ACTIVE IMAGING SYSTEM AND METHOD FOR ADJUSTABLE SELECTIVE DEPTH OF FIELD IMAGING

TECHNICAL FIELD

The invention relates to an active imaging system and method for adjustable selective depth of field (DoF) imaging.

BACKGROUND

There are active imaging systems that actively image a scene at a selected DoF (i.e., a selected range) from a camera, without imaging the scene at other DoFs from the camera. Such active imaging systems have the following advantages: dazzling of the active imaging system can be avoided, image scattering (e.g., due to fog) can be avoided, undesired reflections from vegetation can be avoided, etc.

The current solution for actively imaging a scene only at a selected DoF from a camera is achieved by emitting a sequence of pulses by a laser, and gating the camera so that only returns of the pulses from the selected DoF are captured by the camera (the camera shutter is closed when returns from DoFs other than the selected DoF arrive at the camera). This solution is based on a known Time of Flight (ToF) of a respective laser pulse for different ranges from the camera. Since the gating of the camera is performed based on a time differentiation of returns of each of the laser pulses from different distances (i.e., ranges) from the camera, the time period between consecutive laser pulses is at least the time required for all of the returns of the earlier laser pulse to arrive at the camera. Moreover, the laser range resolution limits the pulse width of each of the laser pulses. These constraints necessitate the use of a pulsed laser having short pulses and a low duty cycle, resulting in inefficient usage of the camera, the need to use a complex Q-switch laser (wherein wavelength selection for the laser is limited), and the need to emit high intensity pulses for enabling the detection of returns (due to the short pulse width).

There is thus a need in the art for a new active imaging system and method for adjustable selective DoF imaging that overcomes at least the aforesaid deficiencies.

References considered to be relevant as background to the presently disclosed subject matter are listed below. Acknowledgement of the references herein is not to be inferred as meaning that these are in any way relevant to the patentability of the presently disclosed subject matter.

U.S. Patent Application Publication No. 2011/0134436 A1, published on June 9, 2011, discloses methods and devices for acquiring depth resolved aberration information using principles of low coherence interferometry and performing coherence gated wavefront sensing (CG-WFS). The wavefront aberrations are collected using spectral domain low coherence interferometry (SD-LCI) or time domain low coherence interferometry (TD-LCI) principles. When using SD-LCI, chromatic aberrations can also be evaluated. Methods and devices are disclosed in using a wavefront corrector to compensate for the aberration information provided by CG-WFS, in a combined imaging system, that can use one or more channels from the class of (i) optical coherence tomography (OCT), (ii) scanning laser ophthalmoscopy, (iii) microscopy, such as confocal or phase microscopy, (iv) multiphoton microscopy, such as harmonic generation and multiphoton absorption. In particular, a swept source (SS) is used that drives both an OCT channel and a coherence gated wavefront sensor, where: a) both channels operate according to SS-OCT principles; b) OCT channel integrates over at least one tuning scan of the swept source to provide a TD-OCT image of the object; and c) CG-WFS integrates over at least one tuning scan of the swept source to provide an en-face TD-OCT mapping of the wavefront. For some implementations, simultaneous and dynamic aberration measurements/correction with the imaging process is achieved. The methods and devices for depth resolved aberrations disclosed, will find applications in wavefront sensing and adaptive optics imaging systems that are more tolerant to stray reflections from optical interfaces, such as reflections from the microscope objectives and cover slip in microscopy and when imaging the eye, the reflection from the cornea.

US Patent No. 6,852,991 B2, published on February 8, 2005, relates to an optoelectronic sensor which has a transmission device for transmitting a strip illumination in the direction of an object zone, a reception device for receiving light reflected or remitted from the object zone and for outputting at least one corresponding reception signal and an evaluation device for evaluating the at least one reception signal. A division of the strip illuminated object region into a plurality of monitoring segments is provided. Furthermore, a distance measuring device is provided by which, for at least one monitoring segment, the distance to an object disposed therein can be determined.

European Patent Application Publication No. 3,745,185 A1, published on December 2, 2020, discloses a depth camera assembly (DCA) that determines distances between the DCA and objects in a local area within a field of view of the DCA. The DCA includes an illumination source configured to modulate a structured light pattern by a carrier signal so an intensity of

the structured light pattern varies over time based on the carrier signal and to emit the modulated structured light pattern. An imaging device is configured to capture the modulated structured light pattern and the imaging device includes a detector comprising a plurality of pixel groups each including one or more pixels. Each pixel group includes multiple charge storage regions and the detector is configured to accumulate charge from light captured by a pixel group in one of the charge storage regions included in the pixel group based on a frequency and a phase of the carrier signal.

U.S. Patent Application Publication No. 2016/0349359 A1, published on December 1, 2016, discloses achieving a reduction in interference between different time of flight (ToF) cameras used for depth measurements and operating in the same application environment using a spread spectrum technique in which the cyclical operations of a pulsed light source such as a laser or light emitting diode (LED) and gated image sensor are varied in a pseudo-random manner in each camera. In an alternative embodiment, spread spectrum logic is applied in a ToF camera that employs phase modulation techniques.

U.S. Patent No. 6,788,420, published on September 7, 2004, relates to a heterodyne interferometer system with a pre-processing of the target signal to isolate and remove self-interference signals using a known phase modulation of the carrier signal's frequency. Where self-interference signals do not include a time delay inherent in the target signal that travels to the target reflector, by selecting a modulation frequency tuned to the time delay and then filtering the resultant signal the target beam can be isolated and the self-interference signal can be effectively removed The system includes a modulation unit to apply a phase modulation to the carrier signal, and a mixing unit that demodulates the target signal at the modulation frequency to isolate the target beam.

European Patent Application Publication No. 0449337A2, published on October 2, 1991, presents an electro-optical camera system. A light source (e.g. laser) is modulated by an electro-optic modulator (such as a Pockels cell) and transmitted out through an optical system toward a static target scene. The light backscattered from the target scene is then focused by the same optics back through the same Pockels cell onto a two-dimensional array camera such as a CCD or a CID (charge-couple device or charge injection device). A computer determines the frequency modulation period of each pixel in the array as the frequency of the electro-optic modulator is varied. This period is inversely proportional to the range of the target in the direction defined by the pixel location. Thus, all three spatial coordinates (two angles and a

range) of each target area sensed by each pixel are determined. The computer will display the array of range data using a suitable output device such as a video display unit or a printer.

U.S. Patent No. 4,935,616, published on June 19, 1990, discloses a laser source that is operated continuously and modulated periodically (typically sinusoidally). A receiver imposes another periodic modulation on the received optical signal, the modulated signal being detected by an array of detectors of the integrating type. Range to the target is determined by measuring the phase shift of the intensity modulation on the received optical beam relative to a reference. The receiver comprises a photoemitter for converting the reflected, periodically modulated, return beam to an accordingly modulated electron stream. The electron stream is modulated by a local demodulation signal source and subsequently converted back to a photon stream by a detector. A charge coupled device (CCD) array then averages and samples the photon stream to provide an electrical signal in accordance with the photon stream.

U.S. Patent Application Publication No. 2010/0033727 A1, published on February 11, 2010, presents an imager that can provide separated images corresponding to differing depths in a sample. In accordance with some embodiments, an imager can include a light source; a sample arm that receives light from the light source, directs the light to a sample, and captures light returning from the sample; a modulation source that provides different modulations corresponding to differing imaging depths in the sample; a detector system to receive the captured light from the sample with the different modulations; and a processor that receives signals from the detector system and separates a plurality of images corresponding with the differing image depths in the sample.

U.S. Patent Application Publication No. 2017/0357004 A1, published on December 14, 2017, relates to a lighting system including a primary light source producing a primary light beam in the direction of a conversion device that returns a secondary light radiation to an optical imaging system forming a projected light beam. A light sensor generates a signal corresponding to the light received by this sensor. The light includes a non-converted light part of the first primary light beam which is returned by the conversion device in the projected light beam and is reflected by an obstacle situated in the zone illustrated by the projected light beam. A control unit has modulation means generating a modulation signal for the primary light, and demodulation means for processing the signal formed by the sensor, and determines a distance between the obstacle and the lighting system.

