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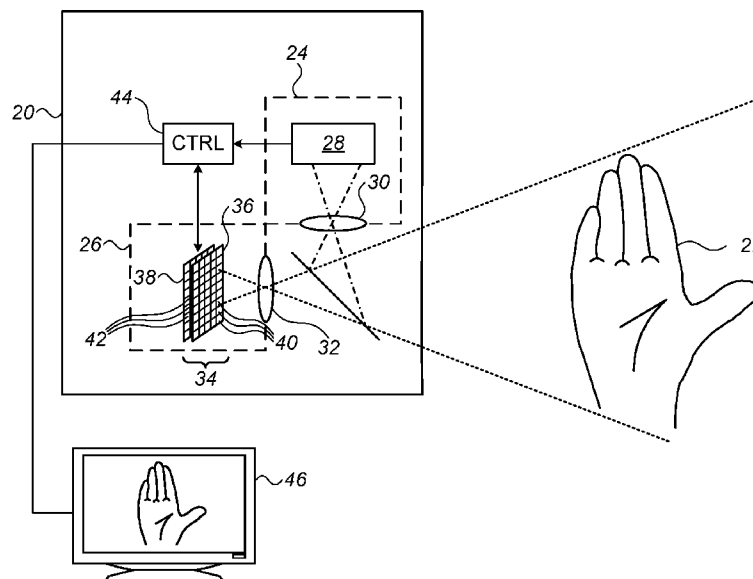
FIG. 1

(57) Abstract: Optical sensing apparatus (20) includes an array (28) of emitters (50), which emit pulses of optical radiation at different, respective times in response to a control input applied to the array. A receiver (26) includes a plurality of detectors (40), which output signals indicative of times of arrival of photons at the detectors. Optics (30, 32) project the optical radiation from the emitters onto respective locations in a scene and image the respective locations onto corresponding pixels of the receiver. A controller (44) controls the emitters to emit the output pulses in a predefined spatio-temporal sequence, and collects and processes the signals output by corresponding pixels in synchronization with the spatio-temporal sequence so as to measure respective times of flight of the pulses to and from the respective locations in the scene.

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TIME-OF-FLIGHT SENSING USING AN ADDRESSABLE ARRAY OF EMITTERS

FIELD OF THE INVENTION

The present invention relates generally to range sensing, and particularly to devices and methods for depth mapping based on time-of-flight measurement.

5   **BACKGROUND**

Time-of-flight (ToF) imaging techniques are used in many depth mapping systems (also referred to as 3D mapping or 3D imaging). In direct ToF techniques, a light source, such as a pulsed laser, directs pulses of optical radiation toward the scene that is to be mapped, and a high-speed detector senses the time of arrival of the radiation reflected from the scene. The depth value

10   at each pixel in the depth map is derived from the difference between the emission time of the outgoing pulse and the arrival time of the reflected radiation from the corresponding point in the scene, which is referred to as the "time of flight" of the optical pulses. The radiation pulses that are reflected back and received by the detector are also referred to as "echoes."

Single-photon avalanche diodes (SPADs), also known as Geiger-mode avalanche

15   photodiodes (GAPDs), are detectors capable of capturing individual photons with very high time-of-arrival resolution, on the order of a few tens of picoseconds. They may be fabricated in dedicated semiconductor processes or in standard CMOS technologies. Arrays of SPAD sensors, fabricated on a single chip, have been used experimentally in 3D imaging cameras. Charbon et al. provide a review of SPAD technologies in "SPAD-Based Sensors," published in *TOF Range-*

20   *Imaging Cameras* (Springer-Verlag, 2013).

SUMMARY

Embodiments of the present invention that are described hereinbelow provide improved apparatus and methods for direct ToF sensing.

There is therefore provided, in accordance with an embodiment of the invention, optical

25   sensing apparatus, including an array of emitters, which are configured to emit pulses of optical radiation at different, respective times in response to a control input applied to the array. A receiver includes a plurality of detectors, which are configured to output signals indicative of times of arrival of photons at the detectors. Optics are configured to project the optical radiation from the emitters onto respective locations in a scene and to image the respective locations onto

30   corresponding pixels of the receiver, each pixel including one or more of the detectors. A controller is coupled to control the emitters to emit the output pulses in a predefined spatio-

temporal sequence, and to collect and process the signals output by corresponding pixels in synchronization with the spatio-temporal sequence so as to measure respective times of flight of the pulses to and from the respective locations in the scene.

In a disclosed embodiment, the emitters include vertical-cavity surface-emitting lasers (VCSELs).

Additionally or alternatively, the detectors include single-photon sensors, and the receiver includes at least one time-to-digital converter (TDC), which outputs a digital value indicative of a delay between a pulse emitted by one of the emitters and receipt of a photon at a corresponding pixel of the receiver. In some embodiments, each of the emitters is driven to emit a series of the pulses in accordance with the predefined spatio-temporal sequence, and the controller is configured to accumulate, for each pixel, a respective histogram of digital values output by the at least one TDC in response to the series of the pulses, and to derive a respective time of flight from the histogram. In one embodiment, the controller is configured to modify the spatio-temporal sequence by varying a number of the pulses in the series of the pulses emitted by each of the emitters.

Further additionally or alternatively, both the emitters and the single-photon sensors are arranged in respective matrices including multiple rows and multiple columns, wherein the at least one TDC includes multiple TDCs with each TDC coupled to a different, respective row of the single-photon sensors, and the spatio-temporal sequence is defined so that at least first and second emitters, in different, respective rows of the array emit the pulses concurrently, while no more than a single emitter in each of the rows is operative at any given time.

In further embodiments, the spatio-temporal sequence is defined so that at least first and second emitters emit respective first and second pulses with an interval between the pulses that is less than half an average of the times of flight of the pulses to and from the respective locations in the scene. In a disclosed embodiment, the at least first and second emitters belong respectively to first and second groups of the emitters, such that the emitters in each of the groups are spaced apart over the array and emit the pulses simultaneously.

