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Quantum-inspired adaptive computational 3D imager

Abstract

A method performed by a photon imaging system comprises: selecting first patterns for illumination, and generating first illumination patterns that are time-varying responsive to the first patterns in order to illuminate a target; detecting light energy of the first illumination patterns that is reflected by the target; constructing histograms of the light energy that is detected; reconstructing an image of the target using the histograms and the first patterns; performing feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured to achieve the operational objective; and responsive to the feedback, selecting the second patterns, and generating second illumination patterns based on the second patterns to illuminate the target.

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Background/Summary

TECHNICAL FIELD

(1) The present disclosure relates to a photonic imaging system and method.

BACKGROUND

(2) A time-correlated single photon counting (TCSPC) imaging system generates illumination patterns, and transmits the illumination patterns through a medium, such as space, air, or water to illuminate a target deployed in the medium. The TCSPC imaging system transmits a number of the illumination patterns over a dwell time, which establishes a video frame rate for the system. The TCSPC imaging system detects light energy of the illumination patterns that is reflected from the target, and reconstructs an image of the target from the detected light. Factors that can corrupt the detected light and degrade a quality of the reconstructed image include optical refraction, diffraction, scattering, and attenuation of the illumination patterns as they propagate through the medium. Conventional TCSPC imaging systems employ limited hardware architectures and fixed, inflexible, processing techniques that make it difficult to balance acceptable TCSPC performance, such as image quality, against the video frame rate, a time to reconstruct the image, and noise mitigation.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. **1** is a high-level block diagram of an example optical environment in which an example quantum-inspired adaptive computational (QIAC) three-dimensional (3D) (QIAC 3D) imager (referred to simply as a "QIAC imager") may be employed.

(2) FIG. **2** is a block diagram that expands on an optical transmitter (TX), an optical receiver (RX), and a controller of the QIAC imager, according to an embodiment.

(3) FIG. **3** shows an example sequence of illumination patterns generated by the QIAC imager when operating in a pattern scanning mode.

(4) FIG. **4** shows an example sequence of illumination patterns generated by the QIAC imager when operating in a raster scanning mode.

(5) FIG. **5** is an illustration of example operations of image reconstruction performed by the QIAC imager.

(6) FIG. **6** is an illustration of an example pixel shifter of the optical TX.

(7) FIG. **7** is an illustration of an example non-imaging optical front-end of the optical RX.

(8) FIG. **8** is a flowchart of example operations performed by the QIAC imager to transmit illumination patterns and process reflections of the illumination patterns in a feedback loop.

(9) FIG. **9** shows high-level example operations performed by the QIAC imager.

(10) FIG. **10** is a block diagram of an example controller of the QIAC imager.

DESCRIPTION

Overview

(11) In an embodiment, a method is performed by a photon imaging system. The method comprises: selecting first patterns for illumination, and generating first illumination patterns that are time-varying responsive to the first patterns in order to illuminate a target; detecting light energy of the first illumination patterns that is reflected by the target; constructing histograms of the light energy that is detected; reconstructing an image of the target using the histograms and the first patterns; performing feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured

to achieve the operational objective; and responsive to the feedback, selecting the second patterns, and generating second illumination patterns based on the second patterns to illuminate the target.

(12) In another embodiment, an apparatus comprises: a controller to select patterns for illumination; an optical transmitter including an individually addressable laser array (IALA) to produce illumination patterns responsive to the patterns, to illuminate a target; and an optical receiver including: a non-imaging lens to receive light energy of the illumination patterns that is reflected by the target, to produce non-imaged light energy; and a single-photon avalanche diode (SPAD) array to detect the non-imaged light energy across the SPAD array, to produce an array of light detections; wherein the controller is configured to: construct histograms of the array of the light detections; and reconstruct an image of the target using the histograms and the patterns.

EXAMPLE EMBODIMENTS

(13) Embodiments presented herein are directed to a quantum-inspired adaptive computational (QIAC) three-dimensional (3D) (QIAC 3D) imager (referred to simply as a “QIAC imager”) that includes an improved hardware architecture and dynamic, adaptive, operational (i.e., performance) objective-based processing techniques configured to achieve improved performance over conventional TCSPC imaging systems. In some aspects, the QIAC imager may be considered an improved TCSPC imaging system that is “quantum-inspired” due, in part, to photonic counting/detection and processing employed by the QIAC imager. The QIAC imager employs an adaptive illuminator to spatially modulate a field-of-view (FOV) and then reconstructs under-sampled images reflected from the FOV in particle induced scattering and turbulent media. Based on the aforementioned features, the QIAC imager maintains or improves a quality of a reconstructed image, while (i) reducing a number, and a video frame rate of, illumination patterns used to reconstruct the image, (ii) minimizing a processing time to reconstruct the image, and (iii) maximizing noise mitigation. These and other advantages and features of the QIAC imager and related methods will become apparent from the ensuing description.

(14) FIG. **1** is a high-level block diagram of an example optical environment **100** in which an example QIAC imager **102** (referred to more generally as a “photon imaging system”) configured according to embodiments presented herein illuminates a target **104** disposed in an optically transmissive medium (e.g., space, air, or water), and processes light energy reflected from the target. QIAC imager **102** may be part of a light detection and ranging (LIDAR) system.