U.S. Patent Application Publication No. 2022/0171070 A1, published on June 2, 2022, discloses a lidar sensor system. The lidar sensor system includes a transmission unit having a

laser source, a phase modulator for modulating a phase of the light of the laser source, and a transmission optic for emitting the modulated light; a reception unit having a reception optic for receiving light reflected from an object and having an evaluation unit for evaluating the light received by the reception optic; the transmission unit being embodied to emit several transmission sequences of the light; each transmission sequence having a first portion and a second portion; the first portion being an unmodulated constant-phase signal; the second portion being a signal phase-modulated by the phase modulator; and the evaluation unit being embodied to determine at least an absolute value of a Doppler frequency based on the first portion, and to determine a distance to the object based on the Doppler frequency and the second portion.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the presently disclosed subject matter and to see how it may be carried out in practice, the subject matter will now be described, by way of non-limiting examples only, with reference to the accompanying drawings. The dimensions of components and features shown in the drawings are chosen for convenience and clarity of presentation and are not necessarily to scale. In the drawings:

Fig. 1 is a block diagram schematically illustrating one example of an active imaging system, in accordance with the presently disclosed subject matter;

Fig. 2 is a block diagram schematically illustrating a first example of an adjustable optical manipulation unit, in accordance with the presently disclosed subject matter;

Fig. 3A is a block diagram schematically illustrating a first example of a filtering and detection unit, in accordance with the presently disclosed subject matter;

Fig. 3B is a block diagram schematically illustrating a second example of a filtering and detection unit, in accordance with the presently disclosed subject matter;

Fig. 4 is a schematic illustration of a first example of an operation of an active imaging system, in accordance with the presently disclosed subject matter;

Fig. 5 is a flowchart illustrating one example of a sequence of operations for illuminating a scene, in accordance with the presently disclosed subject matter;

Fig. 6 is a flowchart illustrating one example of a sequence of operations for an interference-based manipulation of the return light that is returned from at least part of the illuminated scene, in accordance with the presently disclosed subject matter;

Fig. 7 illustrates an example of an operation for performing selective Depth of Field (DoF) imaging, following an interference-based manipulation of the return light returned from at least part of the illuminated scene, in accordance with the presently disclosed subject matter;

Fig. 8 is a flowchart illustrating a second example of a sequence of operations for performing selective DoF imaging, following an interference-based manipulation of the return light, in accordance with the presently disclosed subject matter;

Fig. 9 is a block diagram schematically illustrating one example of a demodulation-based receiving subsystem, in accordance with the presently disclosed subject matter;

Fig. 10 is a schematic illustration of one example of an operation of an active imaging system that includes a demodulation-based receiving subsystem, in accordance with the presently disclosed subject matter; and

Fig. 11 is a flowchart illustrating an example of a sequence of operations for performing selective DoF imaging, in accordance with the presently disclosed subject matter.

DETAILED DESCRIPTION

In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the presently disclosed subject matter. However, it will be understood by those skilled in the art that the presently disclosed subject matter may be practiced without these specific details. In other instances, well-known methods, procedures, and components have not been described in detail so as not to obscure the presently disclosed subject matter.

In the drawings and descriptions set forth, identical reference numerals indicate those components that are common to different embodiments or configurations.

It is to be noted that the expressions "reflections" and "reflected light" are used interchangeably with the terms "returns" and "return light" respectively throughout the disclosure including figures.

Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as “generating”, “transmitting”, “imaging”, “manipulating”, “outputting”, “modulating”, “sampling”, “varying”, “directing”, “filtering”, “attenuating”, “passing”, “demodulating”, “detecting”, “controlling”, “determining” or the like, include actions and/or processes that manipulate and/or transform data into other data, said data represented as physical quantities, e.g. such as

electronic or optical quantities, and/or said data representing the physical objects. The terms "computer", "processor", and "controller" should be expansively construed to cover any kind of electronic device with data processing capabilities, including, by way of non-limiting example, a personal desktop/laptop computer, a server, a computing system, a communication device, a smartphone, a tablet computer, a smart television, a processor (e.g. digital signal processor (DSP), a microcontroller, a field-programmable gate array (FPGA), an application specific integrated circuit (ASIC), etc.), a group of multiple physical machines sharing performance of various tasks, virtual servers co-residing on a single physical machine, any other electronic computing device, and/or any combination thereof.

As used herein, the phrase "for example," "such as", "for instance" and variants thereof describe non-limiting embodiments of the presently disclosed subject matter. Reference in the specification to "one case", "some cases", "other cases" or variants thereof means that a particular feature, structure or characteristic described in connection with the embodiment(s) is included in at least one embodiment of the presently disclosed subject matter. Thus, the appearance of the phrase "one case", "some cases", "other cases" or variants thereof does not necessarily refer to the same embodiment(s).

It is appreciated that, unless specifically stated otherwise, certain features of the presently disclosed subject matter, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the presently disclosed subject matter, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable sub-combination.

In embodiments of the presently disclosed subject matter, fewer, more and/or different stages than those shown in **Figs. 5 to 8 and 11** may be executed. In embodiments of the presently disclosed subject matter one or more stages illustrated in **Fig. 5 to 8 and 11** may be executed in a different order and/or one or more groups of stages may be executed simultaneously. **Figs. 1, 2, 3A, 3B, 4, 9 and 10** illustrate general schematics of the architecture of an active imaging system or a part thereof, in accordance with embodiments of the presently disclosed subject matter. In other embodiments of the presently disclosed subject matter, the system may comprise fewer, more, and/or different modules than those shown in **Figs. 1, 2, 3A, 3B, 4, 9 and 10**.

Any reference in the specification to a method should be applied mutatis mutandis to a system capable of executing the method and should be applied mutatis mutandis to a non-

transitory computer readable medium that stores instructions that once executed by a computer result in the execution of the method.

Any reference in the specification to a system should be applied mutatis mutandis to a method that may be executed by the system and should be applied mutatis mutandis to a non-transitory computer readable medium that stores instructions that may be executed by the system.

Any reference in the specification to a non-transitory computer readable medium should be applied mutatis mutandis to a system capable of executing the instructions stored in the non-transitory computer readable medium and should be applied mutatis mutandis to method that may be executed by a computer that reads the instructions stored in the non-transitory computer readable medium.

Attention is now drawn to **Fig. 1**, a block diagram schematically illustrating one example of an active imaging system 100, in accordance with the presently disclosed subject matter.

In accordance with the presently disclosed subject matter, active imaging system 100 is configured to include a Continuous Wave (CW) light source 105 (e.g., a CW laser), a transmission subsystem 110 and a receiving subsystem 120. CW light source 105 is configured for outputting a coherent continuous beam, as detailed further herein, inter alia with reference to **Fig. 5**. Transmission subsystem 110 is configured to include an optical phase modulator 114 (e.g., an electro-optical phase modulator), the optical phase modulator 114 being configured to phase modulate the coherent continuous beam to generate at least one phase-modulated coherent continuous beam, as detailed further herein, inter alia with reference to **Fig. 5**. Transmission subsystem 110 is configured, using the optical phase modulator 114, to generate and transmit at least one continuous transmission beam for illuminating a scene, as detailed further herein, inter alia with reference to **Fig. 5**.

In some cases, transmission subsystem 110 is configured to include an optical unit 116. Optical unit 116 is configured to control one or more parameters associated with the at least one continuous transmission beam, in some cases, for directing the transmission beam to a region of interest. In some cases, the one or more parameters include at least one of: a line of sight (LOS) direction of the transmission beam, a region of interest for illumination by the transmission beam, a spatial distribution of the transmission beam, or focusing properties of

the transmission beam. In some cases, the optical unit 116 can be two or more optical elements. In some cases, the elements of the optical unit 116 can be distributed.

Receiving subsystem 120 is configured to receive, at any given moment or timeframe, return light reflected or scattered from objects at multiple Depths of Field (DoFs) in at least part of the scene illuminated by the transmission beam (the scene illuminated by the transmission beam is referred to hereinafter, interchangeably, as "the illuminated scene" or "the scene"). An object is defined as something material that may be perceived by the senses, and that is capable of reflecting or scattering light (for example, fog is considered to be an object). Each of the multiple DoFs is associated with a different distance or range of distances from which the return light is returned to the receiving subsystem 120. The objects can include one or more first objects at one or more desired DoFs in the at least part of the scene and one or more second objects at one or more undesired DoFs in the at least part of the scene (the one or more desired DoFs, is referred to hereinafter, interchangeably, as "at least one desired DoF").

Receiving subsystem 120 is configured for selectively imaging the return light (referred to hereinafter, interchangeably, as selective DoF imaging) to image the one or more first objects at the one or more desired DoFs, and to not image or image with a suppressed intensity the one or more second objects at the one or more undesired DoFs. The at least one desired DoF is adjustable. The advantages of adjustable selective DoF imaging can be, for example, one or more of the following: avoiding dazzling of the active imaging system 100, avoiding image scattering (e.g., due to fog), avoiding undesired returns from vegetation, etc. This can improve the imaging of targets of interest in the at least one desired DoF.

Since a CW light source 105 is used, the return light that is reflected or scattered from the first objects in the at least one desired DoF is continuously imaged. Accordingly, the peak power usage of the CW light source 105 is low (in contrast, when laser pulses are used to actively illuminate a scene in a selective DoF imaging system, as described in the Background above, the desired DoF(s) is imaged with suppressed intensity, and accordingly the peak power usage of the light source emitting the laser pulses is substantially higher than the peak power usage of the CW light source 105).

Receiving subsystem 120 is configured to include an adjustable optical manipulation unit 130 and a filtering and detection unit 140. Receiving subsystem 120 is configured, e.g., using adjustable optical manipulation unit 130, to perform at least one phase modulation for continuous manipulation of the return light that is reflected or scattered from the objects in at least part of the illuminated scene, thereby enabling selective DoF imaging, as detailed further

herein, inter alia with reference to **Figs. 2, 4, 6 and 9 to 11**. Receiving subsystem 120 is configured, e.g., using filtering and detection unit 140, to perform the selective DoF imaging by filtering out or attenuating the manipulated return light that is associated with the return light reflected or scattered from the one or more objects at the undesired DoFs in the at least part of the illuminated scene, and by imaging the one or more objects at the one or more desired DoFs in the at least part of the illuminated scene, as detailed further herein, inter alia with reference to **Figs. 3A, 3B and 7 to 11**. It is to be noted that the division of the receiving subsystem 120 into an adjustable optical manipulation unit 130 and a filtering and detection unit 140 is made to isolate the different functions that are performed by the receiving subsystem 120. In some cases, a single element can perform at least some of the functions of both the adjustable optical manipulation unit 130 and the filtering and detection unit 140, as detailed further herein, inter alia, in the section of the present application that describes **Fig. 9**.