In some embodiments, the controller is configured, after measuring first times of flight in accordance with an initial spatio-temporal sequence, to modify the spatio-temporal sequence and measure second times of flight in accordance with the modified spatio-temporal sequence. In one embodiment, the spatio-temporal sequence is modified so as to measure the second times of flight with a resolution that is finer than the resolution of the first times of flight.

There is also provided, in accordance with an embodiment of the invention, a method for optical sensing, which includes emitting pulses of optical radiation from an array of emitters at different, respective times in a predefined spatio-temporal sequence. The optical radiation is projected from the emitters onto respective locations in a scene. The respective locations are imaged onto corresponding pixels of a receiver, which outputs signals indicative of times of arrival of photons at the corresponding pixels. The signals output by corresponding pixels are collected and processed in synchronization with the spatio-temporal sequence so as to measure respective times of flight of the pulses to and from the respective locations in the scene.

The present invention will be more fully understood from the following detailed description of the embodiments thereof, taken together with the drawings in which:

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic side view of a depth mapping device, in accordance with an embodiment of the invention;

Fig. 2 is a block diagram that schematically illustrates an integrated emitter array, in accordance with an embodiment of the invention;

Figs. 3A-C are schematic frontal views of an emitter array, showing successive stages in an emission sequence, in accordance with an embodiment of the invention;

Fig. 4 is a plot that schematically illustrates the timing of pulses in the emission sequence of Figs. 3A-C, in accordance with an embodiment of the invention; and

Figs. 5A and 5B are schematic representation of a scene that is mapped by a depth mapping device, illustrating different, respective operational modes of an emitter array in the device, in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

In direct ToF depth mapping systems that are known in the art, the data acquisition rate is limited by the distance to the target that is to be mapped: The light source emits a bright pulse of radiation, and the system then waits for a time no less than the time of flight of the photons to the target and back to the receiver before the next pulse can be fired. In other words, the system waits a fixed amount of time, which corresponds to the maximum working distance, i.e., the maximum distance to a target object that could be measured by the system. (If the pulse repetition period were to be less than the time of flight, the receiver might not be able to distinguish between the echoes of successive pulses, leading to problems of aliasing in the ToF measurements.) Considering that laser sources used in such systems typically have pulse widths less than 1 ns,

while time of flight (in air) grows at 6 ns per meter of distance to the target, the limitation on the pulse rate means that the light source operates at a very low duty cycle. Therefore, the light source may have to emit very intense pulses in order to achieve good resolution and signal/noise ratio with acceptable measurement throughput.

Embodiments of the present invention that are described herein address these limitations by using an array of emitters, which can be driven to emit pulses of optical radiation at different, respective times in response to a control input applied to the array. Arrays of this sort can be produced, for example, by integrating emitters with control circuits in a single chip. In one such embodiment, a III-V semiconductor substrate on which the emitters are fabricated is bonded to a silicon substrate on which control circuits for the emitters are fabricated. This structure makes it possible to address and fire the emitters in the array individually in substantially any desired spatio-temporal sequence.

In the disclosed embodiments, optics project the optical radiation from the emitters onto respective locations in a scene and image these locations onto corresponding pixels of a receiver. The receiver comprises an array of detectors, which output signals indicative of times of arrival of photons at the detectors. Each pixel comprises one or more of the detectors (i.e., each location in the scene onto which an emitter beam is projected can be imaged back onto a single detector or onto a group of neighboring detectors, whose output signals are then pooled into one pixel). Thus, each pixel detects the time of arrival of the photons transmitted from a particular, corresponding emitter in the array.

This arrangement makes it possible for a controller to control the emitters to emit their output pulses in a predefined spatio-temporal sequence, and to collect and process the signals output by the corresponding pixels in synchronization with the spatio-temporal sequence so as to measure respective times of flight of the pulses to and from the respective locations in the scene. The term "spatio-temporal sequence" refers to the spatial order in which the particular emitters fire their pulses and the intervals between the successive pulses, which may be fired by the same or different emitters.

Various spatio-temporal sequences may be defined in order to optimize performance and meet throughput and resolution requirements. For example, the spatio-temporal sequence may be defined such that multiple emitters, in different locations in the array, emit their pulses simultaneously. Additionally or alternatively, the sequence may be defined so that different emitters in different locations emit their respective pulses with an interval between the pulses that is substantially less than the expected time of flight based on the range of working distances at

which measurements are to be made. For example, the interval between pulses is typically less than half the average of the times of flight of the pulses to and from the respective locations in the scene. In both cases, there is little risk of aliasing, since the resulting echoes will be captured concurrently by different, respective pixels of the receiver. This arrangement is beneficial both in increasing the acquisition throughput of ToF data and increasing the overall duty cycle of the emitter array, and thus mitigating problems that otherwise arise due to emission of very bright pulses with high peak power.

Furthermore, the spatio-temporal sequence may be modified in the course of system operation in order to optimize ToF data acquisition. For example, the sequence may be chosen originally in order to acquire ToF data rapidly at coarse resolution, and then modified to acquire the ToF data at finer resolution, either over the entire field of view of the system or only within a certain reduced region of interest. "Resolution" in this context may mean either or both of transverse resolution, corresponding to the density of the pixels in the resulting depth map, and depth resolution, corresponding to the precision of the measured ToF values. (Depth resolution varies statistically as a function of the number of pulses emitted by a given emitter and sensed at the corresponding pixel in order to generate a ToF measurement for the respective location in the scene.) Alternatively or additionally, the spatio-temporal sequence may be switched over time in order to defeat possible interference due to other radiation sources in the vicinity.

Fig. 1 is a schematic side view of a depth mapping device 20, in accordance with an embodiment of the invention. In the pictured embodiment, device 20 is used to generate depth maps of a scene including an object 22, which in this example is a part of the body of a user of the device. To generate the depth map, an illumination assembly 24 directs pulses of light toward object 22, and a receiver 26 measures the ToF of the photons reflected from the object. (The term "light," as used in the present description and in the claims, refers to optical radiation, which may be in any of the visible, infrared, and ultraviolet ranges.)

