

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization

International Bureau



(10) International Publication Number

WO 2016/025908 A2

(43) International Publication Date
18 February 2016 (18.02.2016)

WIPO | PCT

(51) International Patent Classification:
G01S 7/484 (2006.01) *G01S 17/10* (2006.01)

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(21) International Application Number:
PCT/US2015/045399

(22) International Filing Date:
14 August 2015 (14.08.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/038,065 15 August 2014 (15.08.2014) US

(71) Applicant: US LADAR, INC. [US/US]; 115 West Washington Street, Belleville, Illinois 62220 (US).

(72) Inventor: DUSSAN, Luis Carlos; 5339 Hazel Tine Lane, Dublin, California 94568 (US).

(74) Agents: VOLK, JR., Benjamin L. et al.; One US Bank Plaza, St. Louis, Missouri 63101 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished upon receipt of that report (Rule 48.2(g))

(54) Title: METHODS AND SYSTEMS FOR LADAR TRANSMISSION

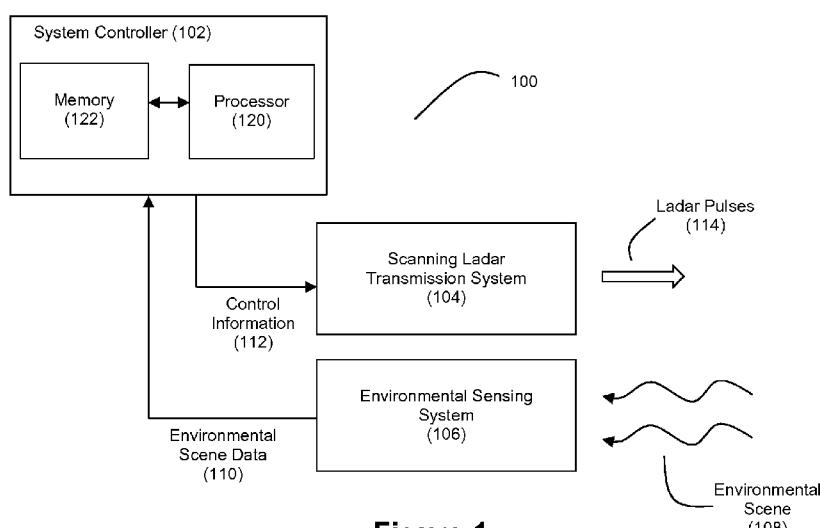


Figure 1

(57) Abstract: Various embodiments are disclosed for improved ladar transmission, including but not limited to example embodiments where closed loop feedback control is used to finely control mirror scan positions, example embodiments where range point down selection is used to improve scanning, and others.

WO 2016/025908 A2

Methods and Systems for Ladar Transmission**Cross-Reference and Priority Claim to Related Patent Applications:**

This patent application claims priority to U.S. provisional patent application serial no.

5 62/038,065, filed August 15, 2014, the entire disclosure of which is incorporated herein by reference.

Introduction:

It is believed that there are great needs in the art for improved computer vision

10 technology, particularly in an area such as automobile computer vision. However, these needs are not limited to the automobile computer vision market as the desire for improved computer vision technology is ubiquitous across a wide variety of fields, including but not limited to autonomous platform vision (e.g., autonomous vehicles for air, land (including underground), water (including underwater), and space, such as autonomous land-based vehicles, autonomous aerial vehicles, etc.), surveillance (e.g., border security, aerial drone monitoring, etc.), mapping (e.g., mapping of sub-surface tunnels, mapping via aerial drones, etc.), target recognition applications, remote sensing, safety alerting (e.g., for drivers), and the like).

15

As used herein, the term “ladar” refers to and encompasses any of laser radar, laser

20 detection and ranging, and light detection and ranging (“lidar”). Ladar is a technology widely used in connection with computer vision. In an exemplary ladar system, a transmitter that includes a laser source transmits a laser output such as a ladar pulse into a nearby environment. Then, a ladar receiver will receive a reflection of this laser output from an object in the nearby environment, and the ladar receiver will process the received reflection

25 to determine a distance to such an object (range information). Based on this range information, a clearer understanding of the environment’s geometry can be obtained by a host processor wishing to compute things such as path planning in obstacle avoidance scenarios, way point determination, etc. However, conventional ladar solutions for computer vision problems suffer from high cost, large size, large weight, and large power requirements as

30 well as large data bandwidth use. The best example of this being vehicle autonomy. These complicating factors have largely limited their effective use to costly applications that require only short ranges of vision, narrow fields-of-view and/or slow revisit rates.