In some cases, active imaging system 100 is further configured to include a controller 150. The controller 150 can include one or more processing units (e.g. central processing units), microprocessors, microcontrollers (e.g. microcontroller units (MCUs)) or any other computing devices or modules, including multiple and/or parallel and/or distributed processing units, which are adapted to independently or cooperatively process data for controlling relevant resources of the active imaging system 100 and for enabling operations related to the resources of the active imaging system 100.

In some cases, active imaging system 100 is configured, e.g., using controller 150, to automatically control the receiving subsystem 120 for performing the selective DoF imaging, e.g., based on one or more targets of interest, as detailed further herein, inter alia with reference to **Figs. 6 and 11**. Additionally, or alternatively, in some cases, a user of the active imaging system 100 controls the operation of the receiving subsystem 120, via a user interface 160, for performing the selective DoF imaging, e.g., based on one or more targets of interest, as detailed further herein, inter alia with reference to **Figs. 6 and 11**.

Attention is now drawn to **Figs. 2 and 4. Fig. 2** is a block diagram schematically illustrating a first example of an adjustable optical manipulation unit 130, in accordance with the presently disclosed subject matter. **Fig. 4** is a schematic illustration of a first example of an operation of an active imaging system 100, in accordance with the presently disclosed subject matter.

In accordance with the presently disclosed subject matter, active imaging system 100 is configured to include a CW light source 105 and a transmission subsystem 110, as illustrated in **Fig. 4**. Transmission subsystem 110 includes an optical phase modulator 114, as illustrated in **Fig. 4**. CW light source 105 is configured to output a coherent continuous beam 405, the coherent continuous beam 405 being a carrier wave having one or more optical frequencies. Optical phase modulator 114 is configured to phase modulate the coherent continuous beam 405 to generate at least one phase-modulated coherent continuous beam, as detailed further herein, inter alia with reference to **Figs. 5 and 10**. In some cases, optical phase modulator 114 is configured to perform a frequency scanning phase modulation of the coherent continuous beam 405. Transmission subsystem 110 is configured, using the optical phase modulator 114, to generate and transmit at least one transmission beam 410 for illuminating a scene. The transmission beam 410 is a continuous repeated transmission sequence of time-based spectrally differentiated transmitted light, as detailed further herein, inter alia with reference to **Figs. 5 and 10**.

In some cases, transmission subsystem 110 is configured to direct the at least one transmission beam 410, e.g., using an optical unit 116 (not shown in **Fig. 4**), to illuminate a region of interest.

Active imaging system 100 is further configured to include a receiving subsystem 120. Receiving subsystem 120 is configured, by an adjustable optical manipulation unit 130, to perform at least one phase modulation for continuous manipulation of the return light (e.g., 430, 440) reflected or scattered from the objects in at least part of the scene. The phase modulation is performed to achieve continuous selective DoF imaging. It is to be noted that the adjustable optical manipulation unit 130 in **Fig. 4** does not itself perform continuous manipulation of the return light (e.g., 430, 440). Rather, the adjustable optical manipulation unit 130 in **Fig. 4** performs at least one phase modulation to generate at least one reference beam 420 that interferes with the return light (e.g., 430, 440) for continuous manipulation of the return light (e.g., 430, 440), as detailed further herein, including, inter alia, with reference to **Fig. 6**.

Although **Fig. 4** illustrates return light (430, 440) returning from two DoFs in at least part of the illuminated scene, this is for illustrative purposes only, and return light can be received by the receiving subsystem 120 from any number of DoFs. Since the transmission beam 410 is a continuous repeated transmission sequence of time-based spectrally differentiated transmitted light, the return light (e.g., 430, 440) that is reflected or scattered

from one or more objects in any one of the DoFs is spectrally differentiated over time. That is, the return light (e.g., 430, 440) is time-based spectrally differentiated return light. Since the return light (e.g., 430, 440) is time-based spectrally differentiated return light that is based on the time-based spectrally differentiated transmitted light of the transmission beam 410, and since the Time-of-Flight (ToF) of the transmission beam 410 is different for each of the DoFs, the return light that is returned to the receiving subsystem 120 from a respective DoF, at any given moment or timeframe, has different optical spectral (frequency and phase) characteristics than the return light that is returned to the receiving subsystem 120 from other DoFs, other than the respective DoF, at the given moment or timeframe. This enables continuous selective DoF imaging, namely the imaging of objects in the at least one desired DoF in at least part of the illuminated scene, and the non-imaging or the imaging with suppressed intensity of the objects at the undesired DoFs in the at least part of the scene.

In accordance with the first example of an adjustable optical manipulation unit 130, as illustrated in **Figs. 2 and 4**, the adjustable optical manipulation unit 130 is configured to include an optical beam sampling unit 202, a reference phase modulator 204, and, optionally, a tunable attenuator 206.

Optical beam sampling unit 202 (not shown in **Fig. 4**) is configured to sample the coherent continuous beam 405 that is output by the CW light source 105, for generating a sampled coherent beam. In some cases, the optical beam sampling unit 202 is an optical fiber splitter.

Reference phase modulator 204 is configured, based on the at least one desired DoF to be imaged, to phase modulate the sampled coherent beam for generating at least one reference beam 420, as detailed further herein, inter alia with reference to **Fig. 6**. The reference beam 420 is a reference sequence of time-based spectrally differentiated light that interferes with the return light (e.g., 430, 440) reflected or scattered from objects in at least part of the illuminated scene, for continuous manipulation of the return light (e.g., 430, 440).

In some cases, the adjustable optical manipulation unit 130 includes both a reference phase modulator 204 and a tunable attenuator 206. The combination of the reference phase modulator 204 and the tunable attenuator 206 is configured for generating the at least one reference beam 420, wherein an intensity of the light of the reference beam 420 varies over time. In some cases, e.g., in which an event camera 310 is used for detection and imaging, the variation in the intensity of the light of the reference beam 420 allows for the imaging of the at least one desired DoF with a grey scale image, and not a black & white image.

Active imaging system 100 is configured to cause the reference beam 420 to interfere with, and consequently manipulate, the return light (e.g., 430, 440) that is returned from at least part of the illuminated scene.

For illustrative purposes only, the return light (430, 440) that is reflected from objects at two DoFs is shown in **Fig. 4**. In the non-limiting illustration of **Fig. 4,** a target of interest 412 and a background 414 (e.g., that blinds the at least one optical detector of the receiving subsystem 120) are shown. In the example of **Fig. 4**, it is desired to image the target of interest 412, and not to image the background 414. In this case, the at least one reference beam 420 manipulates the return light (e.g., 430, 440) for imaging the target of interest 412 and not imaging or imaging with suppressed intensity the background 414.

In some cases, active imaging system 100 can be configured to concurrently image two or more desired DoFs in at least part of an illuminated scene. In accordance with the first example of an adjustable optical manipulation unit 130, as illustrated in **Figs. 2 and 4**, one way in which this can be achieved is by providing a reference phase modulator 204 having multiple phase modulation channels (e.g., of optical fibers). Each phase modulation channel of the phase modulation channels in the reference phase modulator 204 phase modulates the sampled coherent beam (being a sample of the coherent continuous beam 405, as noted above). In some cases, the output of each of the phase modulation channels is a distinct reference beam 420 transmitted to the optical detector (e.g., optical detector, event camera, etc.) for enabling the imaging of some (i.e., one or more) of the two or more desired DoFs. Alternatively, in some cases, the output of the reference phase modulator 204 having multiple phase modulation channels is a single reference beam 420 transmitted to the optical detector for enabling the imaging of the two or more desired DoFs. Another way in which the active imaging system 100 can be configured to concurrently image two or more desired DoFs is by providing an optical phase modulator 114 that includes multiple phase modulation channels (e.g., of optical fibers). Each phase modulation channel of the phase modulation channels in the optical phase modulator 114 phase modulates the coherent continuous beam 405 for enabling the imaging of the two or more desired DoFs. In some cases, the output of each of the phase modulation channels is a distinct phase-modulated coherent continuous beam. Alternatively, in some cases, the output of the optical phase modulator 114 having multiple phase modulation channels is a single phase-modulated coherent continuous beam. In some cases, in accordance with the first example of an adjustable optical manipulation unit 130, as illustrated in **Figs. 2 and 4**, active imaging system 100 can be configured to concurrently image multiple (four or more) desired

DoFs in at least part of the illuminated scene by providing a plurality of phase modulation channels in the reference phase modulator 204 and a plurality of phase modulation channels in the optical phase modulator 114.