Illumination assembly 24 typically comprises an array of emitters, such as a pulsed laser array 28. The lasers emit short pulses of light, with pulse duration in the nanosecond or sub-nanosecond range, and with on-board control that enables the individual lasers to be fired in a desired spatio-temporal sequence with sub-nanosecond precision. Array 28 may comprise, for example, an addressable VCSEL array. Collection optics 30 direct the light toward object 22. Alternatively, other pulse durations and repetition frequencies may be used, depending on application requirements.

Receiver 26 comprises objective optics 32, which image object 22 onto a sensing array 34, so that photons emitted by illumination assembly 24 and reflected from object 22 are incident on the sensing array. In the pictured embodiment, sensing array 34 comprises a sensor chip 36 and a processing chip 38, which are coupled together, for example, using chip stacking techniques that are known in the art. Sensor chip 36 comprises an array of high-speed single-photon detectors, arranged in a matrix of rows and columns.

In some embodiments, the photodetectors in sensor chip 36 comprise an array of SPADs 40, each of which outputs a signal indicative of the times of incidence of photons on the SPAD following emission of pulses by illumination assembly 24. Processing chip 38 comprises an array of processing circuits 42, which are coupled respectively to the sensing elements. Both of chips 36 and 38 may be produced from silicon wafers using well-known CMOS fabrication processes, based on SPAD sensor designs that are known in the art, along with accompanying drive circuits, logic and memory.

Alternatively, the designs and principles of detection that are described herein may be implemented, *mutatis mutandis*, using other circuits, materials and processes. For example, sensing array 34 may comprise an array of avalanche photodiodes with suitable supporting and processing circuits, as are known in the art. All such alternative implementations are considered to be within the scope of the present invention.

Receiver 26 outputs signals that are indicative of respective times of arrival of the photons received at each pixel (corresponding to a SPAD 40 or group of neighboring SPADs), or equivalently, from each location in the scene that is being mapped. These output signals are typically in the form of respective digital values of the times of arrival that are generated by processing circuits 42, although other signal formats, both digital and analog, are also possible. For example, in some embodiments, processing circuits 42 comprise one or more time-to-digital converters (TDCs), which output digital values indicative of the delays between pulses emitted by respective emitters in array 28 and receipt of a photon at a corresponding pixel of receiver 26. Circuits 42 may comprise a respective dedicated TDC for each pixel. Alternatively, for appropriate choices of the spatio-temporal pattern of pulse emission, the TDCs can be shared by multiple pixels, for example with a single TDC per row (or equivalently, per column) of the detector array.

A controller 44 reads out the individual pixel values and processes the times of arrival, in synchronization with the spatio-temporal sequence of emission by the corresponding emitters, in order to generate an output depth map, comprising the ToF measured at each pixel to and from the

respective locations in the scene, or equivalently, the measured depth value. In some embodiments, the spatio-temporal sequence is defined such that each of the emitters in array 28 is driven to emit a series of pulses, and sensing array 34 outputs a digital time-of-arrival value from the appropriate pixel in response to each emitted pulse. Controller 44 accumulates, for each pixel,

5   a respective histogram of the digital values output from the pixel in response to the series of the pulses, and derives the respective time of flight from the histogram, for example by taking the mode of the histogram. This histogram-based approach is useful in smoothing out the statistical variations and noise in photon arrival time, and the depth resolution typically increases with the number of pulses captured at each pixel. Controller 44 conveys the depth map to a receiving

10   device 46, such as a display or a computer or other processor, which segments and extracts high-level information from the depth map, but these features are beyond the scope of the present disclosure.

Although the present description relates to controller 44 and processing chip 38 as separate entities, with a certain division of functions between the controller and processing chip, in practice

15   these entities and their functions may be combined and implemented monolithically on the same integrated circuit. Alternatively, other divisions of functionality between these entities will also be apparent to those skilled in the art and are considered to be within the scope of the present invention. Therefore, in the present description and in the claims, the term "controller" should be understood as encompassing all implementations of the functionalities that are attributed to

20   controller 44 and processing chip 38, whether carried out in hardware logic or in software.

Fig. 2 is a block diagram that schematically illustrates integrated emitter array 28, in accordance with an embodiment of the invention. VCSELs 50 in array 28 are produced by epitaxial growth on a suitable III-V semiconductor substrate 52, such as a GaAs substrate. In a separate step, control circuits for the VCSELs are formed on a silicon substrate 54, using a CMOS

25   process, for example. III-V substrate 52 is then bonded to silicon substrate 54, with each VCSEL 50 in alignment with its respective control circuits. In the pictured embodiment, drive circuits 58 on substrate 54 include a driver for each VCSEL 50, with a separate anode and/or cathode connection to enable independent control of the VCSEL. An addressing circuit 56 triggers drive circuits 58 to fire the VCSELs in accordance with a predefined spatio-temporal sequence, which

30   is input to addressing circuit 56, for example, by controller 44.

Reference is now made to Figs. 3A-C and 4, which schematically illustrate features of a spatio-temporal sequence of emission from array 28, in accordance with an embodiment of the

invention. Figs. 3A-C are frontal views of emitter array 28, showing successive stages in the emission sequence, while Fig. 4 is a plot showing the timing of pulses in the emission sequence.

In the pictured sequence, emitters 50 are divided into groups, labeled 50a, 50b, …, 50j, …. The emitters in each group belong to different, respective rows of the array and are spaced apart along a given column. The emitters in each group emit their respective pulses concurrently, with no more than a single emitter in each of the rows operative at any given time. The three groups that are shown in each of Figs. 3A-C (for example, emitters 50a, emitters 50b and emitters 50c in Fig. 3A) are also spaced apart over array 28. In the pictured sequence, for example, the emitters in each of these groups are located in different rows and in columns that are widely separated. Thus, the respective pixels of sensing array 34 that will receive the reflected photons from these emitters are also widely spaced within each group and among the different groups.