For example, ladar systems are known in the art where a ladar transmitter illuminates a large number of range points simultaneously. Flash ladar is an example of such a system. However, these conventional systems are believed to suffer from a number of shortcomings. For example, flash ladar systems require a very high energy per pulse laser, which is not only 5 costly but can also be an eye hazard. Furthermore, the read-out integrated circuits for flash ladar systems are typically quite noisy. Also, the wide field-of-view signal-to-noise ratio (SNR) for flash ladar systems is typically very low, which results in short ranges, thereby detracting from their usefulness.

In an effort to satisfy the needs in the art for improved ladar-based computer vision 10 technology, disclosed herein are a number of embodiments for methods and systems that apply scanning ladar transmission concepts in new and innovative ways. Scanning ladar differs from flash ladar in that scanning ladar sequentially transmits ladar pulses to targeted range points as opposed to employing largely non-targeted flash illumination. While conventional scanning ladar solves many of the problems experienced in connection with 15 flash ladar, conventional scanning ladar systems typically suffer from bulkiness and frame rate limitations. In an effort to provide additional advancements in the art, disclosed herein are improved scanning ladar transmission techniques

For example, disclosed herein is a method comprising: (1) processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission 20 system, (2) controlling a dynamic scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions based on the processed shot list using closed loop feedback control of the mirror scan positions to target the range points of the processed shot list, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, and (3) transmitting, by the controlled scanning ladar 25 transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern..

In an example embodiment, the scan positions are scan angles for a movable mirror, whereby the movable mirror rotates around an axis to change its scan angle. However, it should be understood that the scan positions need not be limited to scan angles, and other 30 embodiments may scan the movable mirror in lateral and/or elevation directions to define where the system is targeted.

As another example embodiment, disclosed herein is a method comprising: (1) targeting a scanning ladar transmission system to a plurality of range points in accordance

with a dynamic scan pattern by (i) scanning a first mirror on a first axis based on a first voltage waveform, and (ii) scanning a second mirror on a second axis based on a second voltage waveform, wherein the second voltage waveform is a function of the targeted range points, (2) transmitting a plurality of ladar pulses to the targeted range points in accordance 5 with the dynamic scan pattern via the scanning mirror, and (3) adjusting at least one of the first and second voltage waveforms based on closed loop feedback control with respect to at least one of the scanning mirrors.

Further still, disclosed herein as another example embodiment is an apparatus comprising a scanning ladar transmission system, wherein the scanning ladar transmission 10 system comprises: (1) a beam scanner, the beam scanner including a mirror, wherein the beam scanner is configured to (i) scan the mirror to a plurality of mirror scan positions in response to a control signal, and (ii) direct a plurality of incoming ladar pulses onto the scanning mirror for transmitting the ladar pulses toward a plurality of range points, (2) a beam scanner controller, wherein the beam scanner controller is configured to generate the 15 control signal for the beam scanner such that the control signal defines a dynamic scan pattern for the scanning ladar transmission system with respect to the range points, and (3) a closed loop feedback system in operative communication with the beam scanner and the beam scanner controller, wherein the closed loop feedback control system is configured to (i) sense a plurality of actual mirror scan positions for the mirror and (ii) provide a feedback signal to the beam scanner controller indicative of the actual mirror scan positions for the 20 mirror, the feedback signal for use by the beam scanner controller to adjust the control signal in order to keep the transmitted ladar pulses on target toward the range points..

In accordance with yet another example embodiment, disclosed herein is an apparatus comprising: (1) a beam scanner, the beam scanner including a first scanable mirror and a 25 second scanable mirror, wherein the beam scanner is configured to (i) scan the first scanable mirror on a first axis to a plurality of mirror scan positions in response to a first voltage waveform, (ii) scan the second scanable mirror on a second axis to a plurality of mirror scan positions in response to a second voltage waveform, and (iii) direct a plurality of incoming ladar pulses toward a plurality of range points via reflections of the ladar pulses from the first 30 scanable mirror to the second scanable mirror an onward toward the range points, and (2) a beam scanner controller, wherein the beam scanner controller is configured to (i) generate the first and second voltage waveforms for the beam scanner such that the combination of the first and second voltage waveforms defines a dynamic scan pattern for the beam scanner with

respect to the range points, and (ii) adjust at least one of the first and second waveforms based on closed loop feedback control with respect to at least one of the first and second scanable mirrors.