(15) QIAC imager **102** includes an optical transmitter (TX) **106**, an optical receiver (RX) **108**, and a controller **110** coupled to, and configured to control, the optical TX and the optical RX. Optical TX **106** generates a sequence of illumination patterns **111** (also referred to simply as “illumination patterns”) that are time-varying responsive to patterns selected by a pattern selection signal **112**, and transmits the illumination patterns toward target **104**. Optical TX **106** also generates, and provides to optical RX **108**, a TX timing signal **113** that indicates transmit times of illumination patterns **111**.

(16) Optical RX **108** receives reflected light energy **114** from target **104** (i.e., light energy of illumination patterns **111** that is reflected by target **104** toward the optical receiver). TX timing signal **113** triggers optical RX **108** to detect reflected light energy (i.e., photons) to produce light detections **116** (i.e., detected light energy), and provides the same to controller **110**. Controller **110** includes processing modules **118** that perform image reconstruction and adaptive feedback processing based on light detections **116** to produce pattern selection signal **112**, and provides the same to optical TX **106** as a feedback control signal.

(17) Controller **110**, optical TX **106**, and optical RX **108** operate collectively to form a feedback loop that repeatedly/cyclically adapts illumination patterns **111** over time as follows. First, controller **110** provides to optical TX **106** pattern selection signal **112**, and the optical TX **106** generates (and transmits to target **104**) illumination patterns **111** responsive to patterns selected by the pattern selection signal. Second, optical RX **108** detects reflected energy **114** (i.e., reflected illumination patterns) to produce light detections **116**. Fourth, controller **110** processes light

detections **116** to adapt pattern selection signal **112** (i.e., to produce an adapted pattern selection signal). Fifth, optical TX **106** adapts illumination patterns **111** responsive to the adapted pattern selection signal, to produce adapted illumination patterns. The foregoing operations repeat over time.

(18) FIG. **2** is a block diagram of QIAC imager **102** that expands on the block diagram of FIG. **1**. Optical TX **106**, optical RX **108**, and controller **110** are now described in further detail with reference to FIG. **2**. Optical TX **106** includes a codebook **202** of patterns (also referred to as a “pattern codebook”), an individually addressable laser array (IALA) **204**, an optional pixel shifter **206**, and TX optics **208** arranged in series. More generally, any high pixel density individually controllable multi-element illumination device may be employed in optical TX **106**, including, but not-limited to, the IALA, a laser and micro-electromechanical system (MEMS) combination, a laser and digital mirror device (DMD) combination, and the like. Codebook **202** stores patterns (also referred to as “codebook patterns”) used to produce corresponding illumination patterns. Each pattern represents a 2D (i.e., planar) array (e.g., an N×N array) of pixel control elements that each indicate either ON or OFF for a corresponding pixel of a corresponding illumination pattern. Pattern selection signal **112** selects patterns (also referred to as “selected patterns”) to be applied to IALA **204** by codebook **202**, and the codebook applies the (selected) patterns to the IALA.

(19) IALA **204** includes a planar array (e.g., an N×N array) of individually addressable pixels that collectively produce an illumination pattern that has a planar spatial arrangement or spatial grid of illuminated and non-illuminated pixels controlled by the pattern when applied to the IALA. IALA **204** generates the illumination pattern with a fixed resolution that is dictated by a size of each individually addressable pixel of the IALA. To achieve such spatial light modulation, the pattern pixel control elements control (i.e., turn ON or turn OFF) corresponding ones of the individually addressable pixels (e.g., lasers), which represent corresponding ones of the pixels of the illumination pattern. In this way, IALA **204** generates the illumination pattern responsive to the pattern.

(20) By extension, a sequence of different patterns applied to IALA **204** over time cause the IALA to generate a corresponding/matching sequence of time-varying illumination patterns, also referred to as “spatio-temporally modulated light” and “structured illumination.” IALA **204** generates n illumination patterns (responsive to the same number of selected patterns) over a dwell time t, which establishes a video frame rate (VFR) (sometimes referred to simply as a “frame rate”) of the illumination patterns when detected/processed by optical RX **108** and controller **110**, where VFR a n/t. An increase or decrease in the number n during the dwell time t results in a corresponding increase or decrease in the VFR. Similarly, increases or decrease in the dwell time results in a corresponding decrease or increase in the VFR. Optical TX **106** additionally generates, and provides to optical RX **108**, TX timing signal **113** that indicates successive times at which IALA **204** generates illumination patterns during the dwell time, and which triggers optical RX **108** to detect photons of reflections of the illumination patterns.

(21) IALA **204** provides to pixel shifter **206** the illumination patterns with the fixed resolution size. Pixel shifter **206** operates to increase the resolution size of each illumination pattern. Pixel shifter **206** includes an actuator array to physically shift a position of each pixel of each illumination pattern (from IALA **204**) slightly, e.g., to dither the position slightly. The position shift may be less than a full size of each pixel. As a result, pixel shifter **206** generates pixel-shifted illumination patterns, each with an increased resolution size. Pixel shifter **206** transmits the pixel-shifted illumination patterns (as illumination patterns **111**) toward target **104** through TX optics **208**. In some embodiments, pixel shifter **206** may be omitted.

