according to the first step size; and

in accordance with a determination that the first contrast variation rate does not meet the first threshold criterion:

determining a second step size, wherein the second step size is smaller than the previous step size used for moving the optical device to the first position, and

moving the optical device from the first position to the next position according to the second step size.

23. The UAV of claim 20, further comprising a depth sensor, wherein data generated by a depth sensor of the UAV is used determine an initialization distance between the optical device and the image sensor.

24. The UAV of claim 21, wherein determining at least one of the first step size and the second step size includes:

generating a curve based on a plurality of contrast values including the first contrast value;

determining a position of the optical device relative to the image sensor at which the curve has a peak value; and

determining the first step size using the determined position of the optical device relative to the image sensor at which the curve has a peak value.

25. The UAV of claim 24, wherein, in at least one iteration of the repeating operation, the curve is a Bézier curve.

26. The UAV of claim 20, wherein the first contrast value is determined using at least one luminance gradient value from the first image, wherein a respective luminance gradient value is a luminance gradient across a portion of the first image.

27. The UAV of claim 20, wherein the first contrast variation rate is a gradient value indicating a rate of change of a contrast value from a previous image to a current image.

28. The UAV of claim 27, wherein:

a contrast value difference is a difference between the first contrast value and a contrast value of a previous image;

a distance difference is a difference between a first distance between the optical device and the image sensor at which the first image is captured and a previous distance between the optical device and the image sensor at which the previous image was captured; and

the rate of change of the contrast value is the contrast value difference divided by the distance difference.

29. The UAV of claim 20, wherein the one or more processors are further configured for, in response to determining that the second contrast variation rate meets the second threshold criterion, applying a filter to a plurality of obtained contrast values to generate a filtered curve.

30. The UAV of claim 29, wherein the filter is a low pass filter.

31. The UAV of claim 29, wherein the one or more processors are further configured for: determining whether the filtered curve at a current position of the optical device relative to the image sensor satisfies an end criterion, and,

in response to determining that the filtered curve does not satisfy the end criterion:

initializing the optical device at an initial position relative to the image sensor; and repeating the aforementioned operations.

32. The UAV of claim 31, wherein determining whether the filtered curve at the current position of the optical device relative to the image sensor satisfies the end criterion includes determining whether a gradient of the filtered curve at the current position of the optical device relative to the image sensor meets a third threshold criterion.

33. A system for moving an optical device relative to an image sensor to focus an image, the system comprising:

one or more processors; and

an imaging device comprising the image sensor and the optical device;

the one or more processors configured for:

acquiring, by the image sensor, a first image when the optical device is at a first position relative to the image sensor;

obtaining a first contrast value of the first image and a first contrast variation rate at the first position;

determining whether the first contrast variation rate meets a first threshold criterion;

moving the optical device from the first position to a next position in accordance with the determination result;

repeating the aforementioned operations until a second contrast variation rate for a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the next position.

34. The system of claim 33, wherein the second contrast variation rate is determined using a second contrast value obtained for the second image.

35. The system of claim 33, wherein moving the optical device from the first position to the next position in accordance with the determination result further comprises:

in accordance with a determination that the first contrast variation rate meets the first threshold criterion:

determining a first step size, wherein the first step size is greater than a previous step size used for moving the optical device to the first position, and

moving the optical device from the first position to the next position according to the first step size; and

in accordance with a determination that the first contrast variation rate does not meet the first threshold criterion:

determining a second step size, wherein the second step size is smaller than the previous step size used for moving the optical device to the first position, and

moving the optical device from the first position to the next position according to the second step size.

36. The system of claim 34, wherein determining at least one of the first step size and the second step size includes:

generating a curve based on a plurality of contrast values including the first contrast value;

determining a position of the optical device relative to the image sensor at which the curve has a peak value; and

determining the first step size using the determined position of the optical device relative to the image sensor at which the curve has a peak value.

37. The system of claim 36, wherein, in at least one iteration of the repeating operation, the curve is a Bézier curve.

38. The system of claim 33, wherein the first contrast value is determined using at least one luminance gradient value from the first image, wherein a respective luminance gradient value is a luminance gradient across a portion of the first image.

39. The system of claim 33, wherein the first contrast variation rate is a gradient value indicating a rate of change of a contrast value from a previous image to a current image.

40. The system of claim 39, wherein:

a contrast value difference is a difference between the first contrast value and a contrast value of a previous image;

a distance difference is a difference between a first distance between the optical device and the image sensor at which the first image is captured and a previous distance between the optical device and the image sensor at which the previous image was captured; and

the rate of change of the contrast value is the contrast value difference divided by the distance difference.

41. The system of claim 33, wherein the one or more processors are further configured for, in response to determining that the second contrast variation rate meets the second threshold criterion, applying a filter to a plurality of obtained contrast values to generate a filtered curve.

42. The system of claim 41, wherein the filter is a low pass filter.

43. The system of claim 41, wherein the one or more processors are further configured for:

determining whether the filtered curve at the current position of the optical device relative to the image sensor satisfies an end criterion, and,

in response to determining that the filtered curve does not satisfy the end criterion:

initializing the optical device at an initial position relative to the image sensor; and
repeating the aforementioned operations.

44. The system of claim 43, wherein determining whether the filtered curve at the current position of the optical device relative to the image sensor satisfies the end criterion includes determining whether a gradient of the filtered curve at the current position of the optical device relative to the image sensor meets a third threshold criterion.

45. A computer readable storage medium storing one or more programs, the one or more programs comprising instructions, which when executed, cause an imaging device to:

acquire, by an image sensor, a first image when an optical device is at a first position relative to the image sensor;

obtain a first contrast value of the first image and a first contrast variation rate at the first position;

determine whether the first contrast variation rate meets a first threshold criterion;

move the optical device from the first position to a next position in accordance with the determination result; and

repeat the aforementioned operations until a second contrast variation rate for a second image meets a second threshold criterion, wherein the second image is acquired when the optical device is at the next position.