As a result of this spatial distribution, emitters 50a, 50b and 50c (and similarly the emitter groups in Figs. 3B and 3C) can be driven to emit their respective pulses with an interval between the pulses that is substantially shorter than the times of flight of the pulses to and from the respective locations in the scene being mapped by device 20. The wide spacing of the emitters within and between the groups ensures that there will not be significant crosstalk between the pixels, and thus no significant aliasing on this account. For example, the interval between the pulses emitted from the different groups may be less than half the average time of flight, or even substantially less, as shown in Fig. 4. The wide spacing of the emitters is also useful in spreading the emitted power from array 28 widely over the scene being mapped, rather than focusing in a single location at any given time.

Fig. 4 shows an example of this sort of temporal scheme, with a train 62 of optical pulses 60a, 60b and 60c emitted periodically by the groups of emitters 50a, 50b and 50c, respectively. Pulses 60a, 60b, 60c typically have respective pulse widths of 1 ns or less, and the interval between the pulses in each train 62 is likewise on the order of 1 ns. Pulse train 62 is repeated with a period T, which is chosen to be greater than the expected time of flight to and from locations in the scene being mapped, for example 10 ns for nearby targets. The tight spacing of the pulses emitted by the different groups of emitters is useful in increasing the duty cycle and reducing the peak emission power of array 28, as well as increasing the measurement throughput of device 20. Alternatively, other pulse widths and repetition periods may be used, depending on application requirements and choice of components.

Pulse train 62 is typically repeated multiple times for emitters 50a, 50b and 50c, in order to enable controller 44 to build a suitable histogram of photon arrival times at each pixel in these

groups. By virtue of the choice of emitters in these groups, with each group drawn from a separate set of rows of laser array 28, the histograms can be accumulated using a single, respective TDC serving each row of sensor array 34. To identify possible aliasing due to distant objects, the repetition period T may be dithered, in which case aliased histogram peaks (due to distant reflections from a previous pulse train) will be dithered, as well, and can be eliminated from the depth map on this basis.

After applying the desired series of pulse trains 62 to the groups of emitters 50a, 50b and 50c, a similar series of pulse trains is applied to emitters 50d, 50e, and 50f, and then to emitters 50g, 50h and 50j, and so forth until the entire array 28 has been covered. Alternatively, in some embodiments (as illustrated below in Figs. 5A/B, for example), the spatio-temporal sequence may use only a subset of emitters 50 in array 28. Further alternatively, other spatial groupings and temporal sequences may be applied, as long as the separation between the groups in space and time is sufficient to avoid significant crosstalk between different pixels.

Although Figs. 3A-C show an orderly rolling sequence of emission groups, other sorts of spatial patterns, including patterns that are irregular in spatial and/or temporal distribution, may be applied to array 28. Such irregular patterns (possibly including pseudo-random patterns) are useful in avoiding crosstalk and interference due to other depth mapping devices and other radiation sources in the vicinity of device 20.

In some embodiments, SPADs 40 in sensing array 34 are actuated in synchronization with the spatio-temporal sequence of firing emitters 50 in array 28. In other words, each SPAD is actuated only when the corresponding emitter is operative, and is effectively dormant otherwise. This mode of operation is useful in reducing noise in the ToF measurements. When applied in conjunction with the sort of spatio-temporal sequence that is illustrated in Figs. 3A-C, the areas of active pixels and their acquisition triggers will roll smoothly across sensing array 34, thus facilitating efficient, low-noise acquisition of ToF values.

Figs. 5A and 5B are schematic representation of a scene 70 that is mapped by device 20, illustrating different, respective operational modes of the device, in accordance with an embodiment of the invention. Fig. 5A illustrates an initial spatio-temporal sequence, in which only a subset of emitters 50 are actuated (for example, half of the emitters, as illustrated by the respective locations 72 in scene 70 that are illuminated by the emitters). Using this spatio-temporal sequence, controller 44 acquires an initial depth map of the scene with coarse transverse resolution, but with faster throughput than would be achieved if all of the emitters were to be used. Additionally or alternatively, the initial spatio-temporal sequence may include only a relatively

small number of pulses emitted by each of the emitters, so that the depth resolution of the initial depth map is also relatively coarse.

After measuring the times of flight in accordance with the initial spatio-temporal sequence, controller 44 proceeds to re-measure the times of flight in accordance with a modified spatio-temporal sequence, as illustrated in Fig. 5B. Here, for example, a processor analyzing the initial depth map may have recognized an object of interest in scene 70, and therefore instructs controller 44 to acquire times of flight with finer resolution over a limited area 74 within the scene that contains the object of interest. All of emitters 50 that emit beams within area 74 are thus actuated, enabling device 20 to acquire ToF values at respective, densely-spaced locations 76, while the emitters outside this area are not used. Additionally or alternatively, the modified spatio-temporal sequence may include a larger number of pulses by each of the emitters illuminating area 74. By reducing the effective field of view to area 74, device 20 is able to generate a local depth map with finer resolution in the transvers and/or depth dimension, while maintaining high throughput.

In the modified spatio-temporal sequence illustrated in Fig. 5B, emitters 50 outside area 74 are not actuated in order to avoid wasting the resources of device 20 (such as the output power from array 28) on areas of scene 70 that are not of interest. This sort of conservation of resources can be further enhanced by deactivating emitters 50 even within area 74 if they are not able to give usable ToF values. For example, controller 74 may deactivate the emitter (or emitters) irradiating a bright spot 78 in scene 70 upon determining that sensing array 34 is unable to provide usable ToF values in this area due to saturation.