(22) Optical RX **108** includes a non-imaging optical front-end **214**, a single-photon avalanche diode (SPAD) array **216** that includes an array of SPADs, and a time-tagger **218** arranged in series. In an example, non-imaging optical front-end **214** includes a diffuser (e.g., a non-imaging lens, not shown) that receives reflected light energy **114**, and diffuses or spreads the reflected energy to

produce diffuse/non-imaged light energy, and provides the same to SPAD array **216** (i.e., a planar array of individual SPADs). The individual SPADs of SPAD array **216** collectively form a planar light-detection face to receive the non-imaged light energy of each reflected illumination pattern that is spread across the face of the SPAD array.

(23) The individual SPADs detect the diffuse/non-imaged light energy (i.e., photons) impinging on their faces in parallel, to produce an array of light detections (one light detection per SPAD) for each illumination pattern. The array of light detections represent an array of (detected) pixels. Thus, the entire SPAD array **216** functions as a "bucket detector" for photons. Time-tagger **218** applies time stamps (i.e., photon time-of-arrivals) to the light detections (i.e., the photon detections) based on TX timing signal **113**, to produce an array of time-stamped light detections in parallel (e.g., an array of pixels) for each illumination pattern, and forwards the same to controller **110**. Time-tagger **218** uses TX timing signal **113** to determine a time-of-arrival of each photon received/detected by SPAD array **216**. The time stamps correlate the light detections in the array of light detections to each other, and to a corresponding pattern from codebook **202**. The aforementioned parallel photon detection/collection is similar to running a Monte Carlo model in parallel mode. Over time, optical RX **108** provides to controller **110** a sequence of arrays of time-stamped light detections (denoted light detections **116**) corresponding to the sequence of illumination patterns detected by the optical RX.

(24) Controller **110** includes modules **118** to process the arrays of time-stamped light detections (i.e., to process the detected pixel arrays/light detection arrays) to produce/adapt pattern selection signal **112** based on predetermined operational objectives **228**, described below. Operational objectives may also be referred to as "processing objectives," "performance objectives," and "optimization objectives." Also, the terms objective/objectives and criterion/criteria may be used interchangeable. Each objective may include an operational parameter to be optimized, for example. Modules **118** include histogram construction **230**, pattern sensing **232**, and pattern sensing adaptation **234**, which cooperate to reconstruct an image of target **104** (also referred to as a "reconstructed image"), and to produce pattern selection signal **112**, which selects/adapts the patterns/illumination patterns **111** to achieve operational objectives **228**. Non-limiting examples of operational objectives **228** may include/relate to a pixel power in the image, a quality of the image, VFR, a region-of-interest (ROI) of the image, noise (e.g., scatter and turbulence) mitigation, and so on.

(25) Histogram construction **230** receives the arrays of time-stamped light detections. Histogram construction **230** constructs or builds an array of histograms (i.e., a set of histograms) in parallel based on each array of time-stamped light detections, and thus for each (reflected) illumination pattern. The histograms measure light energy detected by corresponding ones of the individual SPADs (i.e., measure the light energy of each detected pixel). Together, histogram construction **230** and time-tagger **218** collectively form a time correlator **237** that correlates the array of histograms to a corresponding pattern from codebook **202**.

(26) Next, histogram construction **230** combines or accumulates each set of histograms into a combined or cumulative histogram for each illumination pattern. The cumulative histogram indicates a total light energy produced by the corresponding illumination pattern. That is, generating the cumulative histogram includes determining the total light energy. Over time, histogram construction **230** generates cumulative histograms **236** for corresponding ones of the illumination patterns (one cumulative histogram per illumination pattern), and provides the same to pattern sensing **232**. Histogram construction **230** may employ compressive sensing (CS) and machine learning (ML) techniques to aid with the histogram reconstruction, such as to remove noise, jitter, and to perform missing pixel estimation from neighboring pixels, for example.

(27) Pattern sensing **232** may receive as inputs cumulative histograms **236** corresponding to illumination patterns **111**, the patterns applied to IALA **204**, and operational objectives **228**. Pattern sensing **232** reconstructs an image of target **104** based on the aforementioned inputs to produce

image content **238** indicative of an image of target **104** in accordance with the objectives. For example, pattern sensing **232** may construct the image to achieve a desired VFR, to focus on a region-of-interest using image/feature templates, and/or to mitigate scatter and/or turbulence. Image content **238** may include a two-dimensional (2D) reflectance (R) map (e.g., a 2D grey-scale image showing reflected power for each pixel), a depth (D) map (which indicates a distance to highest returns), detected power/energy for each of the pixels of each reflected illumination pattern, noise estimates for each reflected illumination pattern, and so on.

(28) Pattern sensing adaptation **234** receives as inputs image content **238** and operational objectives **228**, generates pattern selection signal **112** based on the inputs, and provides the pattern selection signal to optical TX **106**. Pattern selection signal **112** repeatedly selects/adapts patterns used to generate illumination patterns **111** over time according to operational objectives **228**. Together, histogram construction **230**, pattern sensing **232**, and pattern sensing adaptation **234** collectively form a feedback loop **240** that processes the reflected illumination patterns. That is, feedback loop **240** includes feedback processing of the reflected illumination patterns.