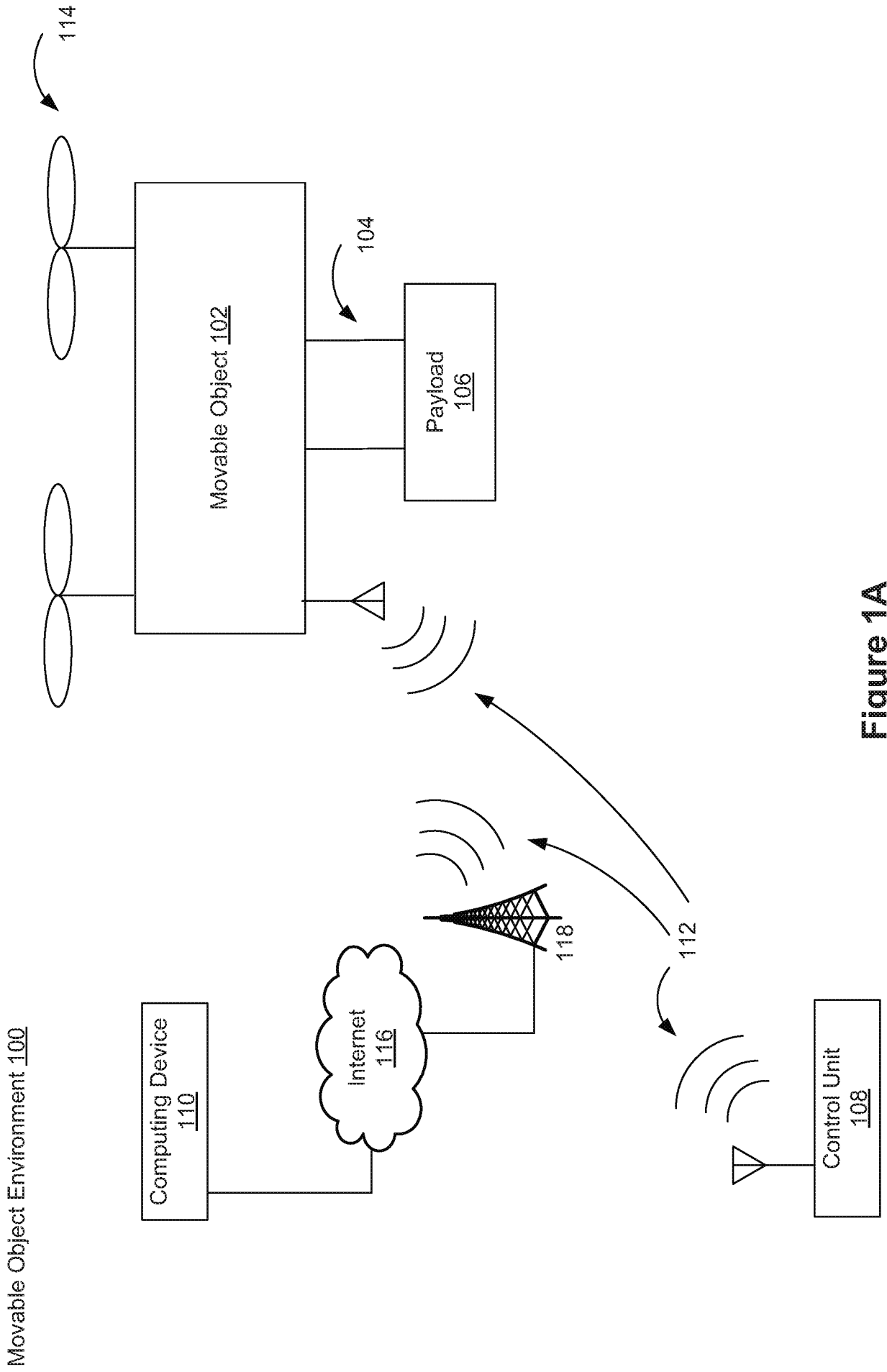


Figure 1A

Movable Object Environment 150

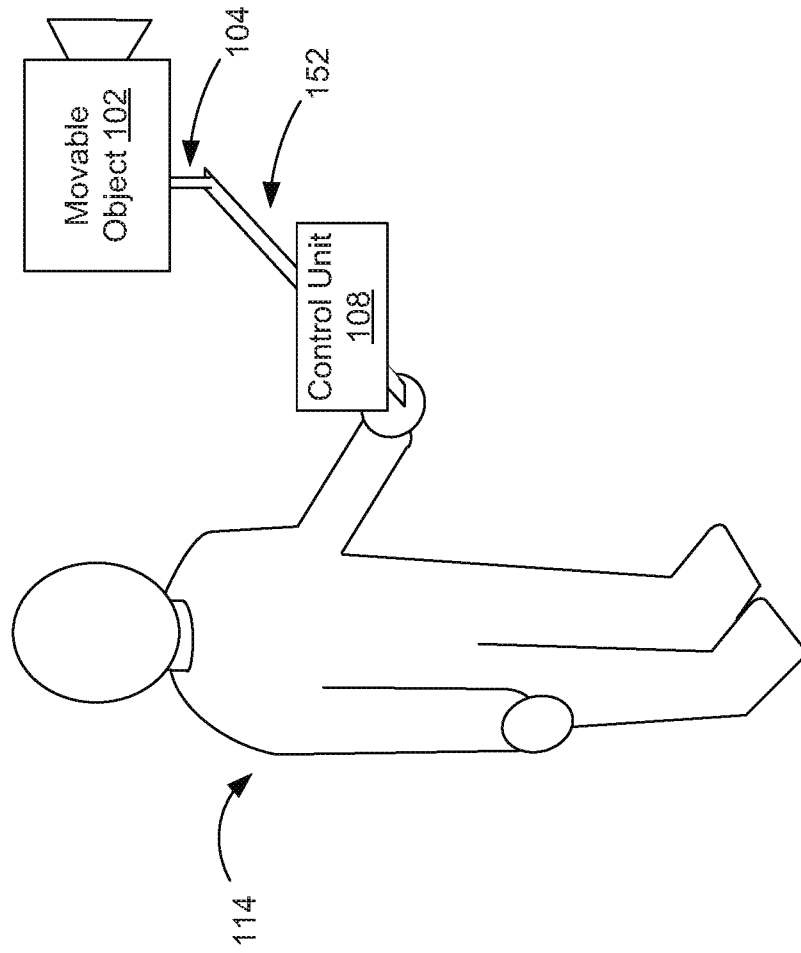


Figure 1B

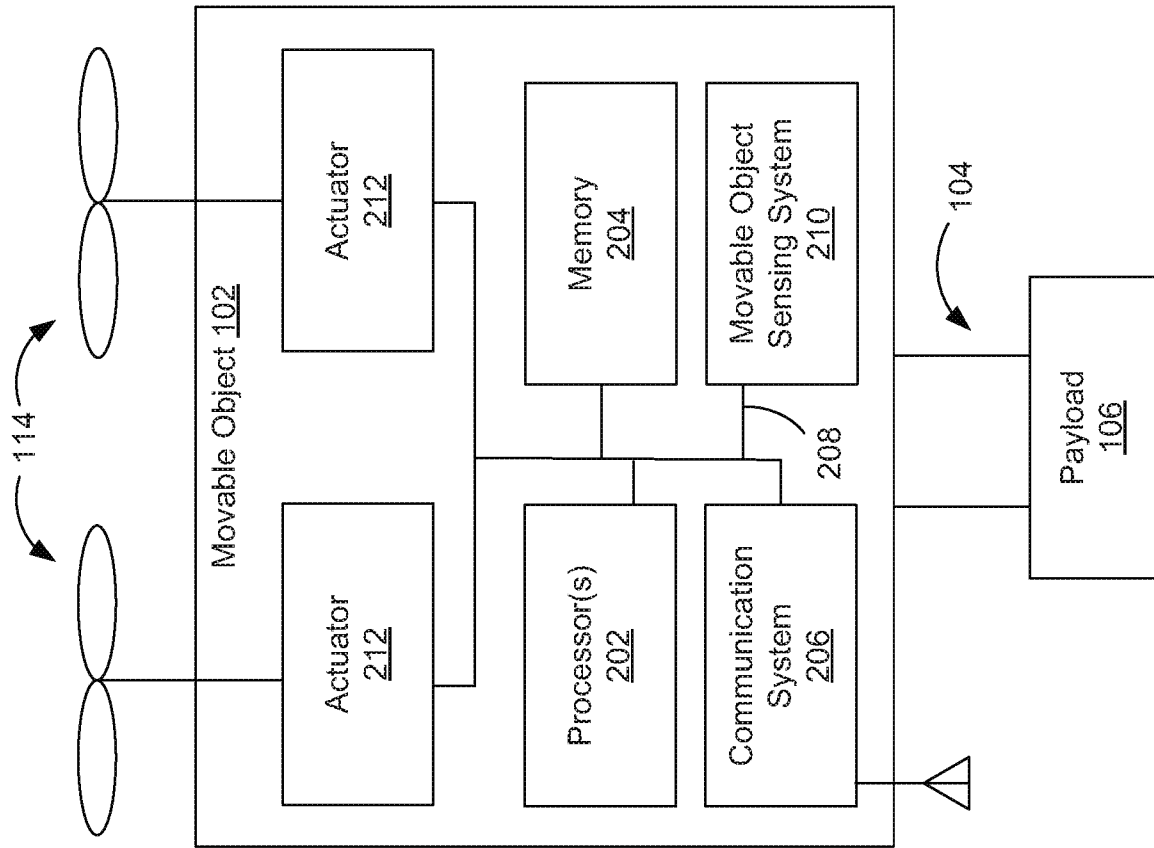


Figure 2A

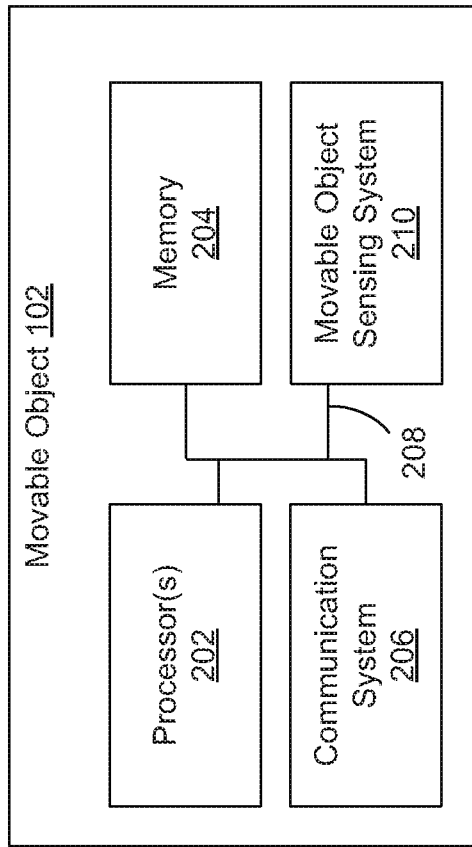


Figure 2B

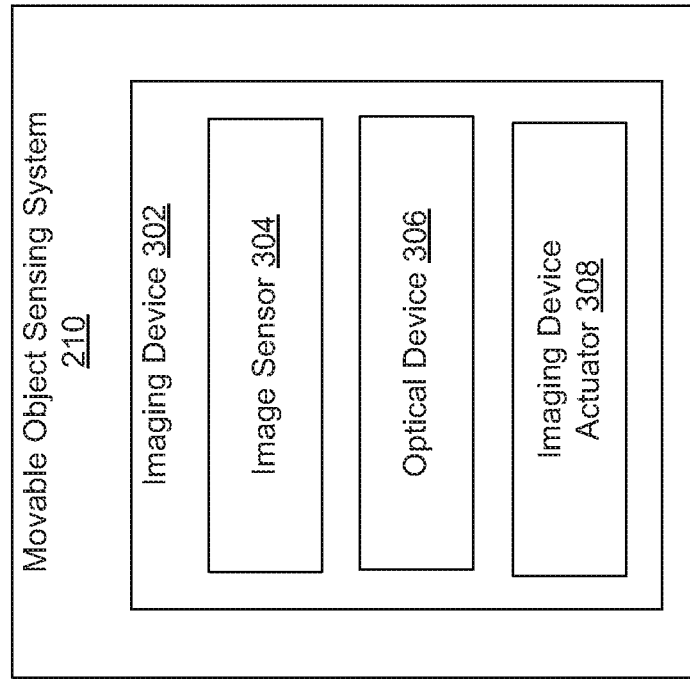


Figure 3

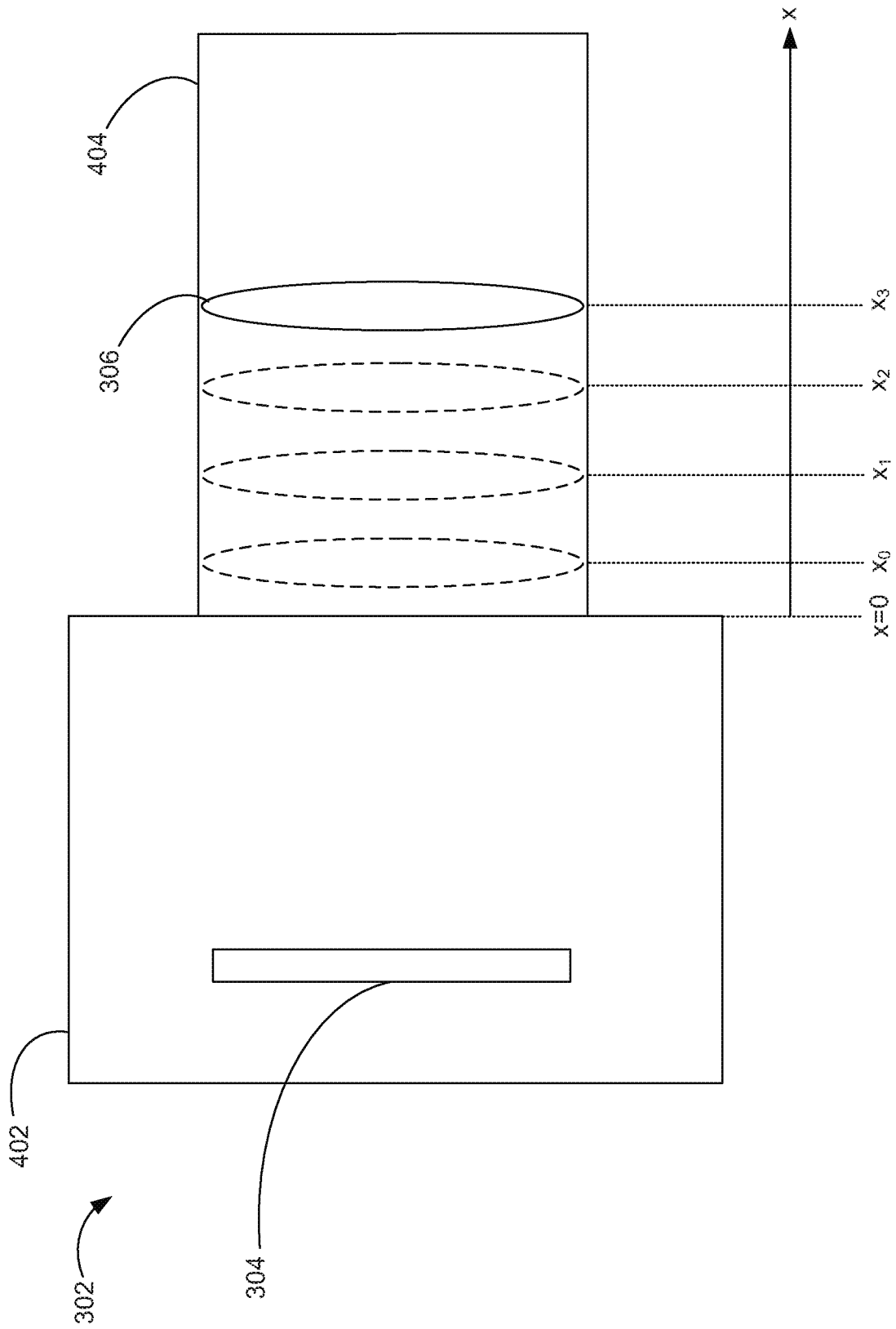


Figure 4