Thus, generally speaking, the parameters of the spatio-temporal sequence, including the choice of emitters and number of pulses applied by each emitter, may be selected and modified in order to give the optimal tradeoff between field of view, resolution and throughput. Although the embodiments described above refer, for the sake of concreteness and clarity, to a specific sort of device architecture that is capable of implementing this approach, the principles of the present invention may similarly be applied using other controllable emitter and sensor arrays, as will be apparent to those skilled in the art after reading the above disclosure. All such alternative implementations are considered to be within the scope of the present invention.

It will thus be appreciated that the embodiments described above are cited by way of example, and that the present invention is not limited to what has been particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and subcombinations of the various features described hereinabove, as well as variations and

modifications thereof which would occur to persons skilled in the art upon reading the foregoing description and which are not disclosed in the prior art.

CLAIMS

1.   Optical sensing apparatus, comprising:

an array of emitters, which are configured to emit pulses of optical radiation at different, respective times in response to a control input applied to the array;

a receiver, comprising a plurality of detectors, which are configured to output signals indicative of times of arrival of photons at the detectors;

optics, which are configured to project the optical radiation from the emitters onto respective locations in a scene and to image the respective locations onto corresponding pixels of the receiver, each pixel comprising one or more of the detectors; and

a controller, which is coupled to control the emitters to emit the output pulses in a predefined spatio-temporal sequence, and to collect and process the signals output by corresponding pixels in synchronization with the spatio-temporal sequence so as to measure respective times of flight of the pulses to and from the respective locations in the scene.

2.   The apparatus according to claim 1, wherein the emitters comprise vertical-cavity surface-emitting lasers (VCSELs).

3.   The apparatus according to claim 1, wherein the detectors comprise single-photon sensors, and the receiver comprises at least one time-to-digital converter (TDC), which outputs a digital value indicative of a delay between a pulse emitted by one of the emitters and receipt of a photon at a corresponding pixel of the receiver.

4.   The apparatus according to claim 3, wherein in accordance with the predefined spatio-temporal sequence, each of the emitters is driven to emit a series of the pulses, and wherein the controller is configured to accumulate, for each pixel, a respective histogram of digital values output by the at least one TDC in response to the series of the pulses, and to derive a respective time of flight from the histogram.

5.   The apparatus according to claim 4, wherein the controller is configured to modify the spatio-temporal sequence by varying a number of the pulses in the series of the pulses emitted by each of the emitters.

6.   The apparatus according to claim 3, wherein both the emitters and the single-photon sensors are arranged in respective matrices comprising multiple rows and multiple columns, wherein the at least one TDC comprises multiple TDCs with each TDC coupled to a different, respective row of the single-photon sensors, and

wherein the spatio-temporal sequence is defined so that at least first and second emitters, in different, respective rows of the array emit the pulses concurrently, while no more than a single emitter in each of the rows is operative at any given time.

7.   The apparatus according to any of claims 1-6, wherein the spatio-temporal sequence is defined so that at least first and second emitters emit respective first and second pulses with an interval between the pulses that is less than half an average of the times of flight of the pulses to and from the respective locations in the scene.

8.   The apparatus according to claim 7, wherein the at least first and second emitters belong respectively to first and second groups of the emitters, such that the emitters in each of the groups are spaced apart over the array and emit the pulses simultaneously.

9.   The apparatus according to any of claims 1-6, wherein the controller is configured, after measuring first times of flight in accordance with an initial spatio-temporal sequence, to modify the spatio-temporal sequence and measure second times of flight in accordance with the modified spatio-temporal sequence.

10.   The apparatus according to claim 9, wherein the spatio-temporal sequence is modified so as to measure the second times of flight with a resolution that is finer than the resolution of the first times of flight.

11.   A method for optical sensing, comprising:

emitting pulses of optical radiation from an array of emitters at different, respective times in a predefined spatio-temporal sequence;

projecting the optical radiation from the emitters onto respective locations in a scene;

imaging the respective locations onto corresponding pixels of a receiver;

outputting signals from the receiver indicative of times of arrival of photons at the corresponding pixels; and

collecting and processing the signals output by corresponding pixels in synchronization with the spatio-temporal sequence so as to measure respective times of flight of the pulses to and from the respective locations in the scene.

12.   The method according to claim 11, wherein the emitters comprise vertical-cavity surface-emitting lasers (VCSELs), and wherein the pulses have a duration that is less than 1 ns.

13.   The method according to claim 11, wherein the receiver comprises a matrix of single-photon sensors, and wherein outputting the signals comprises outputting a digital value indicative

of a delay between a pulse emitted by one of the emitters and receipt of a photon at a corresponding pixel of the receiver.

14.   The method according to claim 13, wherein in accordance with the predefined spatio-temporal sequence, each of the emitters is driven to emit a series of the pulses, and wherein collecting and processing the signals comprises accumulating, for each pixel, a respective histogram of digital values indicative of the delay in response to the series of the pulses, and deriving a respective time of flight from the histogram.

15.   The method according to claim 14, and comprising modifying the spatio-temporal sequence by varying a number of the pulses in the series of the pulses emitted by each of the emitters.

16.   The method according to claim 13, wherein both the emitters and the single-photon sensors are arranged in respective matrices comprising multiple rows and multiple columns, and wherein outputting the digital value comprises coupling a respective time-to-digital converter (TDC) to read out the digital value from each row of the single-photon sensors, and

    wherein the spatio-temporal sequence is defined so that at least first and second emitters, in different, respective rows of the array emit the pulses concurrently, while no more than a single emitter in each of the rows is operative at any given time.

17.   The method according to any of claims 11-16, wherein the spatio-temporal sequence is defined so that at least first and second emitters emit respective first and second pulses with an interval between the pulses that is less than half an average of the times of flight of the pulses to and from the respective locations in the scene.

18.   The method according to claim 17, wherein the at least first and second emitters belong respectively to first and second groups of the emitters, such that the emitters in each of the groups are spaced apart over the array and emit the pulses simultaneously.