(29) Examples of operational objective-based imaging performed by feedback loop **240** are provided below. Generally, the examples assume an initial operation in which pattern sensing adaptation **234** selects initial patterns to generate a number of initial illumination patterns over a dwell time, which establishes an initial VFR and initial sensing conditions. The initial patterns/illumination patterns may include random patterns/illumination patterns to sense the environment. Feedback loop **240** processes reflected light energy **114** for the initial illumination patterns according to one or more of the operational objectives, as listed below. In response, pattern sensing adaptation **234** selects subsequent/adapted illumination patterns for the dwell time or a reduced dwell time. The adapted illumination patterns reflect/achieve the performance objectives. QIAC imager **102** relies on the feedback to adapt the illumination patterns relative to the initial illumination patterns to achieve the operational objectives.

(30) VFR example. In the VFR example, image reconstruction by pattern sensing **232** and pattern selection by pattern sensing adaptation **234** are optimized to select as the new patterns a subset of the initial patterns (i.e., a reduced number of the initial patterns) to produce a suitable image while maintaining a high VFR (e.g., to increase the VFR). The optimization is based on a combination of image quality (e.g., ensuring that image quality meets a quality criteria), a minimum number of patterns, and a minimum dwell time (e.g., to generate a minimum number of patterns during a minimum dwell time while maintaining the image quality). The initial patterns may include m patterns, and the new patterns may include p patterns, where m<<p. The dwell time for the new patterns may be less than the dwell time for the initial patterns. The result may be to increase the VFR.

(31) ROI example. In the ROI example, image reconstruction by pattern sensing **232** and pattern selection by pattern sensing adaptation **234** are optimized to select as the new patterns a subset of the initial patterns that focus primarily on the ROI. Such processing may include, but is not limited to, an ML image classification algorithm to determine objects of interest via template matching (i.e., matching against templates indicative of the ROI or particular image features). Once the processing determines an ROI based on the initial patterns/illumination patterns, the processing selects the new patterns/illumination patterns to only illuminate the ROI (i.e., a reduced number of patterns/illumination patterns), which may increase the VFR (when the dwell time is also reduced) and/or increase resolution. In an example, the initial patterns may include illuminated pixels scattered randomly across all four quadrants of the 2D area of the illumination pattern, while the new patterns only include illuminated pixels grouped into a small area, such as in one of the four quadrants.

(32) Scatter/turbulence mitigation example. In this example, image reconstruction by pattern sensing **232** and pattern selection by pattern sensing adaptation **234** are optimized to select the new patterns based on an image quality measure such as contrast signal-to-noise ratio (CSNR),

backscatter estimation, peak SNR (PSNR)/structural similarity (SSIM), and the like. The optimization mitigates noise and non-image bearing photons caused by scatter and turbulence.

(33) Total light energy example. In this example, image reconstruction by pattern sensing **232** and pattern selection by pattern sensing adaptation **234** are optimized to select the new patterns based on total light energy, e.g., to maximize the total light energy. The processing determines a subset of the initial patterns/illumination patterns that produced the highest total reflected light energy/power (e.g., the top 5%), and selects only that subset (e.g., 5%) as the new patterns/illumination patterns. For a given or reduced dwell time, this may also reduce the VFR.

(34) QIAC imager **102** may operate in multiple scanning modes based on the patterns stored in codebook **202**. FIG. **3** shows an example sequence of four illumination patterns **302** (which represent an example of illumination patterns **111**) generated by optical TX **106** and processed by optical RX **108** when QIAC imager **102** operates in a pattern scanning mode. Illumination patterns **302** each includes a random binary structure. The random binary structure includes a planar array of pixels in which multiple pixels are ON (i.e., turned ON) and multiple pixels are OFF (i.e., turned OFF) concurrently according to a random spatial arrangement based on a Hadamard pattern, for example. A pixel that is ON is referred to as a “beamlet.” Pattern sensing **232** may perform image reconstruction using a single pixel imaging algorithm. Compressive sensing may be achieved via the feedback loop by only selecting patterns that yield the highest reflected energy (which conveys the most-information) for image reconstruction. For example, based on the feedback loop, select only 16 highest energy patterns among 64 initial patterns as the subsequent patterns to reconstruct an 8×8 pixel image.

(35) FIG. **4** shows an example sequence of four illumination patterns **402** (which represent an example of illumination patterns **111**) generated by optical TX **106** and processed by optical RX **108** when QIAC imager **102** operates in a raster scanning mode. Illumination patterns **402** each includes a random single illuminated pixel, while all other pixels are OFF. Stated otherwise, the raster scanning samples each pixel individually at any given time. For example, a sequence of 64 pixels/patterns are used to generate an 8×8 image. Compressive sensing may be achieved by skipping pixels, estimating skipped pixels (e.g., interpolating adjacent skipped pixels), and optimizing via combined compressive sensing and ML (e.g., use only 32 pixels to reconstruct and 8×8 image.

(36) FIG. **5** is an illustration of example image reconstruction **500** performed by QIAC imager **102**. In the example, at **502**, optical TX **106** generates illumination patterns **504**, **506**, and **508** (also referred to as “masks”), transmits the same to target **104**, and provides TX timing signal **113** to optical RX **108**. TX timing signal **113** includes timing pulses that coincide with each of the transmitted illumination patterns. Using the techniques described above and time correlator **237**, at **510**, optical RX **108** detects three reflected illumination patterns and time-tags the same using the timing pulses to produce three arrays of time-stamped light detections (e.g., light detections **116**), and provides the same to controller **110**. Controller **110** (e.g., histogram construction **230**) constructs cumulative histograms **514**, **516**, and **518** for corresponding ones of illumination patterns **504**, **506**, and **508** using corresponding ones of the three arrays of time-stamped light detections. At **520**, controller **110** (e.g., pattern sensing **232**) combines cumulative histograms **514**, **516**, and **518** into a composite measurement signal **522**, and reconstructs and image **524** from the composite measurement signal.