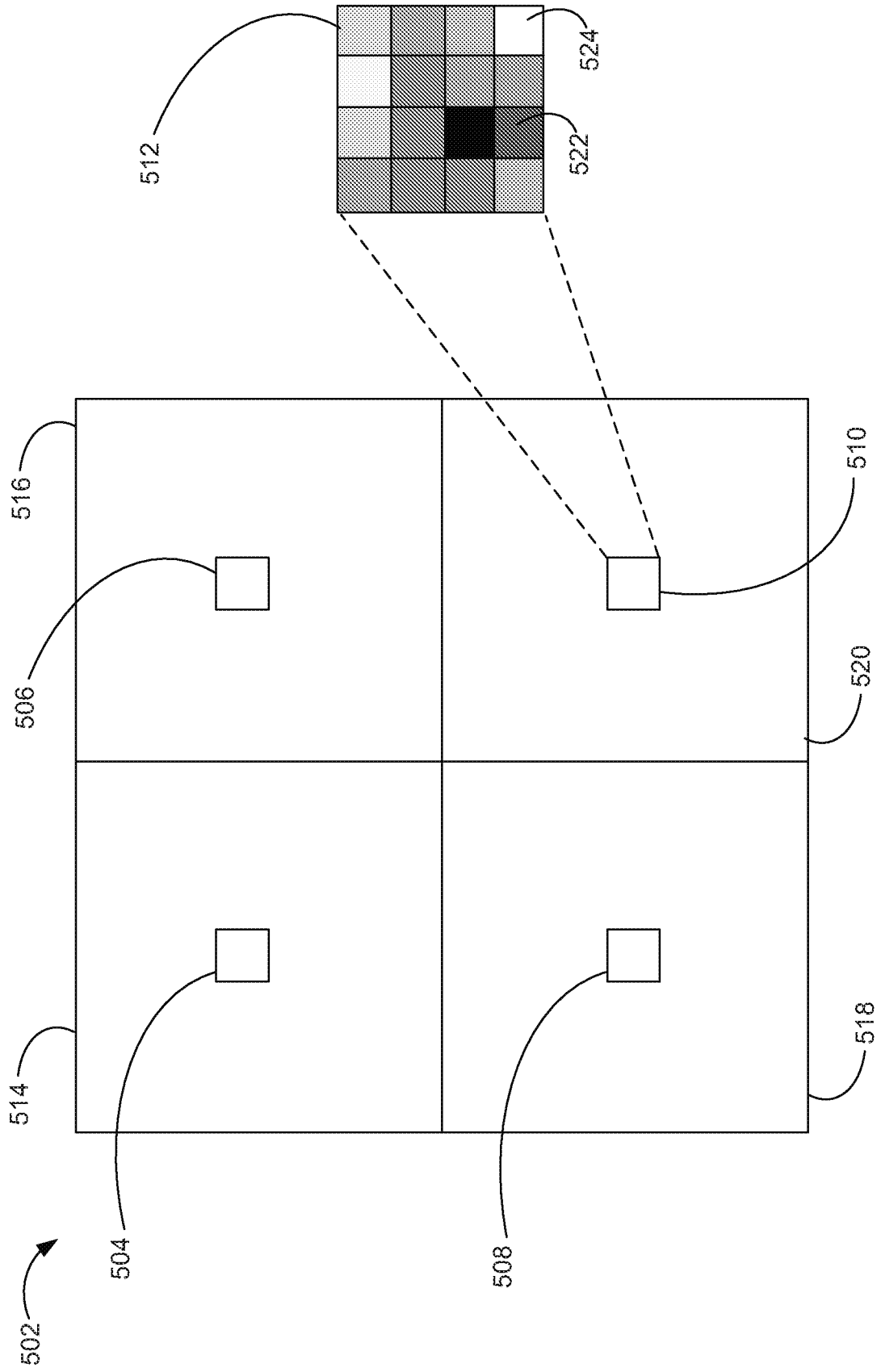


Figure 5

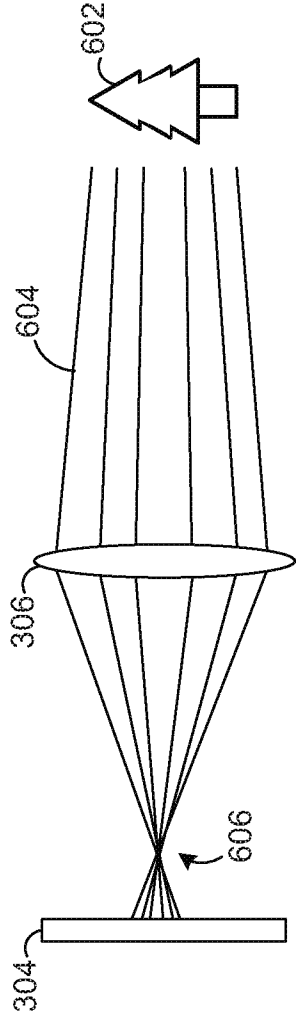


Figure 6A

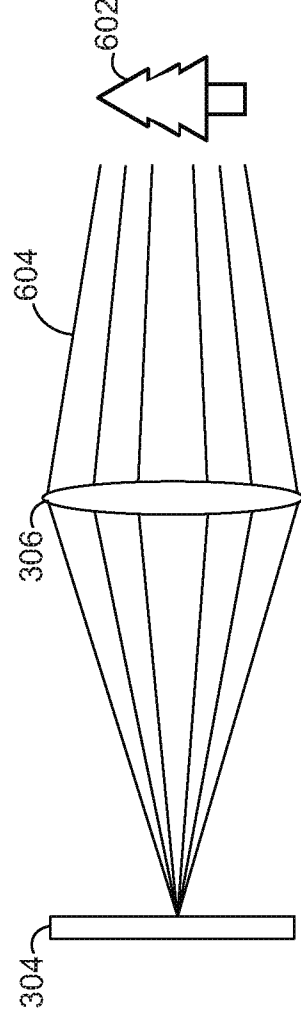


Figure 6B

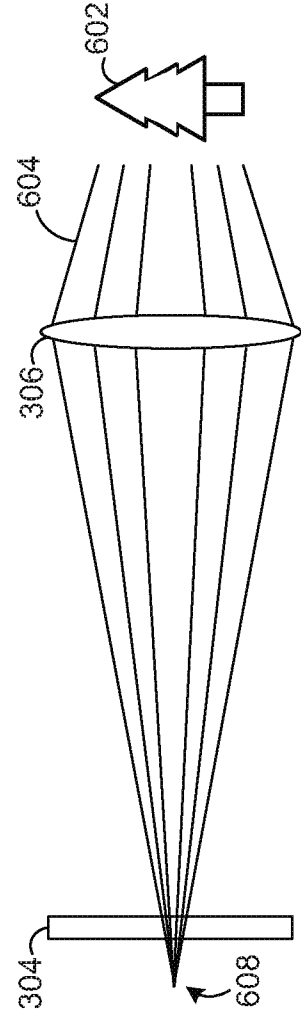


Figure 6C

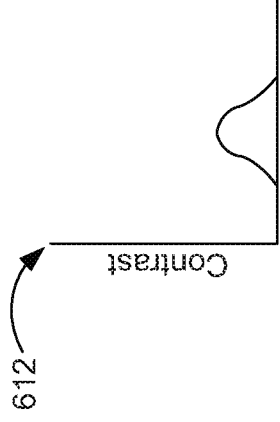


Figure 6D

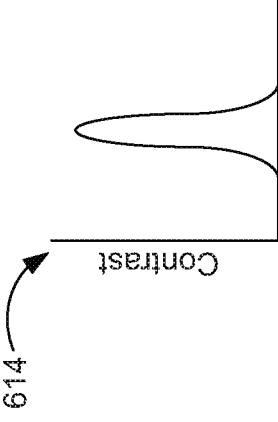


Figure 6E

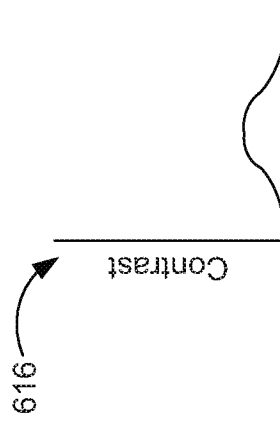


Figure 6F