Receiving subsystem 120 is configured, e.g., by filtering and detection unit 140, to perform selective DoF imaging, i.e., imaging of only the at least one desired DoF, by filtering out or attenuating the manipulated return light (e.g., 445) that is associated with the return light (e.g., 440) reflected or scattered from the objects at undesired DoFs. For the purposes of this disclosure, the filtering out or attenuating of the manipulated return light (e.g., 445) that is associated with the return light (e.g., 440) reflected or scattered from the objects at the undesired DoFs can be either: (a) the filtering out or attenuating of the manipulated return light (e.g., 445) itself, or (b) the filtering out or attenuating of electrical signal(s) indicative of this manipulated return light (e.g., 445), following the conversion, by at least one optical detector, of the manipulated return light (e.g., 445) into electrical signal(s). For a receiving subsystem 120 that includes an adjustable optical manipulation unit 130 that generates at least one reference beam 420 to interfere with the return light (e.g., 430, 440) for manipulating the return light (e.g., 430, 440), as in **Figs. 2 and 4**, filtering and detection unit 140 can be configured, in some cases, to include an event camera 310, as illustrated in **Fig. 3A**, and, in some cases, to include at least one optical detector 320 and at least one electrical filter 330, as illustrated in **Fig. 3B**. The performance of the selective DoF imaging using an event camera 310 is detailed further herein, inter alia with reference to **Fig. 7**. The performance of the selective DoF imaging using an optical detector 320 and an electrical filter 330 is detailed further herein, inter alia with reference to **Fig. 8**.

Attention is now drawn to **Fig. 5**, a flowchart illustrating one example of a sequence of operations 500 for illuminating a scene, in accordance with the presently disclosed subject matter.

In accordance with the presently disclosed subject matter, a continuous wave (CW) light source 105 is configured for outputting a coherent continuous beam 405 **(block 504)**. In some cases, the CW light source 105 is a CW laser. The coherent continuous beam 405 is a carrier wave having one or more optical frequencies. Assuming that: (i) the coherent continuous beam 405 has a single optical frequency f_0, and (ii) the CW light source 105 lacks an optical spectral bandwidth, the electric field, E, of the coherent continuous beam 405 can be defined, at least in some cases, by Equation 1:

$$E = E_0 \cos(\omega t) = Re(\tilde{E}), \qquad \text{(Equation 1)}$$

wherein the complex electric field, representing the electric field as a complex number, is $\tilde{E} = E_0 e^{i\omega t}$, and

wherein the angular frequency $\omega = 2\pi f_0$.

Transmission subsystem 110 is configured to include an optical phase modulator 114. Optical phase modulator 114 is configured, based on at least one modulating wave (e.g., an electronic modulating wave) that is input to the optical phase modulator 114, to phase modulate the coherent continuous beam 405 to generate at least one phase-modulated coherent continuous beam **(block 508)**.

In some cases, a modulating wave that is input to the optical phase modulator 114 is of a phase, $\phi(t)$, that grows linearly with time: $\phi(t)=\Delta\omega \cdot t \ mod \ 2\pi$. Alternatively, in some cases, a modulating wave that is input to the optical phase modulator 114 is of a sine periodic phase: $\phi(t)=A_0 \sin(\Delta\omega \cdot t)$. In some cases, a frequency of a modulating wave that is input to the optical phase modulator 114 varies over time, resulting in the output of a frequency-scanning phase-modulated transmission beam 410 by transmission subsystem 110. In some cases, the change in angular frequency, $\Delta\omega$, is temporally chirped. For example, the change in angular frequency, $\Delta\omega$, can be temporally chirped in accordance with Equation 2:

$$\Delta\omega = (\Omega \cdot t)/\tau. \qquad \text{(Equation 2)}$$

Equation 2 provides that the angular frequency is linearly swept at a rate Ω/τ. Ω and τ are constant parameters of frequency and time units, respectively. In practice, the phase, $\phi(t)$, does not grow to infinity in time, but rather is periodically swept over.

Transmission subsystem 110 is configured, using the optical phase modulator 114, to generate and transmit at least one transmission beam 410 for illuminating a scene. The transmission beam 410 is a continuous repeated transmission sequence of time-based spectrally differentiated transmitted light that is directed, e.g., using an optical unit 116, towards a scene (e.g., a region of interest) to illuminate the scene **(block 512)**.

Assuming that the electric field, E, of the coherent continuous beam 405 is defined by Equation 1, the transmission beam 410 can have, at least in some cases, a complex electric field that is defined by Equation 3:

$$\tilde{E}_t = E_0 e^{i(\omega t + \phi(t))} \quad \text{(Equation 3)}$$

Moreover, given that the electric field of the transmission beam 410 is defined by Equation 3, the electric field of the return light that is returned from a given DoF in a scene that is illuminated by the transmission beam 410 is (ideally) defined by Equation 4:

$$\tilde{E}_R = E_0 r_i e^{i(\omega(t-t_i)+\phi(t-t_i))}, \quad \text{(Equation 4)}$$

wherein r_i parametrizes the reflected fraction of the transmission beam 410 that is returned from the given DoF to the receiving subsystem 120, and

wherein t_i is the Time-of-Flight (ToF) of the transmission beam 410 to and back from the given DoF.

Attention is now drawn to **Fig. 6**, a flowchart illustrating one example of a sequence of operations 600 for an interference-based manipulation of the return light (e.g., 430, 440) that is returned from at least part of the illuminated scene, in accordance with the presently disclosed subject matter.

In accordance with the presently disclosed subject matter, in some cases, e.g., as shown in **Figs. 2 and 4**, an adjustable optical manipulation unit 130 is configured to generate at least one reference beam 420 that is emitted towards an optical detector (e.g., event camera 310, optical detector 320) of receiving subsystem 120 for continuous manipulation of the return light (e.g., 430, 440) that is returned from at least part of a scene illuminated by the transmission subsystem 110.

In order to generate the at least one reference beam 420, receiving subsystem 120 is configured, by an optical beam sampling unit 202, to sample the coherent continuous beam 405 that is output by the CW light source 105, for generating a sampled coherent beam **(block 604)**.

Receiving subsystem 120 is further configured, by a reference phase modulator 204, to phase modulate the sampled coherent beam, based on at least one desired DoF to be imaged, for generating the at least one reference beam 420. The reference beam 420 is a reference

sequence of time-based spectrally differentiated light (i.e., light that is spectrally differentiated over time). For an embodiment in which one transmission beam 410 and one reference beam 420 are generated (wherein the reference phase modulator 204 includes a single phase modulation channel and the optical phase modulator 114 includes a single phase modulation channel), the reference phase modulator 204 performs a phase modulation that is similar to the phase modulation that is performed by the optical phase modulator 114 (even if there are multiple transmission beams 410 (or transmission sub-beams, each output by at least one of two or more phase modulation channels in optical phase modulator 114) and/or multiple reference beams 420 (or reference sub-beams, each output by at least one of two or more phase modulation channels in reference phase modulator 204), at least one of the channels of the reference phase modulator 204 performs a phase modulation that is similar to the phase modulation that is performed by at least one of the channels of the optical phase modulator 114). For example, if the optical phase modulator 114 performs a phase modulation in accordance with a modulating wave of a phase, $\phi(t)$, that grows linearly with time: $\phi(t)=\Delta\omega\cdot t \ mod\ 2\pi$, then the reference phase modulator 204 performs the phase modulation in accordance with a modulating wave of the same linearly-growing phase. As an additional example, if the optical phase modulator 114 performs a phase modulation in accordance with a modulating wave of a sine periodic phase, $\phi(t)= A_0\sin(\Delta\omega\cdot t)$, then the reference phase modulator 204 performs the phase modulation in accordance with a modulating wave of the same sine periodic phase. However, the modulating wave in accordance with which the reference phase modulator 204 is phase-modulated is of a phase, $\phi_r(t)$, that is delayed by a constant time delay, Δt, with respect to the phase, $\phi(t)$, of the modulating wave in accordance with which the optical phase modulator 114 is phase-modulated, as follows: $\phi_r(t)=\phi(t-\Delta t)$. The constant time delay, Δt, is determined based on the desired DoF to be imaged. In view of the foregoing, the complex electric field of the reference beam 420, $\tilde{E}_r$, in the above embodiment (one transmission beam 410 and one reference beam 420 are generated), can be defined, at least in some cases, by Equation 5:

$$\tilde{E}_r = E_0 \epsilon e^{i(\omega t+\phi(t-\Delta t))}. \qquad \text{(Equation 5)}$$

In some cases, the constant time delay, Δt, can be entered by the user of the active imaging system 100 to the active imaging system 100, e.g., based on one or more targets of interest, to adjust the modulating wave with which the reference phase modulator 204 is

modulated for imaging the desired DoF. For example, a function generator can calculate Δt based on the desired DoF to be imaged, and the user, in turn, can enter Δt to the active imaging system 100. Alternatively, in some cases, Δt can be set by the user by modifying the phase difference between the modulating wave for the reference phase modulator 204 and the modulating wave for the optical phase modulator 114, e.g., by using a knob that interfaces with the active imaging system 100, to image the desired DoF (for example, based on one or more targets of interest). As a further alternative, active imaging system 100 can be configured, e.g., using controller 150, to provide Δt, e.g., based on one or more targets of interest (the targets of interest can be determined, for example, based on readings from a radar).