(37) FIG. **6** is an illustration of pixel shifter **206** according to an embodiment. In the example of FIG. **6**, pixel shifter includes an array of optical actuators, each generally represented as an optical actuator **602** in FIG. **6**. Optical actuator **602** is configured for rotational displacement bi-directionally (e.g., by 1-5 degrees) about an axis **604** of the optical actuator, as shown by arrows **606**, responsive to a control signal CS generated locally in optical TX **106**. The array of optical actuators (including optical actuator **602**) receives from IALA **204** an illumination pattern **608** including an input array of pixels. The array of optical actuators produce an output array of pixels

at an array position that depends on the displacement. In the example of FIG. **6**, the optical actuators (e.g., optical actuator **602**) produces, from the input array, output arrays **610**, **612**, **614**, and **616** at first, second, third, and fourth array positions that are slightly shifted relative to each other when the optical actuator is in first, second, third, and fourth actuator position, respectively. Dithering the displacement of the optical actuators (e.g., optical actuator **602**) in this manner generates illumination patterns that have higher pixel resolutions from the perspective of image reconstruction algorithms than without the dithering.

(38) FIG. **7** is an illustration of non-imaging optical front-end **214**, according to an embodiment. In the example of FIG. **7**, non-imaging optical front-end includes a spectral filter **702** tuned to a wavelength of light (e.g., a green light) used by optical TX **106** to generate illumination patterns **111**, a plano-convex lens **704**, an iris **706**, and a diffuser **708** (e.g., non-imaging lens) in series with each other. Spectral filter **702** spectrally filters reflected light energy **114** to produce filtered light, and provides the same to plano-convex lens **704**. Plano-convex lens **704** passes the filtered light to diffuser **708** through iris **706**. Diffuser **708** diffuses or spreads the filtered light (as non-imaged light) across the light detection surface of SPAD array **216** in order to illuminate all of the individual SPAD detectors of the SPAD array.

(39) FIG. **8** is a flowchart of example operations **800** performed by a photon imaging system (e.g., QIAC imager **102**). Operations **800** are described above.

(40) **802** includes selecting first patterns for illumination, and generating first illumination patterns responsive to the first patterns in order to illuminate a target. The first illumination patterns may include a first number of the first illumination patterns that are generated/transmitted over a first dwell time to establish a first VFR (e.g., the first number/the first dwell time).

(41) **804** includes detecting light energy of the first illumination patterns that is reflected by the target.

(42) **806** includes constructing histograms of the light energy that is detected.

(43) **808** reconstructing an image of the target using the histograms and the first patterns.

(44) **810** performing feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured to achieve the operational objective. In an example, the feedback is configure to selecting only a subset of the first patterns as the second patterns, i.e., there are fewer second patterns than first patterns.

(45) When the operational objective includes focusing on a region-of-interest, noise mitigation, and optimizing on total energy, one or more of reconstructing the image and/or the feedback processing may include determining a region-of-interest of the target, determining a measure of noise that reduces a quality of the image, and determining total light energies produced by corresponding ones of the first illumination patterns.

(46) **812** includes responsive to the feedback, selecting the second patterns, and generating second illumination patterns based on the second patterns to illuminate the target. The second illumination patterns may be generated over a second dwell time that is less than the first dwell time to establish a second VRF that is greater than the first VFR.

(47) **814** includes, after generating the second illumination patterns, repeating detecting, reconstructing, and performing the feedback processing using the second illumination patterns.

(48) FIG. **9** shows high-level example operations **900** performed by QIAC imager **102**. **902** includes generating, from codebook content (i.e., patterns) an initial sequence of random 2D illumination patterns (which, over time, collectively form initial 3D random sensing patterns) generated at a video frame rate to illuminate a target. **904** includes acquiring measurements of light reflections of the 3D sensing patterns from the target. **906** includes detection/image reconstruction of the target in a compressive sensing domain based on the measurements. **908** includes codebook content (e.g., pattern) and video frame rate adaptation based on the compressive sensing and

operational objectives.

(49) In summary, embodiments presented herein are directed to a QIAC imager that can actively adapt (e.g., change) sensing patterns to optimize objective-based imaging (e.g., detection, tracking, classification, and the like) in degraded visual environments. The system includes a high pixel density individually controllable multi-element illumination device (e.g., an IALA and pixel shifter) integrated with an improved quantum-inspired TCSPC receiver. The quantum-inspired TCSPC receiver implements a multi-element detection architecture for single pixel TCSPC imaging, such as a quantum-inspired Monte Carlo simulation on hardware.

(50) The system provides multiple levels of speed improvement enabled by an improved hardware/firmware architecture to achieve a desired video frame rate. The system employs ML-based pattern adaptation and optimization, and context-aware histogram reconstruction to reduce sensing pattern shots (i.e., reduce the number of samples and dwell time). This has been shown to achieve a higher signal-to-noise ratio with reduced samples.