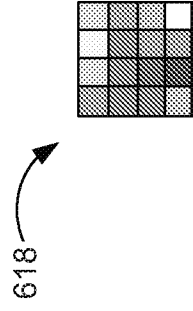


Figure 6G

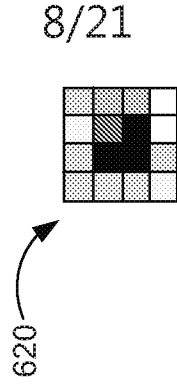


Figure 6H

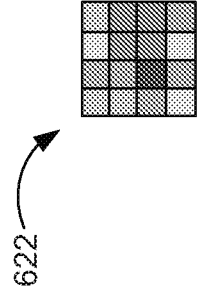


Figure 6I

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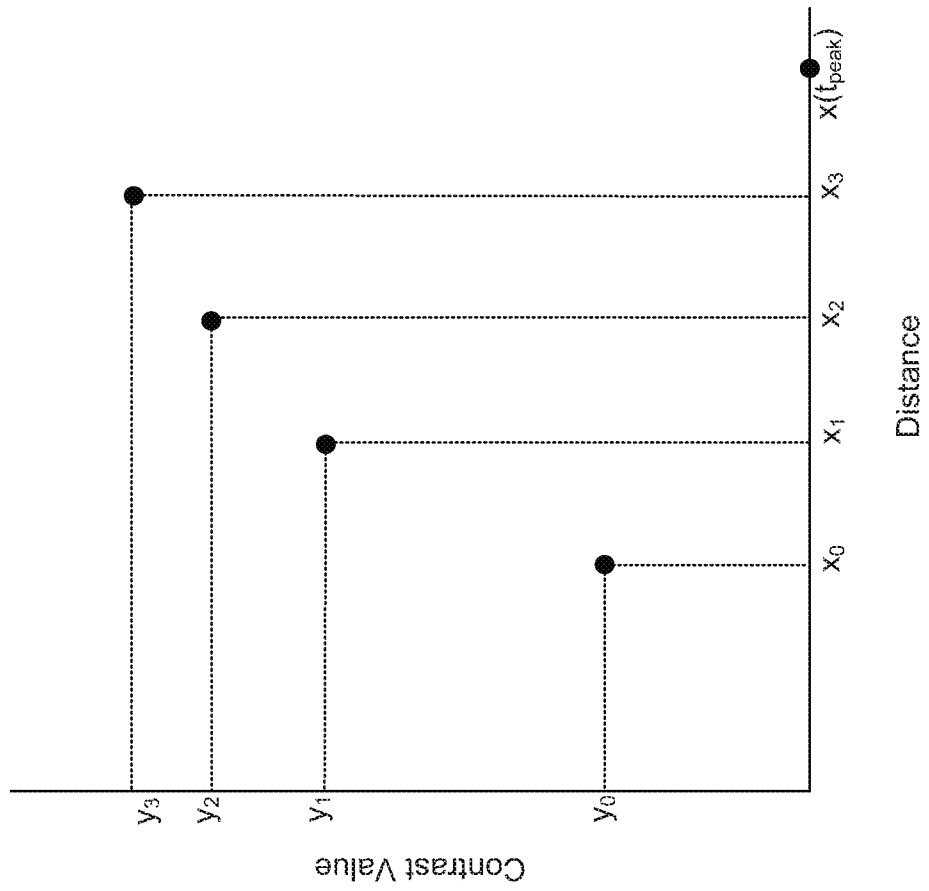


Figure 7

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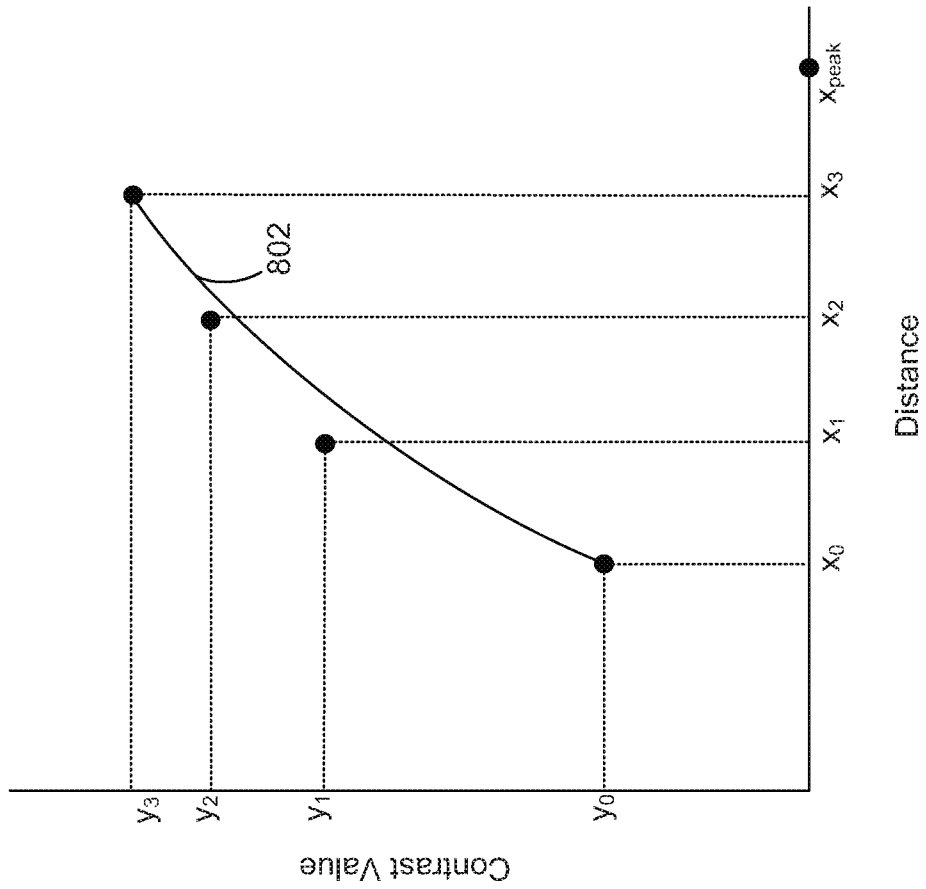