In some cases, receiving subsystem 120 is configured to include a tunable attenuator 206. A combination of the reference phase modulator 204 and the tunable attenuator 206 is configured to generate the at least one reference beam 420, wherein an intensity of the light of the reference beam 420 varies over time. In some cases, e.g., in which an event camera 310 is used for detection and imaging, the variation in the intensity of the light of the reference beam 420 allows for the imaging of the at least one desired DoF with a grey scale image, and not a black & white image.

As noted above, reference beam 420 is emitted towards the optical detector (e.g., event camera 310, optical detector 320) of receiving subsystem 120 to interfere with the return light (e.g., 430, 440) that is returned from at least part of the scene illuminated by the at least one transmission beam 410, for simultaneously manipulating all of the return light (e.g., 430, 440) **(block 608)**. The complex electric field, $\tilde{E}_d$, of the manipulated return light (e.g., 435, 445) from any given DoF in at least part of the illuminated scene is the sum of the complex electric field, $\tilde{E}_R$, of the return light (e.g., 430, 440) that is returned from the given DoF and the complex electric field, $\tilde{E}_r$, of the reference beam 420 that interferes with the return light (e.g., 430, 440).

The interference of the reference beam 420 with the return light (e.g., 430, 440) results in the manipulation of the return light (e.g., 430, 440) into manipulated return light (e.g., 435, 445) having intensity fluctuations. The return light (e.g., 430) that is reflected or scattered from the one or more objects at the at least one desired DoF has, following the manipulation thereof into manipulated return light (e.g., 435), intensity fluctuations at frequencies that provides for the imaging of the manipulated return light (e.g., 435), as detailed further herein, inter alia with reference to **Figs. 7 and 8**. Moreover, the return light (e.g., 440) that is reflected or scattered from the one or more objects at the undesired DoFs has, following the manipulation thereof into manipulated return light (e.g., 445), intensity fluctuations at frequencies that results in the

filtering or attenuation of the manipulated return light (e.g., 445), and consequently the non-imaging or imaging with a suppressed intensity of the manipulated return light (e.g., 445).

Since the reference beam 420 is generated for the continuous imaging of only the manipulated return light (e.g., 435) associated with the return light (e.g., 430) reflected or scattered from the one or more objects at the at least one desired DoF, the optical detector (e.g., event camera 310 or optical detector 320) that detects the manipulated return light (e.g., 435) in the present disclosure can have a much slower response (i.e., a narrow bandwidth about DC) than: (i) the optical detector that is used to detect return light when laser pulses are used to actively illuminate a scene in a selective DoF imaging system, as described in the Background above, or (ii) the optical detector that is used in a Frequency-Modulated Continuous Wave (FMCW) system. Indeed, it is desirable that the optical detector in the present disclosure have a slow response. In addition, in contrast to when laser pulses are used to actively illuminate a scene in a selective DoF imaging system, and in contrast to a FMCW system, the output of the optical detector (e.g., event camera 310 or optical detector 320) in the present disclosure is not required to be processed or requires very limited processing in order to image the at least one desired DoF.

It is to be noted that, in some cases, it will be desired not to image a given DoF in a scene, since there is an independent light source at the given DoF that dazzles (i.e., blinds) active imaging system 100 (for example, someone is attempting to blind active imaging system 100 with a laser). In the embodiment in which receiving subsystem 120 includes reference phase modulator 204, there is no concern that the light from the independent light source will interfere with the imaging of the at least one desired DoF, since the interference of the light from the independent light source with the reference beam 420 does not result in a relevant signal for detection (the light from the independent light source is not phase-modulated in a similar manner to the coherent continuous beam 405).

Attention is now drawn to **Fig. 7**, an example of an operation 700 for performing selective DoF imaging, following an interference-based manipulation of the return light (e.g., 430, 440) returned from at least part of an illuminated scene, in accordance with the presently disclosed subject matter.

In accordance with the presently disclosed subject matter, receiving subsystem 120 is configured, following the interference-based manipulation of the return light (e.g., 430, 440), as detailed earlier herein, inter alia with reference to **Fig. 6**, to perform the selective DoF

imaging (i.e., the selective imaging of the at least one desired DoF), by filtering or attenuating the manipulated return light (e.g., 445) that is associated with the return light (e.g., 440) that is reflected or scattered from objects at the undesired DoFs. In some cases, an event camera 310 (also known as a neuromorphic camera, a silicon retina or a dynamic vision sensor) is configured to achieve the selective DoF imaging.

To explain, the event camera 310 is configured to receive the manipulated return light (e.g., 435, 445). Assuming that the coherent continuous beam 405 is of a single frequency f_0, the CW light source 105 lacks an optical spectral bandwidth, and only a single desired DoF is to be imaged, the event camera 310 responds, at least in some cases, to the intensity, I, of the manipulated return light (e.g., 435, 445) from any given DoF, in accordance with Equation 6:

$$2I = \left|\tilde{E}_d\right|^2 = \left|E_0 r_i e^{i(\omega(t-t_i)+\phi(t-t_i))} + E_0 \epsilon e^{i(\omega t+\phi(t-\Delta t))}\right|^2 =$$
$$= |E_0|^2 \cdot \left(|r_i|^2 + \epsilon^* r_i e^{i(-\omega t_i+\phi(t-t_i)-\phi(t-\Delta t))} + c.c. + |\epsilon|^2\right) =$$
$$= |E_0|^2 \cdot \left(|r_i|^2 + \epsilon^* r_i e^{i(-\omega t_i+\Delta\omega(\Delta t-t_i))} + c.c. + |\epsilon|^2\right), \qquad \text{(Equation 6)}$$

wherein $\tilde{E}_d$ is the complex electrical field of the manipulated return light (e.g., 435, 445) that is returned from the given DoF;

wherein $\phi(t-\Delta t)$ is the phase of the modulating wave by which the reference phase modulator 204 is modulated;

wherein r_i parametrizes the reflected fraction of the transmission beam 410 that is returned from the given DoF;

wherein t_i is the Time-of-Flight (ToF) of the transmission beam 410 to and from the given DoF; and

wherein c.c. is the complex conjugate of the term $r_i e^{i(-\omega t_i+\Delta\omega(\Delta t-t_i))}$.

Assuming that $\Delta\omega = (\Omega \cdot t)/\tau$, as detailed earlier herein, inter alia with reference to **Fig. 5**, the above intensity expression becomes:

$$2I = |E_0|^2 \cdot \left(|r_i|^2 + \epsilon^* r_i e^{i\left(-\omega t_i+2\frac{\Omega}{\tau}\cdot t\ \cdot(\Delta t-t_i)+const\right)} + c.c. + |\epsilon|^2\right) =$$
$$= |E_0|^2 \cdot \left(|r_i|^2 + \epsilon^* r_i e^{2i\Omega\frac{(\Delta t-t_i)}{\tau}\cdot t}\ \cdot const + c.c. + |\epsilon|^2\right). \qquad \text{(Equation 7)}$$

I is written as a sum of four terms. The first and last terms are constant in time (i.e., these terms do not represent intensity fluctuations), and are therefore naturally filtered by the event camera 310. The middle terms include intensity frequencies (i.e., frequencies of intensity fluctuations) of $2\Omega((\Delta t - t_i)/\tau)$. For t_i different enough from Δt, i.e., manipulated returns (e.g., 445) that are returned from distances that are outside of the desired DoF (closer or farther than the desired DoF from the event camera 310) by at least a threshold, the intensity frequency of these manipulated returns (e.g., 445) are outside the frequency bandpass region of the event camera's 310 response, and therefore these manipulated returns (e.g., 445) are naturally filtered out by the event camera 310. This results in the event camera 310: (a) filtering out or attenuating the manipulated return light (e.g., 445) that is associated with the return light (e.g., 440) returned from the undesired DoFs, and (b) imaging the manipulated return light (e.g., 435) that is associated with the return light (e.g. 430) returned from the at least one desired DoF **(block 704)**.

It is to be noted that in all cases in which an event camera 310 is used, the at least one reference beam 420 is generated so that: (a) the intensity frequencies (i.e., frequencies of intensity fluctuations) of the manipulated return light (e.g., 445) that is associated with returns (e.g., 440) from undesired DoFs are outside the frequency bandpass region of the event camera's 310 response, and (b) the intensity frequencies of the manipulated return light (e.g., 435) that is associated with returns (e.g., 430) from the at least one desired DoF are within the frequency bandpass region of the event camera's 310 response. This results in the event camera 310: (a) filtering out or attenuating the manipulated return light (e.g., 445) that is associated with the return light (e.g., 440) returned from undesired DoFs (this manipulated return light is naturally filtered out or attenuated by the event camera 310), and (b) imaging the manipulated return light (e.g., 435) that is associated with the return light (e.g. 430) returned from the at least one desired DoF.