(51) An embodiment includes a quantum-inspired SPAD array bucket detector that: uses an entire SPAD array as a bucket detector to build a histogram using all elements of the SPAD array; uses quantum-inspired Monte Carlo simulation on the hardware; is scalable—more array elements results in a shorter times to build histograms; uses a diffuser to project received light onto all elements of the SPAD array; can be implemented in an all-silicon architecture once fully developed.

(52) Another embodiment includes quantum-inspired pattern imaging for underwater imaging, which may use a 5 MHz 515 nm laser, a DMD or IALA illuminator, and a 7×7 SPAD array bucket detector, for example. This incorporates quantum algorithms to capture images in scattering media, and provides further discrimination via photon attributes (e.g., polarization, orbital angular momentum (OAM), coherence, spatial mode, mimicking spontaneous parametric down-conversion (SPDC) using the IALA and the pixel shifter).

(53) Yet another embodiment includes context aware reduction of sensing pattern shots. This uses neighboring pixels and histograms to infill “null pixels” via tensor completion. Reduces the number of samples and dwell time to achieve rate reduction for low probability of intercept (LPI)/low probability of detect (LPD) targets.

(54) Another embodiment includes ML-based pattern adaptation and optimization, which uses an adaptive 3D filtering process to mitigate non-target noise and optimize objective based imaging. The ML process is trained using simulated datasets from known TCSPC imaging models.

(55) FIG. **10** is a block diagram of an example of controller **110** configured to perform operations described herein. Controller **110** includes processor(s) **1060** and a memory **1062** coupled to one another. The aforementioned components may be implemented in hardware (e.g., a hardware processor), software (e.g., a software processor), or a combination thereof. Processor(s) **1060** communicates with optical TX **106** and optical RX **108** over hardware and/or software interfaces **1064**. Interfaces **1064** may also communicate with user devices through which an operator may interact with controller **110** (e.g., to input and receive data, such as operational objectives). Memory **1062** stores control software **1066** (referred as “control logic”), that when executed by the processor(s) **1060**, causes the processor(s), and more generally, controller **110**, to perform the various operations described herein. The processor(s) **1060** may be a microprocessor or microcontroller (or multiple instances of such components). The memory **1062** may include read only memory (ROM), random access memory (RAM), magnetic disk storage media devices, optical storage media devices, flash memory devices, electrical, optical, or other physically tangible (i.e., non-transitory) memory storage devices. Controller **110** may also be discrete logic embedded within an integrated circuit (IC) device.

(56) Thus, in general, the memory **1062** may comprise one or more tangible (non-transitory) computer readable storage media (e.g., memory device(s)) including a first non-transitory computer readable storage medium, a second non-transitory computer readable storage medium, and so on,

encoded with software or firmware that comprises computer executable instructions. For example, control software **1066** includes logic to implement operations performed by the controller **110**.

(57) In addition, memory **1062** stores data **1068** used and produced by control software **1066**.

(58) In some aspects, the techniques described herein relate to a method performed by a photon imaging system including: selecting first patterns for illumination, and generating first illumination patterns that are time-varying responsive to the first patterns in order to illuminate a target; detecting light energy of the first illumination patterns that is reflected by the target; constructing histograms of the light energy that is detected; reconstructing an image of the target using the histograms and the first patterns; performing feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured to achieve the operational objective; and responsive to the feedback, selecting the second patterns, and generating second illumination patterns based on the second patterns to illuminate the target.

(59) In some aspects, the techniques described herein relate to a method, further including: after generating the second illumination patterns, repeating detecting, reconstructing, and performing the feedback processing using the second illumination patterns.

(60) In some aspects, the techniques described herein relate to a method, wherein: selecting the first patterns includes selecting the first patterns from a codebook; and generating the first illumination patterns includes, by an individually addressable light array (IALA), modulating light responsive to the first patterns to produce the first illumination patterns.

(61) In some aspects, the techniques described herein relate to a method, wherein: generating the first illumination patterns further includes pixel shifting modulated light produced by modulating to produce the first illumination patterns as pixel shifted illumination patterns that have a higher pixel resolution than without pixel shifting.

(62) In some aspects, the techniques described herein relate to a method, wherein: selecting the first patterns and generating the first illumination patterns result in pattern scanning an array of pixels to produce the first illumination patterns as a sequence of two-dimensional patterns of illumination pixels.

(63) In some aspects, the techniques described herein relate to a method, further including: receiving the light energy through a non-imaging lens to produce non-imaged light energy, and wherein detecting the light energy includes detecting the non-imaged light energy using a single-photon avalanche diode (SPAD) array to produce an array of light detections in parallel, wherein constructing the histograms includes constructing the histograms in parallel from the array of the light detections.

(64) In some aspects, the techniques described herein relate to a method, further including: combining the histograms into a cumulative histogram, wherein reconstructing includes reconstructing based on the cumulative histogram.

(65) In some aspects, the techniques described herein relate to a method, wherein: selecting the second patterns includes selecting only a subset of the first patterns as the second patterns; and generating the second illumination patterns includes generating only the subset of the first illumination patterns as the second illumination patterns.

(66) In some aspects, the techniques described herein relate to a method, wherein: the operational objective includes increasing a video frame rate of the first illumination patterns while maintaining a predetermined quality of the image; generating the first illumination patterns includes generating the first illumination patterns at a first video frame rate; and generating the second illumination patterns at a second video frame rate that is greater than the first video frame rate to achieve the operational objective.