Figure 8A

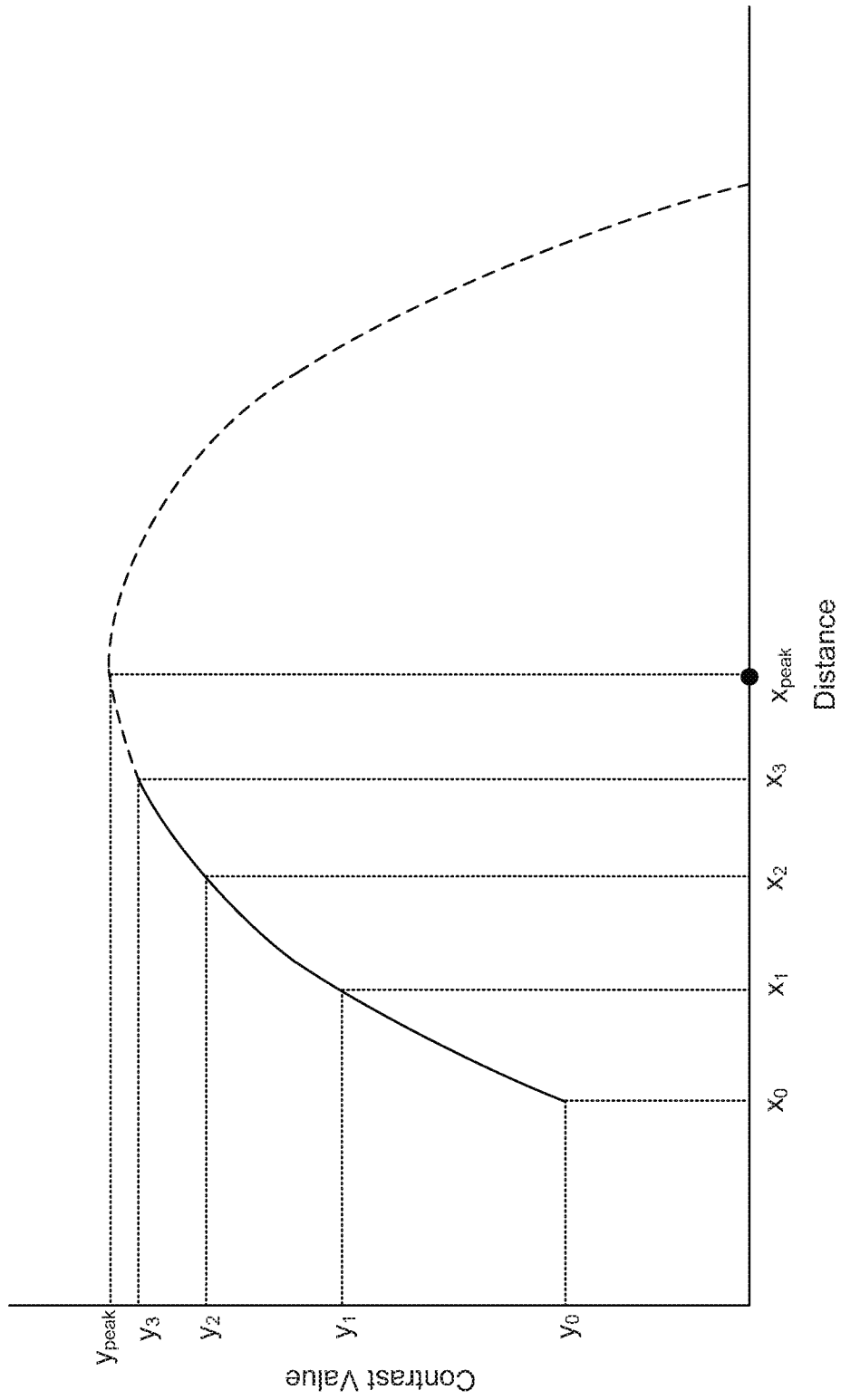


Figure 8B

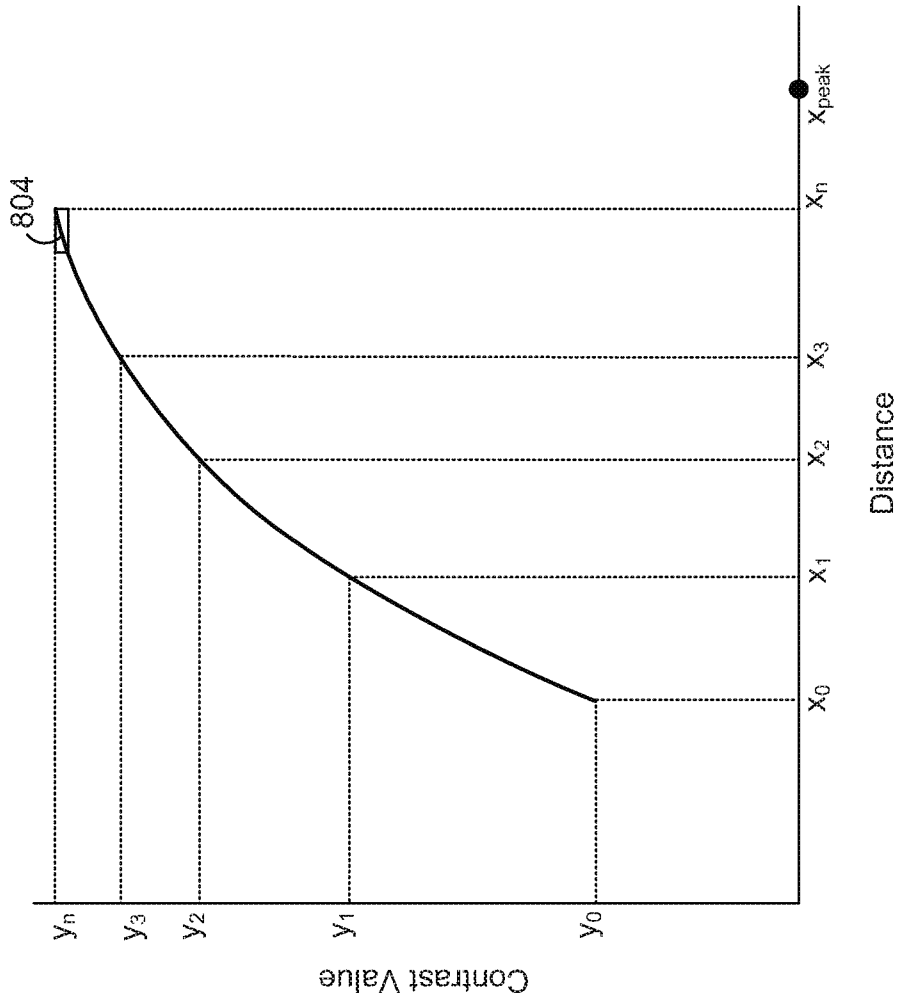


Figure 8C

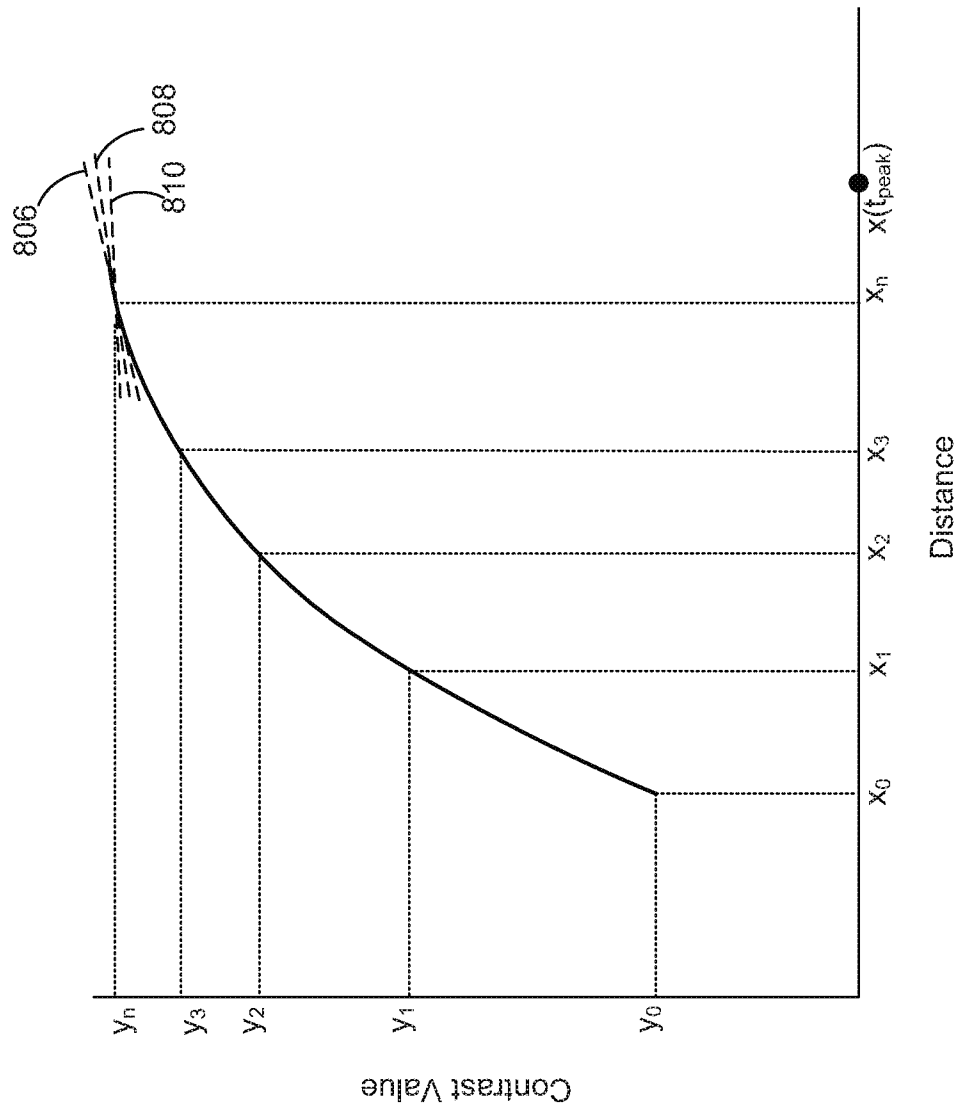