19.   The method according to any of claims 11-16, and comprising, after measuring first times of flight in accordance with an initial spatio-temporal sequence, modifying the spatio-temporal sequence and measuring second times of flight in accordance with the modified spatio-temporal sequence.

20.   The method according to claim 19, wherein the spatio-temporal sequence is modified so as to measure the second times of flight with a resolution that is finer than the resolution of the first times of flight.
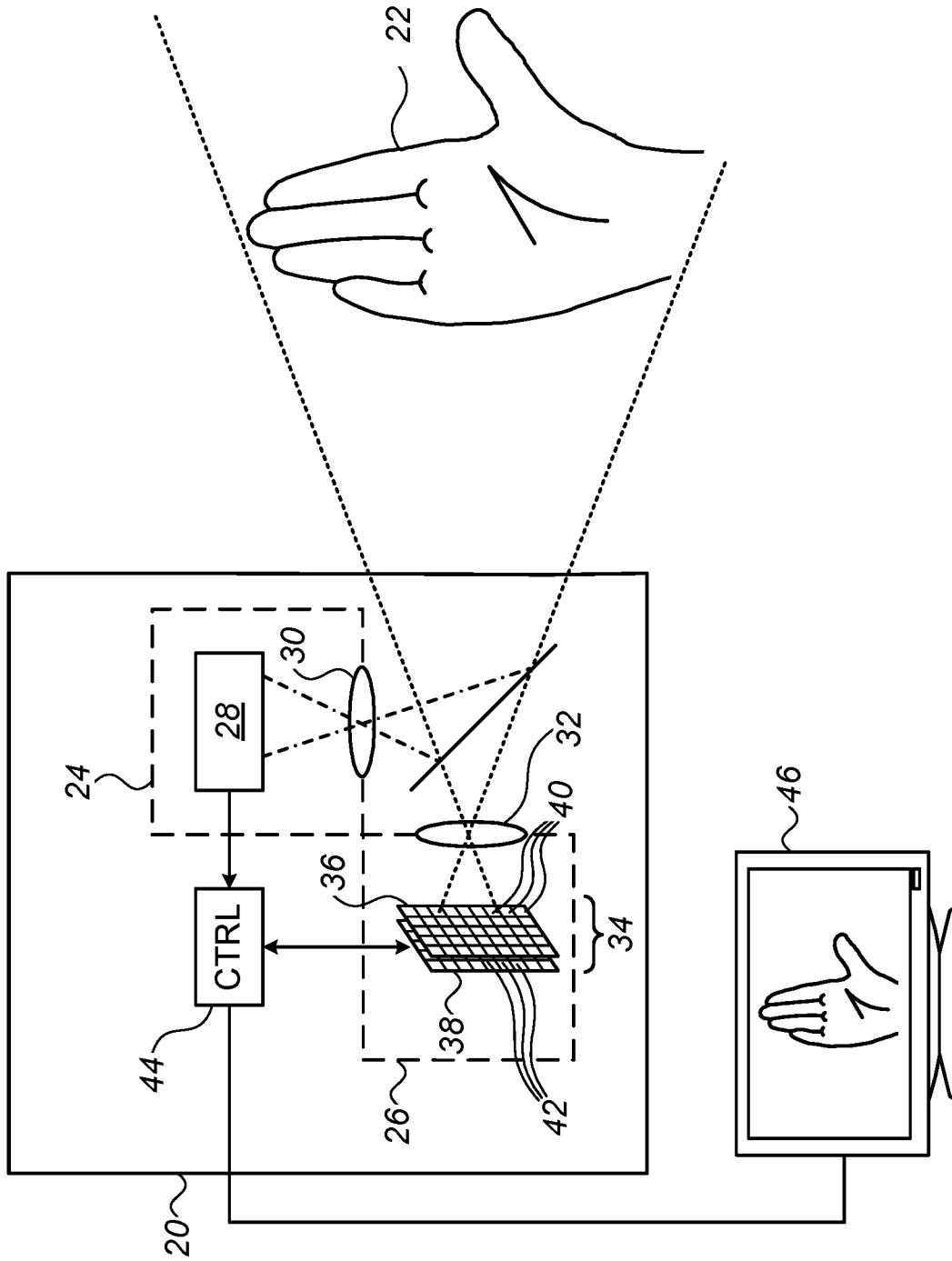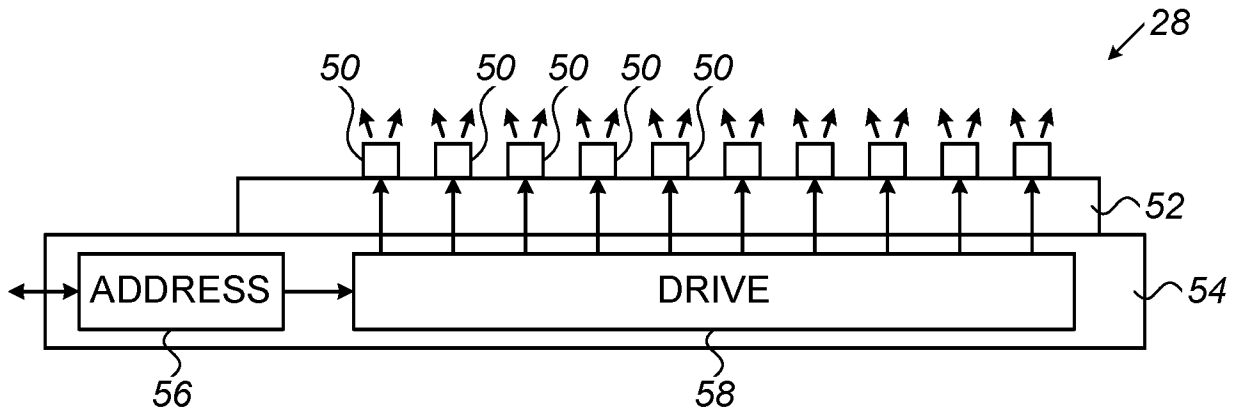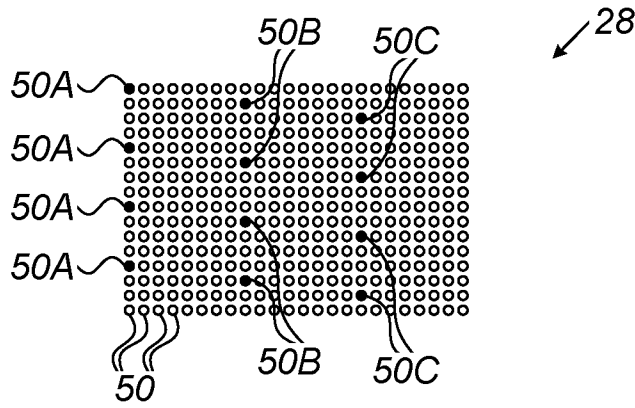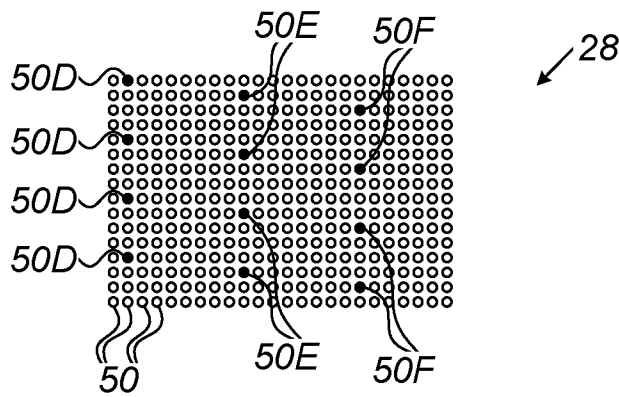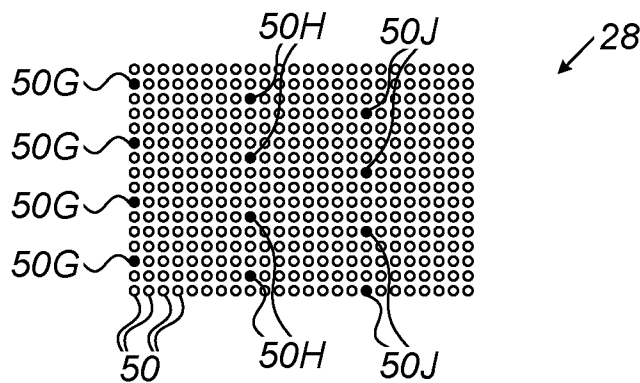
FIG. 1