(67) In some aspects, the techniques described herein relate to a method, wherein: reconstructing the image includes determining a region-of-interest of the target; performing the feedback

processing includes performing the feedback processing based on the region-of-interest as the operational objective; and responsive to the feedback, selecting the second patterns includes selecting only a subset of the first patterns that focus on the region-of-interest as the second patterns.

(68) In some aspects, the techniques described herein relate to a method, further including: determining a measure of noise that reduces a quality of the image; performing the feedback processing includes performing the feedback processing to reduce the measure of the noise as the operational objective; and responsive to the feedback, selecting the second patterns includes selecting the second patterns to reduce the measure of the noise.

(69) In some aspects, the techniques described herein relate to a method, further including: detecting the light energy includes determining total light energies produced by corresponding ones of the first illumination patterns; performing the feedback processing includes performing the feedback processing to maximize the total light energies; and responsive to the feedback, selecting the second patterns includes selecting, as the second patterns, only a subset of the first patterns that produced highest total light energies among the total light energies.

(70) In some aspects, the techniques described herein relate to a method, wherein: reconstructing the image and the feedback processing includes using compressive sensing and machine learning techniques.

(71) In some aspects, the techniques described herein relate to an apparatus including: a controller to perform selecting first patterns for illumination; an optical transmitter to perform generating first illumination patterns that are time-varying based on the first patterns, to illuminate a target; an optical receiver to detect light energy of the first illumination patterns reflected by the target; and wherein the controller is configured to perform: constructing histograms of the light energy that is detected; reconstructing an image of the target using the histograms and the first patterns; feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured to achieve the operational objective; and responsive to the feedback, selecting the second patterns; wherein the optical transmitter is configured to perform generating second illumination patterns based on the second patterns to illuminate the target.

(72) In some aspects, the techniques described herein relate to an apparatus, wherein the controller, the optical transmitter, and the optical receiver are configured to perform: repeating detecting, reconstructing, and the feedback processing using the second illumination patterns.

(73) In some aspects, the techniques described herein relate to an apparatus, wherein: the controller includes a codebook and the controller is configured to perform selecting the first patterns by selecting the first patterns from the codebook; and the optical transmitter includes an individually addressable light array (IALA), and the IALA is configured to perform modulating light responsive to the first patterns to produce the first illumination patterns.

(74) In some aspects, the techniques described herein relate to an apparatus, wherein: the optical receiver includes: a non-imaging lens to diffuse the light energy to produce diffuse light energy; and a single-photon avalanche diode (SPAD) array to detect the diffuse light energy to produce an array of light detections; and the controller is configured to perform constructing the histograms by constructing the histograms from the array of the light detections.

(75) In some aspects, the techniques described herein relate to an apparatus including: a controller to select patterns for illumination; an optical transmitter including an individually addressable laser array (IALA) to produce illumination patterns responsive to the patterns, to illuminate a target; and an optical receiver including: a non-imaging lens to receive light energy of the illumination patterns that is reflected by the target, to produce non-imaged light energy; and a single-photon avalanche diode (SPAD) array to detect the non-imaged light energy across the SPAD array, to produce an array of light detections; wherein the controller is configured to: construct histograms of the array

of the light detections; and reconstruct an image of the target using the histograms and the patterns.
(76) In some aspects, the techniques described herein relate to an apparatus, wherein the optical transmitter further includes a pixel shifter following the IALA to pixel-shift modulated light produced by the IALA, to produce the illumination patterns as pixel-shifted illumination patterns.
(77) In some aspects, the techniques described herein relate to an apparatus, wherein the controller is further configured to: combine the histograms into a cumulative histogram, wherein the controller is configured to reconstruct the image using the cumulative histogram.
(78) In some aspects, the techniques described herein relate to a non-transitory computer readable medium encoded with instructions that, when executed by a processor of a photon imaging system, cause the processor to perform: selecting first patterns for illumination, and generating first illumination patterns that are time-varying responsive to the first patterns in order to illuminate a target; detecting light energy of the first illumination patterns that is reflected by the target; constructing histograms of the light energy that is detected; reconstructing an image of the target using the histograms and the first patterns; performing feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured to achieve the operational objective; and responsive to the feedback, selecting the second patterns, and generating second illumination patterns based on the second patterns to illuminate the target.
(79) In some aspects, the techniques described herein relate to a non-transitory computer readable medium, further comprising instructions to cause the processor to perform: after generating the second illumination patterns, repeating detecting, reconstructing, and performing the feedback processing using the second illumination patterns.
(80) The above description is intended by way of example only. Although the techniques are illustrated and described herein as embodied in one or more specific examples, it is nevertheless not intended to be limited to the details shown, since various modifications and structural changes may be made within the scope and range of equivalents of the claims.