Figure 8D

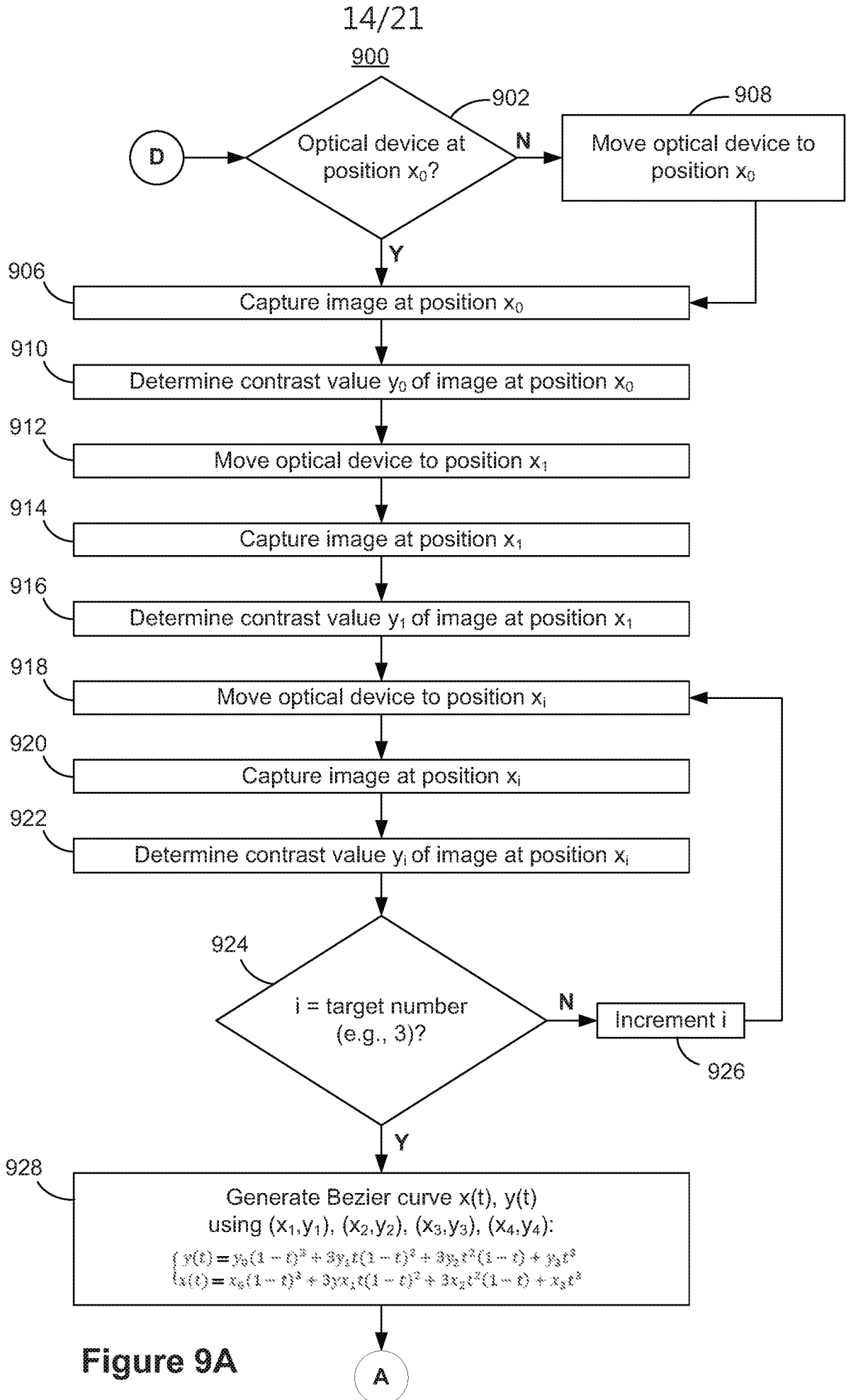


Figure 9A

900

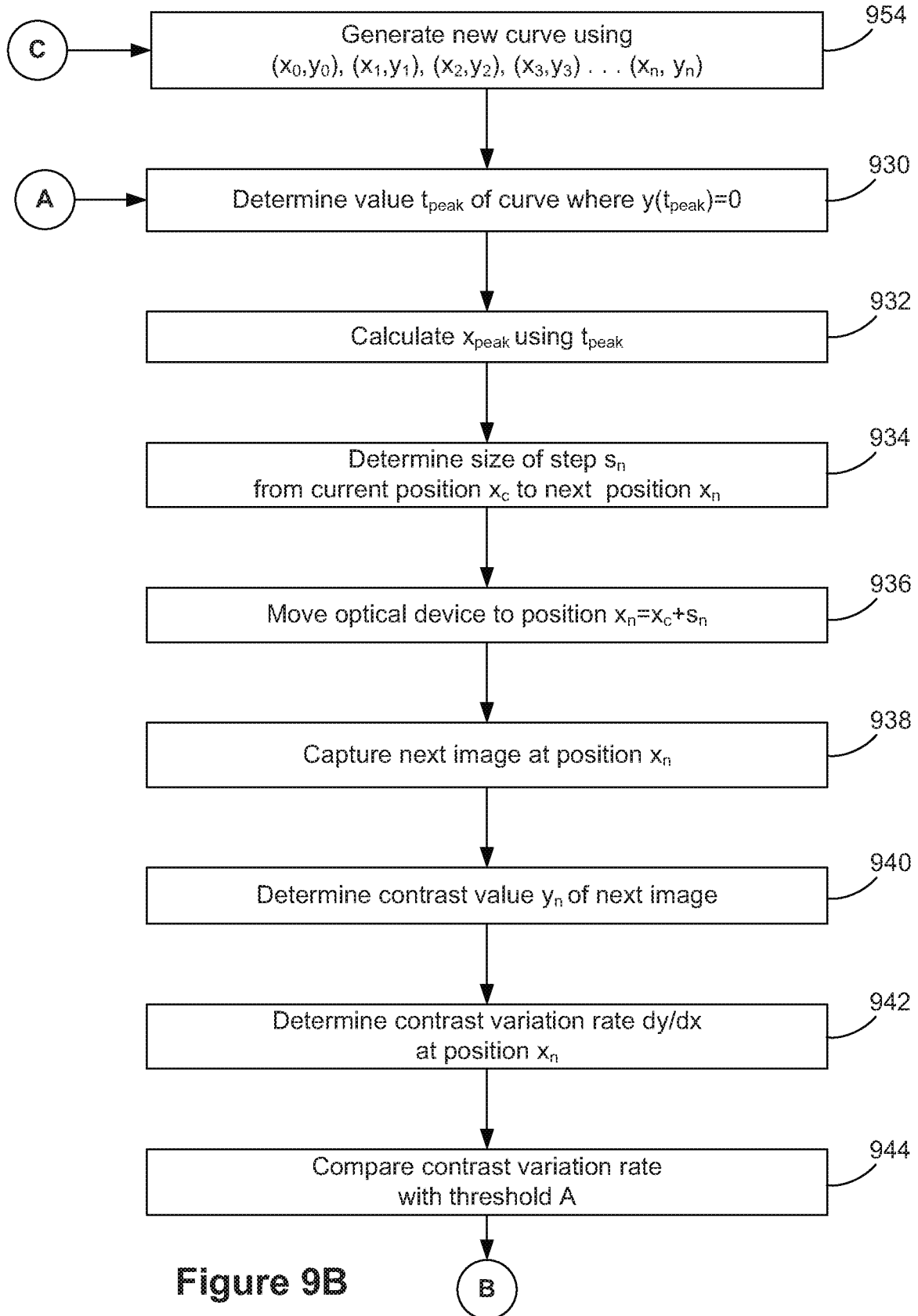


Figure 9B

900