FIG. 2

FIG. 3A

FIG. 3B

FIG. 3C
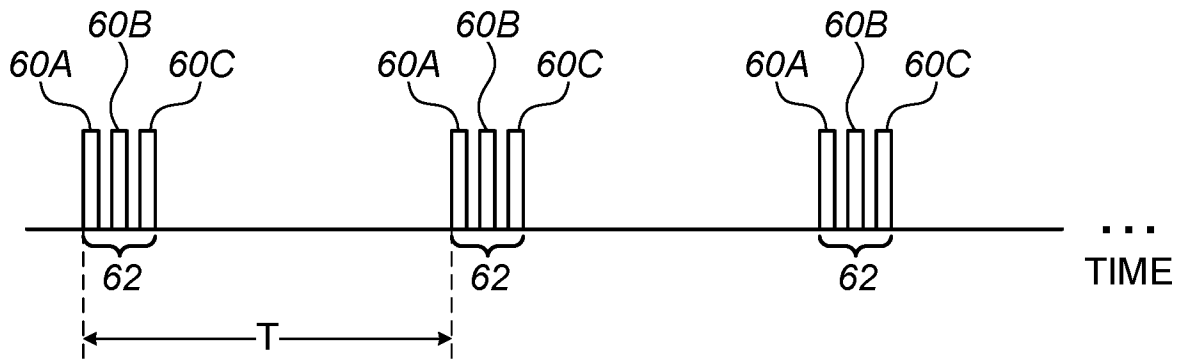
FIG. 4
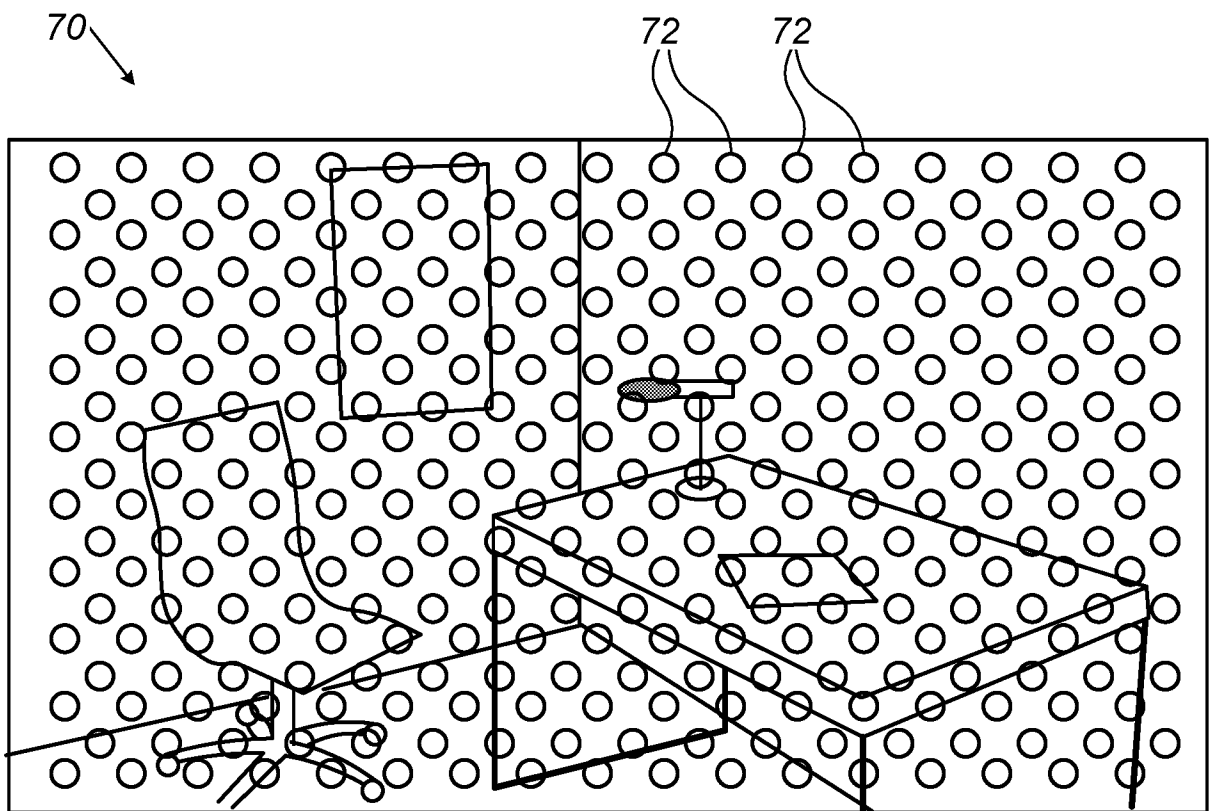
FIG. 5A
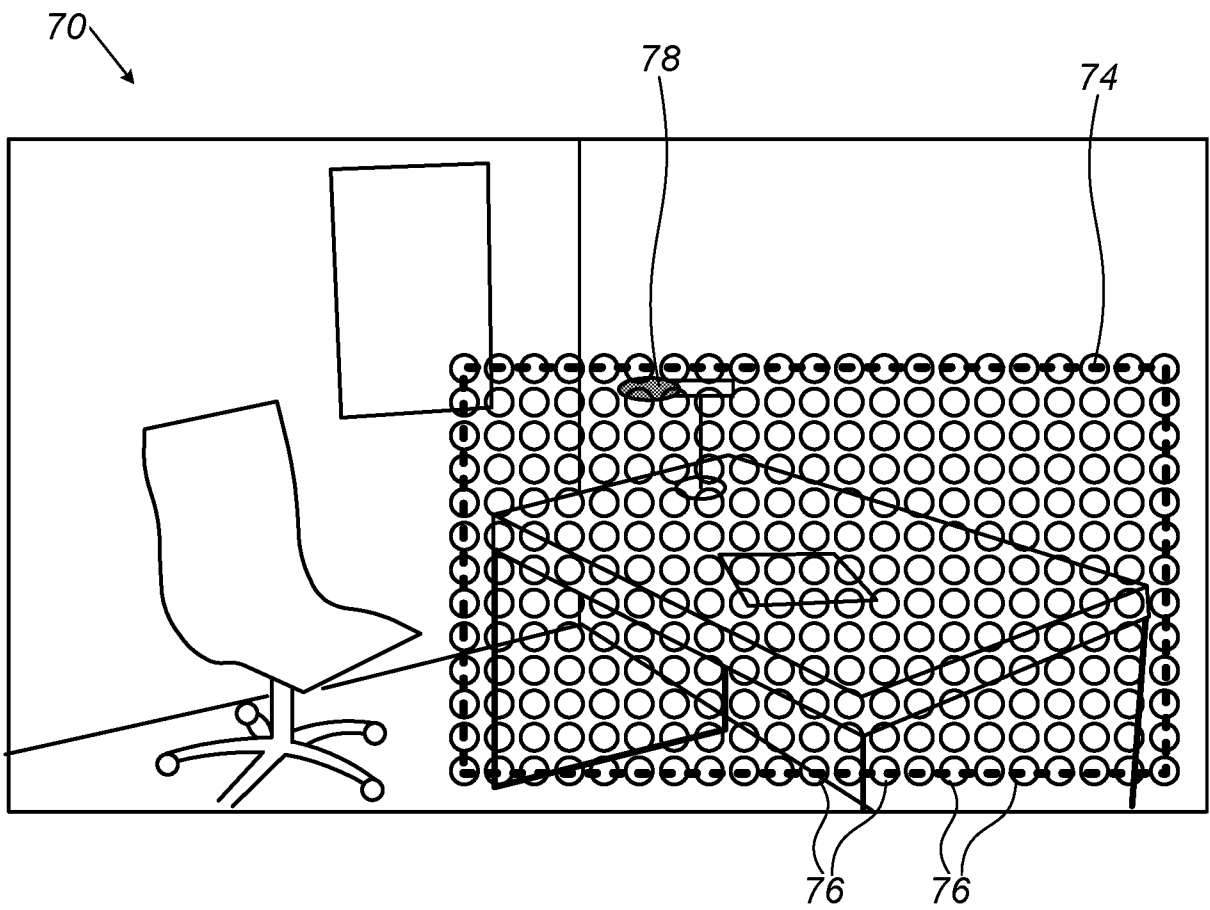
FIG. 5B

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01S17/10   G01S17/89   G01S7/481   G01S7/484
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/131080 A1 (RETTERATH JAMIE E [US] ET AL) 14 May 2015 (2015-05-14) abstract; figures 3,12 paragraphs [0046] - [0049], [0075], [0079] - [0081] -----	1-4,6, 11-14,16
X	US 2017/219695 A1 (HALL DAVID S [US] ET AL) 3 August 2017 (2017-08-03) abstract; figure 3 paragraphs [0022], [0046], [0059] -----	1,5,6, 11,15,16
X	EP 2 827 175 A2 (PRINCETON OPTRONICS INC [US]) 21 January 2015 (2015-01-21) abstract; figures 4,7,10 paragraphs [0047], [0049] - [0050], [0084] -----	1,2, 9-12,19, 20

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 September 2018	27/09/2018

Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Lupo, Emanuela

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Form PCT/ISA/210 (second sheet) (April 2005)

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			US	2015260830 A1	17-09-2015