In some cases, the imaging of the manipulated return light (e.g., 435) by the event camera 310 results in the generation of a black and white image of the at least one desired DoF. Alternatively, in some cases, the imaging of the manipulated return light (e.g., 435) by the event camera 310 results in the generation of a grey scale image of the at least one desired DoF. In order for the event camera 310 to generate a grey scale image of the at least one desired DoF, the receiving subsystem 120 is configured to generate a reference beam 420, wherein, due to the use of a tunable attenuator 206, the intensity of the light of the reference beam 420

varies over time. The reason that the intensity of the light of the reference beam 420 must vary over time in order for the event camera 310 to provide the grey scale image is because the output values of the pixels of the event camera 310 are binary, and accordingly, without varying the intensity of the light of the reference beam 420 over time, the event camera 310 would provide a binary (black & white) image.

By performing the selective DoF imaging by an event camera 310, at least the following advantages are achieved: (i) a high dynamic range (the dynamic range of the event camera 310 is greater than the dynamic range of widely-used cameras on the order of 120dB); and (ii) a high detection rate (the detection rate of the event camera 310 is greater than the detection rate of widely-used cameras by at least an order of 1 MHz).

Attention is now drawn to **Fig. 8**, a flowchart illustrating a second example of a sequence of operations 800 for performing selective DoF imaging, following an interference-based manipulation of the return light (e.g., 430, 440), in accordance with the presently disclosed subject matter. The interference-based manipulation of the return light (e.g., 430, 440) is detailed earlier herein, inter alia with reference to **Fig. 6**.

In accordance with the presently disclosed subject matter, in some cases, as an alternative to using an event camera 310 to perform the selective DoF imaging, active imaging system 100 performs the selective DoF imaging using at least one optical detector 320 and at least one electrical filter 330.

The optical detector 320 is configured to convert the manipulated return light (e.g., 435, 445) into one or more electrical signals **(block 804)**. In some cases, optical detector 320 is one of: a camera, a pixelated optical detector, a video digital camera, an array of optical detectors, or an array of photodetectors.

The electrical filter 330 is configured to filter out or attenuate components of the electrical signals (output by the optical detector 320) that are indicative of the manipulated return light (e.g., 445) associated with the return light (e.g., 440) reflected or scattered from objects at the undesired DoFs. Moreover, the electrical filter 330 is configured to pass the components of the electrical signals that are indicative of the manipulated return light (e.g., 435) associated with the return light (e.g., 430) reflected or scattered from objects at the at least one desired DoF, thereby enabling the imaging of the at least one desired DoF (e.g., by optical detector 320). It is to be noted that the electrical filter 330 can be downstream of the optical detector 320 or can be included within the optical detector 320. The electrical filter 330 is tuned

to filter out or attenuate electrical components that are indicative of light having frequencies of intensity fluctuations that are outside the passband of frequencies that are passed by the electrical filter 330 (the frequencies of intensity fluctuations is defined earlier herein, inter alia with reference to **Fig. 7**), these electrical components being indicative of the manipulated return light (e.g., 445) that is associated with the return light (e.g., 440) returned from the undesired DoFs. To explain, adjustable optical manipulation unit 130 is configured, using reference phase modulator 204, to generate at least one reference beam 420, as detailed earlier herein, inter alia with reference to **Fig. 6**. The reference beam 420 is directed to interfere with the return light (e.g., 430, 440) to generate the manipulated return light (e.g., 435, 445). The reference beam 420 is generated so that the manipulated return light (e.g., 445) that is associated with the return light (e.g., 440) returned from the undesired DoFs has intensity fluctuations at frequencies that are outside of the passband of frequencies that are passed by the electrical filter 330. Moreover, the reference beam 420 is generated so that the manipulated return light (e.g., 435) that is associated with the return light (e.g., 430) returned from the at least one desired DoF has intensity fluctuations at one or more frequencies that are within the passband of frequencies that are passed by the electrical filter 330. Accordingly, electrical filter 330 is configured to filter out or attenuate the components of the electrical signals that are indicative of the manipulated return light (e.g., 445) associated with the return light (e.g., 440) returned from the undesired DoFs, and to pass the components of the electrical signals that are indicative of the manipulated return light (e.g., 435) that is associated with the return light (e.g., 430) returned from the at least one desired DoF, thereby enabling the imaging of the at least one desired DoF **(block 808)**.

Attention is now drawn to **Figs. 9 and 10**. **Fig. 9** is a block diagram schematically illustrating one example of a demodulation-based receiving subsystem 120, in accordance with the presently disclosed subject matter. **Fig. 10** is a schematic illustration of one example of an operation of an active imaging system 100 that includes a demodulation-based receiving subsystem 120, in accordance with the presently disclosed subject matter.

In accordance with the presently disclosed subject matter, active imaging system 100 is configured to include a CW light source 105 and a transmission subsystem 110, as shown in **Fig. 10**. Transmission subsystem 110 is configured to include an optical phase modulator 114 (e.g., an electro-optical phase modulator), as shown in **Fig. 10**.

CW light source 105 (e.g., CW laser) is configured to output a coherent continuous beam 405. The coherent continuous beam 405 is a carrier wave having one or more optical frequencies. Assuming that: (i) the coherent continuous beam 405 has a single optical frequency f_0, and (ii) the CW light source 105 lacks an optical spectral bandwidth, the electric field, E, of the coherent continuous beam 405 can be defined, in some cases, by Equation 1: $E = E_0 \cos(\omega t) = Re(E_0 e^{i\omega t})$, as detailed earlier herein, inter alia with reference to **Fig. 5**.

Optical phase modulator 114 is configured, based on at least one modulating wave (e.g., an electronic modulating wave) that is input to the optical phase modulator 114, to phase modulate the coherent continuous beam 405 to generate at least one phase-modulated coherent continuous beam. It is to be noted that, in some cases, optical phase modulator 114 can include two or more phase modulation channels (e.g., of optical fibers), i.e., optical phase modulator 114 can phase modulate the coherent continuous beam 405, based on two or more modulating waves, as detailed earlier herein, inter alia with reference to the description of **Fig. 4**.

In some cases, a modulating wave that is input to the optical phase modulator 114 is of a phase, $\phi(t)$, that grows linearly with time: $\phi(t)=\Delta\omega \cdot t \ mod \ 2\pi$. Alternatively, in some cases, a modulating wave that is input to the optical phase modulator 114 is of a sine periodic phase: $\phi(t)=A_0 \sin(\Delta\omega \cdot t)$. In some cases, a frequency of a modulating wave that is input to the optical phase modulator 114 varies over time, resulting in the output of a frequency-scanning phase-modulated transmission beam 410 by the transmission subsystem 110. In some cases, the change in angular frequency, $\Delta\omega$, is temporally chirped. For example, the change in angular frequency, $\Delta\omega$, can be temporally chirped in accordance with Equation 2: $\Delta\omega = (\Omega \cdot t)/\tau$, as detailed earlier herein, inter alia with reference to **Fig. 5**.

Transmission subsystem 110 is configured, using the optical phase modulator 114, to generate and transmit at least one transmission beam 410 for illuminating a scene. The transmission beam 410 is a continuous repeated transmission sequence of time-based spectrally differentiated transmitted light that is directed, e.g., using an optical unit 116, towards a scene (e.g., a region of interest) to illuminate the scene.

Assuming that the electric field, E, of the coherent continuous beam 405 is defined by Equation 1, a respective transmission beam 410 can have, at least in some cases, a complex electric field, $\tilde{E}_t$, that is defined by Equation 3: $\tilde{E}_t = E_0 e^{i(\omega t + \phi(t))}$.

Receiving subsystem 120 is configured to receive return light (e.g., 430, 440), as illustrated in **Fig. 10**, the return light being reflected or scattered from objects in at least part of

the scene that is illuminated by the transmission beam 410. Although **Fig. 10** illustrates return light (430, 440) returning from two DoFs in the at least part of the scene, this is for illustrative purposes only, and return light can be received by the receiving subsystem 120 from any number of DoFs. Since the transmission beam 410 is a continuous repeated transmission sequence of time-based spectrally differentiated transmitted light, the return light (e.g., 430, 440) that is returned from the one or more objects in any one of the DoFs in the at least part of the scene, due to the impact of the transmission beam 410 on the objects, is time-based spectrally differentiated return light (i.e., return light that is spectrally differentiated over time). Since the return light (e.g., 430, 440) is time-based spectrally differentiated return light that is based on the time-based spectrally differentiated transmitted light of the transmission beam 410, and since the Time-of-Flight (ToF) of the transmission beam 410 is different for each of the DoFs, the return light that is returned to the receiving subsystem 120 from a respective DoF, at any given moment or timeframe, has different optical spectral (frequency and phase) characteristics than the return light that is returned to the receiving subsystem 120 from other DoFs, other than the respective DoF, at the given moment or timeframe. This enables continuous selective DoF imaging, namely the imaging of the return light reflected or scattered from the one or more objects at the at least one desired DoF in at least part of the illuminated scene (following the manipulation of this return light), and the non-imaging or the imaging with suppressed intensity of the return light reflected or scattered from the one or more objects at the undesired DoFs in the at least part of the illuminated scene.