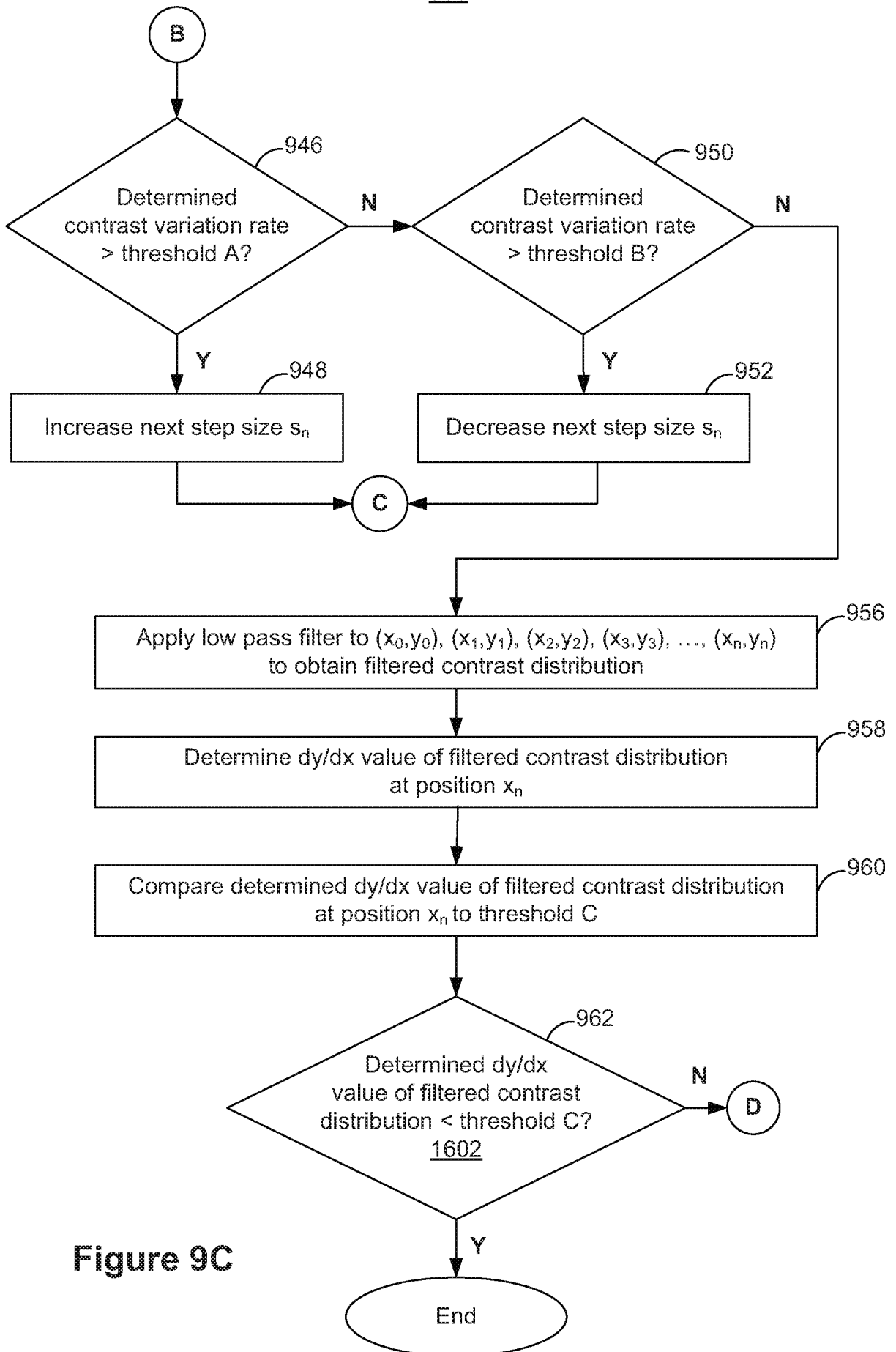


Figure 9C

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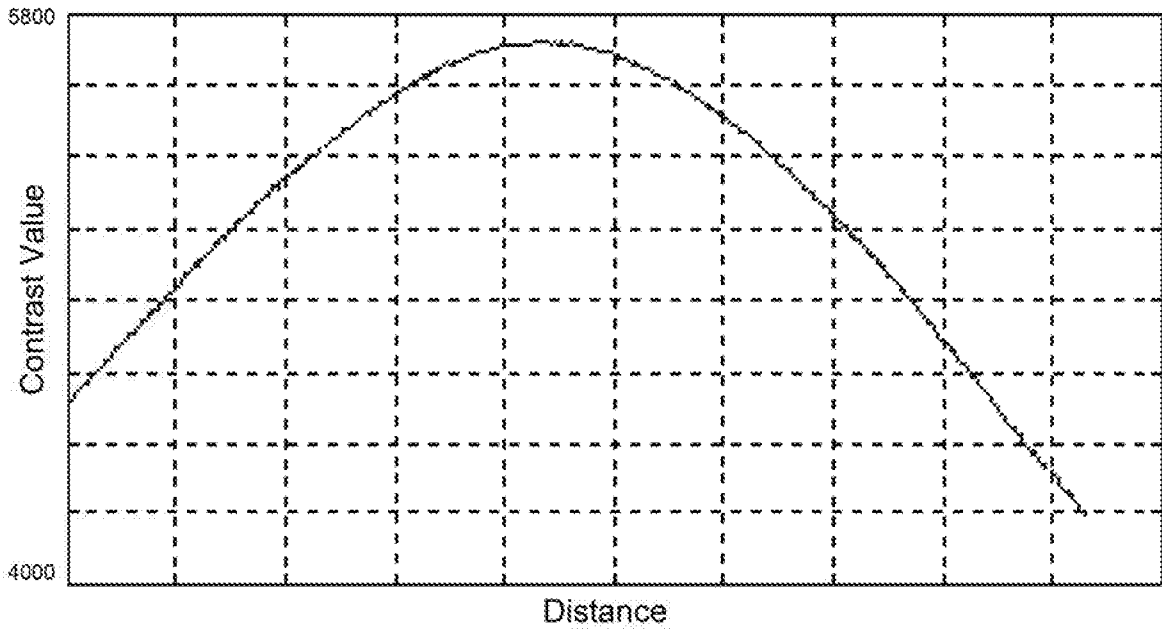