Claims

1. A method performed by a photon imaging system comprising: selecting first patterns for illumination, and generating first illumination patterns that are time-varying responsive to the first patterns in order to illuminate a target; detecting light energy of the first illumination patterns that is reflected by the target; constructing histograms of the light energy that is detected; reconstructing an image of the target using the histograms and the first patterns; performing feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured to achieve the operational objective; and responsive to the feedback, selecting the second patterns, and generating second illumination patterns based on the second patterns to illuminate the target.
2. The method of claim 1, further comprising: after generating the second illumination patterns, repeating detecting, reconstructing, and performing the feedback processing using the second illumination patterns.
3. The method of claim 1, wherein: selecting the first patterns includes selecting the first patterns from a codebook; and generating the first illumination patterns includes, by an individually addressable light array (IALA), modulating light responsive to the first patterns to produce the first illumination patterns.
4. The method of claim 3, wherein: generating the first illumination patterns further includes pixel shifting modulated light produced by modulating to produce the first illumination patterns as pixel shifted illumination patterns that have a higher pixel resolution than without pixel shifting.

5. The method of claim 1, wherein: selecting the first patterns and generating the first illumination patterns result in pattern scanning an array of pixels to produce the first illumination patterns as a sequence of two-dimensional patterns of illumination pixels.
6. The method of claim 1, further comprising: receiving the light energy through a non-imaging lens to produce non-imaged light energy, and wherein detecting the light energy includes detecting the non-imaged light energy using a single-photon avalanche diode (SPAD) array to produce an array of light detections in parallel, wherein constructing the histograms includes constructing the histograms in parallel from the array of the light detections.
7. The method of claim 6, further comprising: combining the histograms into a cumulative histogram, wherein reconstructing includes reconstructing based on the cumulative histogram.
8. The method of claim 1, wherein: selecting the second patterns includes selecting only a subset of the first patterns as the second patterns; and generating the second illumination patterns includes generating only the subset of the first illumination patterns as the second illumination patterns.
9. The method of claim 8, wherein: the operational objective includes increasing a video frame rate of the first illumination patterns while maintaining a predetermined quality of the image; generating the first illumination patterns includes generating the first illumination patterns at a first video frame rate; and generating the second illumination patterns at a second video frame rate that is greater than the first video frame rate to achieve the operational objective.
10. The method of claim 1, wherein: reconstructing the image includes determining a region-of-interest of the target; performing the feedback processing includes performing the feedback processing based on the region-of-interest as the operational objective; and responsive to the feedback, selecting the second patterns includes selecting only a subset of the first patterns that focus on the region-of-interest as the second patterns.
11. The method of claim 1, further comprising: determining a measure of noise that reduces a quality of the image; performing the feedback processing includes performing the feedback processing to reduce the measure of the noise as the operational objective; and responsive to the feedback, selecting the second patterns includes selecting the second patterns to reduce the measure of the noise.
12. The method of claim 1, further comprising: detecting the light energy includes determining total light energies produced by corresponding ones of the first illumination patterns; performing the feedback processing includes performing the feedback processing to maximize the total light energies; and responsive to the feedback, selecting the second patterns includes selecting, as the second patterns, only a subset of the first patterns that produced highest total light energies among the total light energies.
13. The method of claim 1, wherein: reconstructing the image and the feedback processing includes using compressive sensing and machine learning techniques.
14. An apparatus comprising: a controller to perform selecting first patterns for illumination; an optical transmitter to perform generating first illumination patterns that are time-varying based on the first patterns, to illuminate a target; an optical receiver to detect light energy of the first illumination patterns reflected by the target; and wherein the controller is configured to perform: constructing histograms of the light energy that is detected; reconstructing an image of the target using the histograms and the first patterns; feedback processing of the image based on an operational objective, associated with one or more of generating illumination patterns or reconstructing the image, to produce feedback for selecting second patterns that differ from the first patterns and are configured to achieve the operational objective; and responsive to the feedback, selecting the second patterns; wherein the optical transmitter is configured to perform generating second illumination patterns based on the second patterns to illuminate the target.
15. The apparatus of claim 14, wherein the controller, the optical transmitter, and the optical receiver are configured to perform: repeating detecting, reconstructing, and the feedback processing using the second illumination patterns.

16. The apparatus of claim 14, wherein: the controller includes a codebook and the controller is configured to perform selecting the first patterns by selecting the first patterns from the codebook; and the optical transmitter includes an individually addressable light array (IALA), and the IALA is configured to perform modulating light responsive to the first patterns to produce the first illumination patterns.
17. The apparatus of claim 14, wherein: the optical receiver includes: a non-imaging lens to diffuse the light energy to produce diffuse light energy; and a single-photon avalanche diode (SPAD) array to detect the diffuse light energy to produce an array of light detections; and the controller is configured to perform constructing the histograms by constructing the histograms from the array of the light detections.
18. An apparatus comprising: a controller to select patterns for illumination; an optical transmitter including an individually addressable laser array (IALA) to produce illumination patterns responsive to the patterns, to illuminate a target; and an optical receiver including: a non-imaging lens to receive light energy of the illumination patterns that is reflected by the target, to produce non-imaged light energy; and a single-photon avalanche diode (SPAD) array to detect the non-imaged light energy across the SPAD array, to produce an array of light detections; wherein the controller is configured to: construct histograms of the array of the light detections; and reconstruct an image of the target using the histograms and the patterns.
19. The apparatus of claim 18, wherein the optical transmitter further includes a pixel shifter following the IALA to pixel-shift modulated light produced by the IALA, to produce the illumination patterns as pixel-shifted illumination patterns.
20. The apparatus of claim 19, wherein the controller is further configured to: combine the histograms into a cumulative histogram, wherein the controller is configured to reconstruct the image using the cumulative histogram.