For illustrative purposes only, the return light (430, 440) from two DoFs is shown in **Fig. 10**. In the non-limiting illustration of **Fig. 10,** a target of interest 412 and a background 414 (e.g., that blinds the at least one optical detector 912 of the receiving subsystem 120) are shown. In the example of **Fig. 10**, it is desired to image a first DoF that includes the target of interest 412, and not to image a second DoF, different than the first DoF, that includes the background 414.

If the electric field of the transmission beam 410 is defined by Equation 3: $\tilde{E}_t = E_0 e^{i(\omega t + \phi(t))}$, the electric field of the return light that is returned from a given DoF in a scene that is illuminated by the transmission beam 410 is (ideally) defined by Equation 4:

$$\tilde{E}_R = E_0 r_i e^{i(\omega(t-t_i)+\phi(t-t_i))}, \quad \text{(Equation 4)}$$

wherein r_i parametrizes the reflected fraction of the transmission beam 410 that is returned from the given DoF, and

wherein t_i is the Time-of-Flight (ToF) of the transmission beam 410 to and back from the given DOF.

In some cases, active imaging system 100 is configured to include a demodulation-based receiving subsystem 120 for performing the selective DoF imaging, as shown in **Figs. 9 and 10**. The demodulation-based receiving subsystem 120 is configured to include a phase demodulator 904, at least one optical filter 908, and at least one optical detector 912.

Phase demodulator 904 is configured to phase demodulate the return light (e.g., 430, 440) that is returned from at least part of the scene illuminated by the transmission beam 410, based on the at least one desired DoF to be imaged. The phase-demodulated return light forms at least one demodulation beam of manipulated (demodulated) return light, as detailed further herein, inter alia with reference to **Fig. 11**.

The at least one optical filter 908 is configured, based on the optical spectral (frequency and phase) characteristics of the demodulation beam, to pass the manipulated return light in the demodulation beam that is associated with the return light (e.g., 430) returned from the at least one desired DoF, due to the illumination of the desired DoF by the transmission beam 410, and to filter out or attenuate the manipulated return light in the demodulation beam that is associated with the return light (e.g., 440) returned from the undesired DoFs.

In some cases, optical filter 908 can be one of the following: a cavity filter, a bandpass filter, a natural density filter, a lowpass filter, an atomic line filter, or a monochromator.

The at least one optical detector 912 is positioned downstream of the optical filter 908. Optical detector 912 is configured to detect the manipulated return light in the demodulation beam that is associated with the return light (e.g., 430) returned from the at least one desired DoF (this manipulated return light is passed by the optical filter 908), in order to image the at least one desired DoF.

In some cases, optical detector 912 is one of: a camera, a pixelated optical detector, a video digital camera, an array of optical detectors, or an array of photodetectors.

Fig. 9 illustrates the phase demodulator 904, the optical filter 908 and the optical detector 912 as distinct elements of the receiving subsystem 120. It is to be noted, however, that, in some cases, two or more of: the phase demodulation, the optical filtering, and the optical detection can be performed by a single element. In some cases, the optical filter 908 can be

tunable, in order to filter out or attenuate the manipulated return light in the demodulation beam that is based on the return light (e.g., 440) returned from the undesired DoFs.

Attention is now drawn to **Fig. 11**, a flowchart illustrating one example of a sequence of operations 1100 for performing selective DoF imaging, in accordance with the presently disclosed subject matter.

In accordance with the presently disclosed subject matter, phase demodulator 904 is configured to phase demodulate the return light (e.g., 430, 440) that is returned from at least part of a scene illuminated by the transmission subsystem 110, based on the at least one desired DoF to be imaged, for generating at least one demodulation beam of manipulated (demodulated) return light. The phase demodulation is performed so that the manipulated return light in the demodulation beam that is based on returns from the at least one desired DoF has one or more desired optical spectral (frequency and phase) characteristics for imaging the at least one desired DoF **(block 1104)**.

Phase demodulator 904 is configured to include one or more phase demodulation channels (e.g., of optical fibers), each of the phase demodulation channels being configured, based on a distinct modulating wave (e.g., an electronic modulating wave) that is input to the phase demodulator 904, to phase demodulate the return light (e.g., 430, 440). For an embodiment in which one transmission beam 410 is generated and only one desired DoF is to be imaged, the phase demodulator 904 performs a phase demodulation that is based on the phase modulation that is performed by the optical phase modulator 114 (even if there are multiple transmission beams 410 and/or multiple phase demodulation channels, at least one of the phase demodulation channels of the optical phase demodulator 904 performs a phase demodulation that is based on the phase modulation that is performed by at least one of the channels of the optical phase modulator 114). For example, if the optical phase modulator 114 performs a phase modulation in accordance with a modulating wave of a phase, $\phi(t)$, that grows linearly with time: $\phi(t)=\Delta\omega\cdot t \ mod \ 2\pi$, then the optical phase demodulator 904 performs a phase demodulation in accordance with a modulating wave of the same linearly-growing phase. As an additional example, if the optical phase modulator 114 performs a phase modulation in accordance with a modulating wave of a sine periodic phase, $\phi(t) = A_0\sin(\Delta\omega\cdot t)$, then the optical phase demodulator 904 performs a phase demodulation in accordance with a modulating wave of the same sine periodic phase. However, the modulating wave in accordance with which the optical phase demodulator 904 performs phase demodulation is of

a phase, $\phi_d(t)$, that is of a constant time delay and of an opposite polarity with respect to the phase, $\phi(t)$, of the modulating wave in accordance with which the optical phase modulator 114 is phase-modulated, as follows: $\phi_d(t) = -\phi(t-\Delta t)$ (assuming that the optical filter 908 is configured to pass only the optical frequencies of the coherent continuous beam 405). The constant time delay, Δt, is based on the desired DoF to be imaged. In view of the foregoing, the complex electrical field, $\tilde{E}_d$, of the demodulated beam in the above embodiment can be defined, at least in some cases, by Equation 8:

$$\tilde{E}_d = E_0 r_i e^{i(\omega(t-t_i)+\phi(t-t_i)-\phi(t-\Delta t))}, \qquad \text{(Equation 8)}$$

wherein r_i parametrizes the reflected fraction of the transmission beam 410 that is returned from the desired DoF, and

wherein t_i is the Time-of-Flight (ToF) of the transmission beam 410 to and back from the desired DoF.

In some cases, the constant time delay, Δt, can be entered by the user of the active imaging system 100 to the active imaging system 100, e.g., based on one or more targets of interest, to adjust the modulating wave with which the phase demodulator 904 is modulated for imaging the desired DoF. For example, a function generator can calculate Δt based on the desired DoF to be imaged, and the user, in turn, can enter Δt to the active imaging system 100. Alternatively, in some cases, Δt can be set by the user by modifying the phase difference between the modulating wave for the phase demodulator 904 and the modulating wave for the optical phase modulator 114, e.g., by using a knob that interfaces with the active imaging system 100, to image the desired DoF (for example, based on one or more targets of interest). As a further alternative, active imaging system 100 can be configured, e.g., using controller 150, to provide Δt, e.g., based on one or more targets of interest (the targets of interest can be determined, for example, based on readings from a radar).

With respect to Equation 8, even without specifying the phase $\phi(t)$, it is observed that the manipulated return light in the demodulation beam that is associated with returns from the desired DoF has a complex electrical field having the optical spectral characteristics of the coherent continuous beam 405, in accordance with Equation 9:

$$\tilde{E}_d \approx E_0 r_i e^{i\omega(t-t_i)} \quad \text{(Equation 9)}$$

For an exact calculation of the complex electrical field strength, $\tilde{E}_d$, of the demodulation beam, it is assumed that: (a) the optical filter 908 passes only the optical frequencies of the coherent continuous beam 405, and (b) the phase of the modulating wave by which the demodulator 904 demodulates the return light grows linearly as follows: $\phi(t)=\Delta\omega \cdot t$. In this case, the complex electrical field, $\tilde{E}_d$, of the demodulation beam is, at least in some cases, in accordance with Equation 10, as follows:

$$\tilde{E}_d = E_0 r_i e^{i(\omega(t-t_i)+\Delta\omega(\Delta t-t_i))}. \quad \text{(Equation 10)}$$

Repeating this for $\Delta\omega=(\Omega/\tau)\cdot t$, as defined earlier herein, inter alia with reference to Fig. 5, $\tilde{E}_d$ can be written in accordance with Equation 11, as follows:

$$\tilde{E}_d = E_0 r_i e^{i(\omega(t-t_i)+2\Omega\frac{(\Delta t-t_i)}{\tau}\cdot t+const)} = const \cdot E_0 r_i e^{i\left(\omega+2\Omega\frac{(\Delta t-t_i)}{\tau}\right)t} \quad \text{(Equation 11)}$$

In accordance with Equation 11, the demodulation beam has an angular optical frequency of $\omega + 2\Omega((\Delta t-t_i)/\tau)$.