Figure 10A

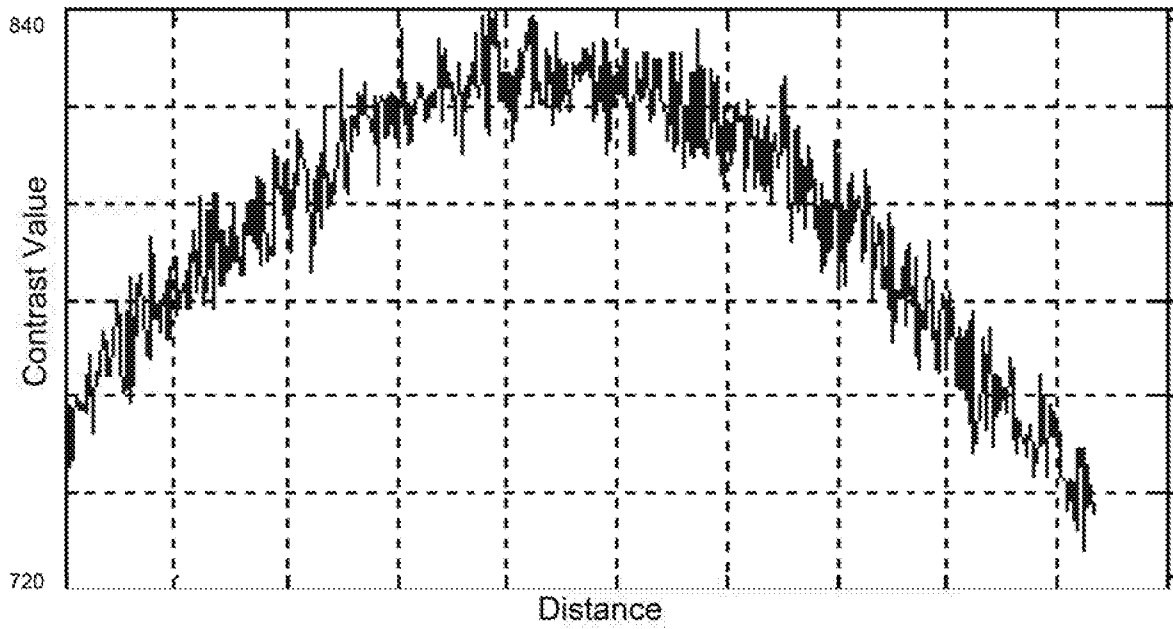


Figure 10B

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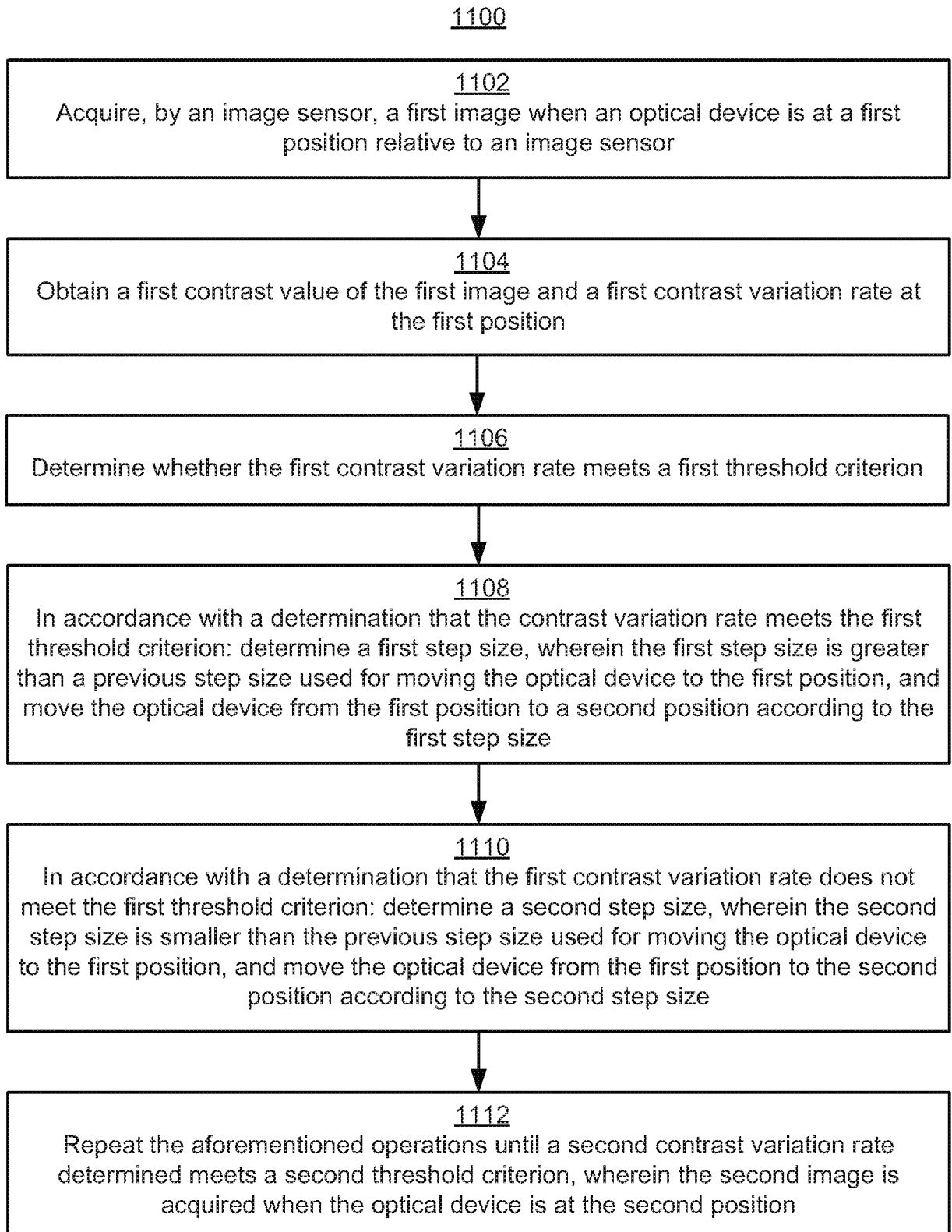


Figure 11A

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11001114

Determining that the first contrast variation rate meets the first threshold criterion includes comparing the first contrast variation rate to a first threshold gradient value

1116

The first contrast variation rate meets the first threshold criterion when the first contrast variation rate exceeds a first threshold gradient value

1118

Determining that the second contrast variation rate meets the second threshold criterion includes comparing the second contrast variation rate to a second threshold gradient value, wherein the second threshold gradient value is less than the first threshold gradient value.

1120

Determining at least one of the first step size and the second step size includes: generating a curve based on a plurality of contrast values including the first contrast value; determining a position of the optical device relative to the image sensor at which the curve has a peak value; and determining the first step size using the determined position of the optical device relative to the image sensor at which the curve has a peak value

1122

In at least one iteration of the repeating operation, the curve is a Bézier curve

1124

The Bézier curve is a cubic Bézier curve

1126

In at least one iteration of the repeating operation, the curve is determined using a non-linear least squares analysis.

Figure 11B

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11001128

The first contrast value is determined using at least one luminance gradient value from the first image, wherein a respective luminance gradient value is a luminance gradient across a portion of the first image

1130

The first contrast value is determined using an average of a plurality of luminance gradient values from the first image

1132

In response to determining that the second contrast variation rate meets the second threshold criterion, applying a filter to a plurality of obtained contrast values to generate a filtered curve

1134

The filter is a low pass filter

1136

The low pass filter is a one-dimensional Gaussian filter

1138

Determine whether the filtered curve at the current position of the optical device relative to the image sensor satisfies an end criterion, and, in response to determining that the does not satisfy the end criterion: initialize the optical device at an initial position relative to the image sensor; and repeat the aforementioned operations

1140

Determining whether the filtered curve at the current position of the optical device relative to the image sensor satisfies the end criterion includes determining whether a gradient of the filtered curve at the current position of the optical device relative to the image sensor meets a third threshold criterion

Figure 11C

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11001142

The second contrast variation rate is determined using a second contrast value obtained for the second image

1144

The first contrast variation rate is a gradient value indicating a rate of change of a contrast value from a previous image to a current image

1146

A contrast value difference is a difference between the first contrast value and a contrast value of a previous image; a distance difference is a difference between a first distance between the optical device and the image sensor at which the first image is captured and a previous distance between the optical device and the image sensor at which the previous image was captured; and the rate of change of the contrast value is the contrast value difference divided by the distance difference

Figure 11D

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2016/079506

A. CLASSIFICATION OF SUBJECT MATTER		
G03B 13/36(2006.01)i		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols)		
G03B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)		
CNPAT, CNKI, GOOGLE, EPODOC, WPI: contrast, variation, difference, rate, gradient, focus, automatic, step, threshold, optical, sensor		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 2648401 A1 (NEC CASIO MOBILE COMMUNICATIONS, LTD.) 09 October 2013 (2013-10-09) description, paragraphs [0010], [0020]-[0021], [0039]-[0040], and Fig. 3	1-45
A	CN 103235397 A (HUAWEI TECHNOLOGIES CO., LTD.) 07 August 2013 (2013-08-07) the whole document	1-45
A	CN 102629978 A (SHENZHEN INFINOVA SCIENCE AND TECHNOLOGY CO., LTD.) 08 August 2012 (2012-08-08) the whole document	1-45
A	CN 102129146 A (NIKON CORP.) 20 July 2011 (2011-07-20) the whole document	1-45
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search		Date of mailing of the international search report
04 January 2017		18 January 2017
Name and mailing address of the ISA/CN		Authorized officer
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Facsimile No. (86-10)62019451		Telephone No. (86-10)62413996

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2016/079506

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				CN	103222258	A	24 July 2013
				CN	103222258	B	08 June 2016
				WO	2012073779	A1	07 June 2012
				EP	2648401	B1	26 August 2015
				US	2013229547	A1	05 September 2013
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