With respect to another example embodiment, described herein is a method comprising: (1) receiving frame data representative of an environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area, (2) performing corner detection on the frame data to identify a corner feature within the environmental scene, and (3) selecting a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning ladar transmission system, wherein the subset includes a plurality of points corresponding to the identified corner feature within the environmental scene, and wherein the method steps are performed by a processor.

Also described herein as an example embodiment is an apparatus comprising a processor configured to (1) receive frame data representative of an environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area, (2) perform corner detection on the frame data to identify a corner feature within the environmental scene, and (3) select a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning ladar transmission system, wherein the subset includes a plurality of points corresponding to the identified corner feature within the environmental scene.

As still another example embodiment, disclosed herein is a method comprising: (1) receiving frame data representative of an environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area, (2) identifying a plurality of frame data segments corresponding to different segments of the environmental scene, (3) analyzing each of a plurality of the identified frame data segments separately to identify high contrast areas within such frame data segments, and (4) selecting a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning ladar transmission system, wherein the subset includes a relatively higher concentration of range points within an area of the environmental scene corresponding to identified high contrast areas than within another area of the environmental scene, and wherein the method steps are performed by a processor.

Further still, as another example embodiment, disclosed herein is an apparatus comprising a processor configured to (1) receive frame data representative of an

environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area, (2) identify a plurality of frame data segments corresponding to different segments of the environmental scene, (3) analyze each of a plurality of the identified frame data segments separately to identify high 5 contrast areas within such frame data segments, and (4) select a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning ladar transmission system, wherein the subset includes a relatively higher concentration of range points within an area of the environmental scene corresponding to identified high contrast areas than within another area of the environmental scene.

10 With respect to yet another example embodiment, described herein is a method comprising (1) generating a point cloud via ladar, the point cloud being representative of an environmental scene and comprising a plurality of range points, and (2) compressing the point cloud by (i) processing data representative of the environmental scene, and (ii) based on the processing, selecting a plurality of the range points in the point cloud for retention in a 15 compressed point cloud, the compressed point cloud comprising fewer range points than the generated point cloud, and wherein the compressing step is performed by a processor. In example embodiments, the point cloud can be generated via scanning ladar or via flash ladar.

Also disclosed as an example embodiment is an apparatus comprising: (1) a ladar system, the ladar system configured to generate a point cloud via ladar, the point cloud being 20 representative of an environmental scene and comprising a plurality of range points, and (2) a processor, the processor configured to compress the point cloud by (i) processing data representative of the environmental scene, and (ii) based on the processing, selecting a plurality of the range points in the point cloud for retention in a compressed point cloud, the compressed point cloud comprising fewer range points than the generated point cloud.

25 As another example, disclosed herein is a method comprising: (1) processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system, wherein the scanning ladar transmission system comprises (i) a first mirror that is scanable with respect to a first axis, and (ii) a second mirror that is scanable with respect to second axis that is orthogonal to the first axis, wherein the second mirror 30 comprises a spinning polygon mirror, (2) controlling a dynamic scan pattern for the scanning ladar transmission system by scanning a first mirror and the spinning polygon mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list, wherein the combination of the mirror scan positions for the first

mirror and spinning polygon mirror define the range points to which the scanning ladar transmission system is targeted, and (3) transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern.

5 In accordance with another example embodiment, disclosed herein is an apparatus comprising a scanning ladar transmission system configured to direct a plurality of ladar pulses toward a plurality of range points via a plurality of scanable mirrors, wherein the scanning ladar transmission system comprises (1) a beam scanner, the beam scanner including a first mirror and a second mirror, wherein the first mirror comprises a spinning polygon mirror, wherein the beam scanner is configured to (i) scan the first mirror to a plurality of mirror scan positions in response to a first control signal to target the scanning ladar transmission system along a first axis, and (ii) scan the second mirror to a plurality of mirror scan positions in response to a second control signal to target the scanning ladar transmission system along a second axis, and wherein the combination of the mirror scan 10 positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted, and (2) a beam scanner controller, wherein the beam scanner controller is configured to generate the first and second control signals for use by the beam scanner such that the first and second control signals define a dynamic scan pattern for the scanning ladar transmission system with respect to the range points.