It is to be noted, however, that, in some cases, the optical filter 908 can be configured to pass manipulated return light that has optical spectral characteristics that are different than the optical spectral characteristics of the coherent continuous beam 405 (and to filter out or attenuate the manipulated return light that has optical spectral characteristics that are the same as the optical spectral characteristics of the coherent continuous beam 405). For instance, by inputting a modulating wave having a phase of $\phi_d(t) = -\phi(t-\Delta t-((\tau/2\Omega)\ (\tilde{\omega}-\omega))$ into the optical phase demodulator 904, the demodulation beam will have an angular optical frequency of $\tilde{\omega}+2\Omega((\Delta t-t_i)/\tau)$. In such as case, optical filter 908 can be configured to filter around $\tilde{\omega}$ ($\neq\omega$), resulting in the filtering out or attenuating of the manipulated return light of the demodulation beam that is based on the returns from the undesired DoFs.

Returning to **Fig. 11**, at least one optical filter 908 is configured to filter out or attenuate the manipulated return light in the demodulation beam that is associated with the return light

returned from the undesired DoFs, based on its optical spectral characteristics, as explained above **(block 1108)**.

At least one optical detector 912 is configured to detect the manipulated return light that is associated with the return light returned from the at least one desired DoF (this manipulated return light is passed by the optical filter 908), for imaging the at least one desired DoF **(block 1112)**.

Since the demodulation beam is generated for the continuous detection of only the manipulated return light in the demodulation beam that is associated with the return light (e.g., 430) returned from the at least one desired DoF, optical detector 912 can have a much slower response than: (i) the optical detector that is used to detect return light that is returned when laser pulses are transmitted to actively illuminate a scene for selective DoF imaging, or (ii) the optical detector that is used in a FMCW system. Indeed, it is desirable that the optical detector 912 have a slow response. In addition, in contrast to when laser pulses are used to actively illuminate a scene in a selective DoF imaging system, and in contrast to a FMCW system, the output of the optical detector 912 is not required to be processed or requires very limited processing in order to image the at least one desired DoF. Indeed, the manipulated return light (e.g., 445) that is associated with the undesired DoFs is ideally filtered, by optical filter 908, in its entirety, resulting in the ability of even a naked human eye to obtain the image of the at least one desired DoF.

As noted above, in some cases, it will be desired not to image a given DoF in a scene, since there is an independent light source at the given DoF that dazzles (i.e., blinds) active imaging system 100 (for example, someone is attempting to blind active imaging system 100 with a laser). In the embodiment in which receiving subsystem 120 includes phase demodulator 904, optical filter 908, and optical detector 912, there is no concern that the light from the independent light source will interfere with the imaging of the at least one desired DoF, since the light from the independent light source will not pass the optical filter 908.

It is to be noted that, with reference to **Figs. 5 to 8 and 11**, some of the blocks can be integrated into a consolidated block or can be broken down to a few blocks and/or other blocks may be added. It is to be further noted that some of the blocks may be optional. It should be also noted that whilst the flow diagrams are described also with reference to the system elements that realizes them, this is by no means binding, and the blocks can be performed by elements other than those described herein.

It is to be understood that the presently disclosed subject matter is not limited in its application to the details set forth in the description contained herein or illustrated in the drawings. The presently disclosed subject matter is capable of other embodiments and of being practiced and carried out in various ways. Hence, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting. As such, those skilled in the art will appreciate that the conception upon which this disclosure is based may readily be utilized as a basis for designing other structures, methods, and systems for carrying out the several purposes of the present presently disclosed subject matter.

It will also be understood that the system according to the presently disclosed subject matter can be implemented, at least partly, as a suitably programmed computer. Likewise, the presently disclosed subject matter contemplates a computer program being readable by a computer for executing the disclosed method. The presently disclosed subject matter further contemplates a machine-readable memory tangibly embodying a program of instructions executable by the machine for executing the disclosed method.

CLAIMS:

1. An active imaging system, comprising:

a continuous wave (CW) light source configured for outputting a coherent continuous beam;

a transmission subsystem comprising an optical phase modulator, the optical phase modulator being configured to phase modulate the coherent continuous beam to generate at least one phase-modulated coherent continuous beam, wherein the transmission subsystem is configured, using the optical phase modulator, to generate and transmit at least one transmission beam that illuminates a scene, the transmission beam being a continuous repeated transmission sequence of time-based spectrally differentiated transmitted light; and

a receiving subsystem configured to perform at least one phase modulation for continuous manipulation of time-based spectrally differentiated return light reflected or scattered from multiple objects in at least part of the scene, the multiple objects including one or more first objects at one or more desired DoFs in the at least part of the scene and one or more second objects at one or more undesired DOFs in the at least part of the scene, wherein the phase modulation for the continuous manipulation of the return light is performed to image the first objects, and to not image or image with a suppressed intensity the second objects.

2. The active imaging system of claim 1, wherein the receiving subsystem comprises:

an optical beam sampling unit configured to sample the coherent continuous beam, for generating a sampled coherent beam; and

a reference phase modulator configured, based on the one or more desired DoFs, to phase modulate the sampled coherent beam for generating at least one reference beam, the reference beam being a reference sequence of time-based spectrally differentiated light that interferes with the return light for the continuous manipulation of the return light.

3. The active imaging system of claim 2, wherein the receiving subsystem further comprises:

a tunable attenuator, wherein a combination of the reference phase modulator and the tunable attenuator is configured for generating the at least one reference beam, wherein an intensity of the light of the reference beam varies over time.

4. The active imaging system of claim 2, wherein the receiving subsystem further comprises:

an event camera configured, based on frequencies of intensity fluctuations of the manipulated return light, to filter out or attenuate the manipulated return light that is associated with the return light reflected or scattered from the second objects, and to image the first objects.

5. The active imaging system of claim 2, wherein the receiving subsystem further comprises:

at least one optical detector configured to convert the manipulated return light into one or more electrical signals; and

at least one electrical filter configured, based on frequencies of intensity fluctuations of the manipulated return light, to filter out or attenuate components of the electrical signals that are indicative of the manipulated return light associated with the return light reflected or scattered from the second objects, and to pass the components of the electrical signals that are indicative of the manipulated return light associated with the return light reflected or scattered from the first objects, thereby enabling the imaging of the first objects.

6. The active imaging system of claim 1, wherein the receiving subsystem comprises:

a phase demodulator configured, based on the one or more desired DoFs, to phase demodulate the return light, for generating at least one demodulation beam of the manipulated return light.

7. The active imaging system of claim 6, wherein the receiving subsystem further comprises:

at least one optical filter configured to filter out or attenuate the manipulated return light that is associated with the return light reflected or scattered from the second objects; and

at least one optical detector, being downstream of the optical filter, the optical detector being configured to detect the manipulated return light that is associated with the return light reflected or scattered from the first objects, for imaging the first objects.

8. An active imaging method, comprising:

outputting, by a continuous wave (CW) light source, a coherent continuous beam;

phase modulating the coherent continuous beam, by an optical phase modulator included in a transmission subsystem, to generate at least one phase-modulated coherent continuous beam;

generating and transmitting at least one transmission beam that illuminates a scene, by the transmission subsystem, using the optical phase modulator, the transmission beam being a continuous repeated transmission sequence of time-based spectrally differentiated transmitted light; and

performing at least one phase modulation, by a receiving subsystem, for continuous manipulation of time-based spectrally differentiated return light reflected or scattered from multiple objects in at least part of the scene, the multiple objects including one or more first objects at one or more desired DoFs in the at least part of the scene and one or more second objects at one or more undesired DOFs in the at least part of the scene, wherein the phase modulation for the continuous manipulation of the return light is performed to image the first objects, and to not image or image with a suppressed intensity the second objects.

9. The active imaging method of claim 8, wherein the performing at least one phase modulation comprises:

sampling the coherent continuous beam, by an optical beam sampling unit, for generating a sampled coherent beam; and

phase modulating the sampled coherent beam, based on the one or more desired DoFs, by a reference phase modulator, to generate at least one reference beam, the reference beam being a reference sequence of time-based spectrally differentiated light that interferes with the return light for the continuous manipulation of the return light.

10. The active imaging method of claim 9, wherein the at least one reference beam is generated by a combination of the reference phase modulator and a tunable attenuator, and wherein an intensity of the light of the reference beam varies over time.

11. The active imaging method of claim 9, further comprising:

filtering out or attenuating the manipulated return light that is associated with the return light reflected or scattered from the second objects and imaging the first objects, by an event camera, based on frequencies of intensity fluctuations of the manipulated return light.

12. The active imaging method of claim 9, further comprising:

converting the manipulated return light into one or more electrical signals, by at least one optical detector; and

performing, by at least one electrical filter, based on frequencies of intensity fluctuations of the manipulated return light: (a) filtering out or attenuating components of the electrical signals that are indicative of the manipulated return light associated with the return light reflected or scattered from the second objects, and (b) passing the components of the electrical signals that are indicative of the manipulated return light associated with the return light reflected or scattered from the first objects, thereby enabling the imaging of the first objects.

13. The active imaging method of claim 8, wherein the performing at least one phase modulation comprises:

phase demodulating the return light, by a phase demodulator, based on the one or more desired DoFs, for generating at least one demodulation beam of the manipulated return light.

14. The active imaging method of claim 13, further comprising:

filtering out or attenuating, by at least one optical filter, the manipulated return light that is associated with the return light reflected or scattered from the second objects; and

detecting, by at least one optical detector that is downstream of the optical filter, the manipulated return light that is associated with the return light reflected or scattered from the first objects, for imaging the first objects.