15

20 As another example, disclosed herein is a method comprising: (1) processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system, (2) controlling a dynamic scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list, wherein the mirror 25 scan positions define where the scanning ladar transmission system is targeted, wherein the dynamic scan pattern includes at least one member of the group consisting of interline skipping and interline detouring, and (3) transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern.

30 Also disclosed as an example embodiment is a method comprising translating by a processor a range point list for ladar scanner targeting into a shot list for ladar scanner targeting in a manner whereby the shot list supports a dynamic scan pattern which includes at least one member of the group consisting of interline skipping and interline detouring,

wherein the range point list comprises a plurality of range points, and wherein the shot list comprises a plurality of ordered range points from the range point list.

Further still, disclosed herein as another example embodiment is an apparatus comprising a scanning ladar transmission system configured to transmit a plurality of ladar pulses toward a plurality of range points in accordance with a dynamic scan pattern that includes at least one member of the group consisting of interline skipping and interline detouring.

In an example embodiment, such an apparatus may further comprise (1) a processor configured to process a plurality of range points to create an ordered set of range points, each range point having an associated row identifier and an associated column identifier that together define a mirror scan position, the ordered set serving as a shot list for the scanning ladar transmission system, wherein the processor, as part of the processing operation, is further configured to: (i) determine, based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to scan from a current row to another row, whether any interline skips are to be used by the scanning ladar transmission system to target the range points, (ii) sort the range points into the ordered set based on the interline skip determinations, and (iii) in response to a determination that an interline skip is to be used, tag the shot list with interline skip identifier within the ordered set at a location where the interline skip is to be performed, and (2) a beam scanner of the scanning ladar transmission system, the beam scanner comprising a mirror, the beam scanner configured to scan the mirror to a plurality of mirror scan positions in accordance with the shot list including any interline skip identifiers present therein to target the range points via the dynamic scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, and wherein the scanning ladar transmission system is further configured to transmit, via the scanning mirror, a plurality of ladar pulses toward the range points of the shot list in accordance with the dynamic scan pattern.

In another example embodiment, such an apparatus may further comprise (1) a processor configured to process a plurality of range points to create an ordered set of range points, each range point having an associated row identifier and an associated column identifier that together define a mirror scan position, the ordered set serving as a shot list for the scanning ladar transmission system, wherein the processor, as part of the processing operation, is further configured to: (i) determine, based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to (a) scan from a current

row to another row, (b) scan to a range point in the another row, and (c) return to the current row, whether any interline detours are to be used for the scanning ladar transmission system to target the range points, (ii) sort the range points into the ordered set based on the interline detour determinations, and (iii) in response to a determination that an interline detour is to be used, tag the shot list with interline detour identifier within the ordered set at a location where the interline detour is to be performed, and (2) a beam scanner of the scanning ladar transmission system, the beam scanner comprising a mirror, the beam scanner configured to scan the mirror to a plurality of mirror scan positions in accordance with the shot list including any interline detour identifiers present therein to target the range points via the dynamic scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, and wherein the scanning ladar transmission system is further configured to transmit, via the scanning mirror, a plurality of ladar pulses toward the range points of the shot list in accordance with the dynamic scan pattern.

As yet another example, disclosed herein is a method comprising: (1) processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system, (2) controlling a spiral dynamic scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list according to the spiral dynamic scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, and (3) transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the spiral dynamic scan pattern.

In an example embodiment, the scan positions are scan angles for a movable mirror, whereby the movable mirror rotates around an axis to change its scan angle. However, it should be understood that the scan positions need not be limited to scan angles, and other embodiments may scan the movable mirror in lateral and/or elevation directions to define where the system is targeted.

Also disclosed as an example embodiment is a method comprising translating by a processor a range point list for ladar scanner targeting into a shot list for ladar scanner targeting in a manner whereby the shot list supports a spiral dynamic scan pattern, wherein the range point list comprises a plurality of range points, and wherein the shot list comprises a plurality of ordered range points from the range point list.

With respect to still another example embodiment, disclosed herein is an apparatus comprising a scanning ladar transmission system configured to direct a plurality of ladar pulses toward a plurality of range points via a plurality of scanable mirrors, wherein the scanning ladar transmission system comprises: (1) a beam scanner, the beam scanner including a first mirror and a second mirror, wherein the beam scanner is configured to (i) scan the first mirror to a plurality of mirror scan positions in response to a first driving voltage to target the scanning ladar transmission system along a first axis, and (ii) scan the second mirror to a plurality of mirror scan positions in response to a second driving voltage to target the scanning ladar transmission system along a second axis, and wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted, and (2) a beam scanner controller, wherein the beam scanner controller is configured to generate the first and second driving voltages for use by the beam scanner such that the first and second driving voltages define a spiral dynamic scan pattern for the scanning ladar transmission system with respect to the range points.

As another example, disclosed herein is a method comprising: (1) processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system, (2) controlling a dynamic scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, wherein the dynamic scan pattern comprises a macro scan pattern and a base dynamic scan pattern embedded within the macro scan pattern, and (3) transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern.

In accordance with another example embodiment, disclosed herein is an apparatus comprising a scanning ladar transmission system configured to direct a plurality of ladar pulses toward a plurality of range points via a plurality of scanable mirrors, wherein the scanning ladar transmission system comprises: (1) a beam scanner, the beam scanner including a first mirror and a second mirror, wherein the beam scanner is configured to (i) scan the first mirror to a plurality of mirror scan positions in response to a first control signal to target the scanning ladar transmission system along a first axis, and (ii) scan the second mirror to a plurality of mirror scan positions in response to a second control signal to target

the scanning ladar transmission system along a second axis, and wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted, and (2) a beam scanner controller, wherein the beam scanner controller is configured to generate the first and second control signals for 5 use by the beam scanner such that the first and second control signals define a dynamic scan pattern for the scanning ladar transmission system with respect to the range points, the dynamic scan pattern comprises a macro scan pattern with and a base dynamic scan pattern embedded within the macro scan pattern.

As yet another example, disclosed herein is a method comprising: (1) controlling a 10 scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions to target a plurality of range points according to the scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, and (2) transmitting, by the controlled scanning ladar transmission system, a plurality of modulated ladar pulses toward the range points in accordance with the scan 15 pattern.

Also disclosed as an example embodiment is an apparatus comprising a scanning ladar transmission system comprising a mirror, the scanning ladar transmission system configured to (1) scan the mirror to a plurality of mirror scan positions to control a scan pattern for the scanning ladar transmission system and target a plurality of range points 20 according to the scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, and (2) transmit, via the scanned mirror, a plurality of modulated ladar pulses toward the range points in accordance with the scan pattern.

These and other features and advantages of the present invention will be described hereinafter to those having ordinary skill in the art.

25

Brief Description of the Drawings:

Figure 1 depicts an example system embodiment.

Figure 2A depicts an example process flow implemented by the system controller of Figure 1.

30 Figure 2B depicts an example environmental scene image that includes selected range points for ladar targeting.

Figure 2C depicts an example embodiment for a dynamic range point selection algorithm.

Figure 2D depicts an example embodiment for a fill point selection algorithm of an exemplary dynamic range point selection algorithm.

Figure 3 depicts an example embodiment for a scanning ladar transmission system.

Figures 4A-C depicts how positioning errors with respect to the scanning mirrors of a beam scanner can affect the useable scan area for ladar targeting.

Figure 5 depicts an example embodiment of a beam scanner in combination with closed feedback control of mirror scan positions.

Figures 6A-C depicts example embodiments for closed loop optical feedback systems for use to finely control mirror scan positions.

Figure 7A depicts an example embodiment for error correction in a closed loop feedback system.

Figures 7B and 7C depict example voltage waveforms that relate to controlling the mirror scan positions.

Figures 8A-F depicts examples of dynamic scan patterns that can be used by the scanning ladar transmission system.

Figure 9A depicts an example embodiment for converting a list of range points into a shot list for ladar targeting.

Figure 9B depicts another example embodiment for converting a list of range points into a shot list for ladar targeting.

Figure 9C-F depicts examples of range point list-to-shot list conversions.

Figure 10 depicts an example embodiment for a beam scanner controller.

Figures 11A-G depict example embodiments for beam scanners that employ at least one scanning mirror in combination with a spinning polygon mirror.

Figures 12A and B depict examples of laser pulse encoding patterns that can be used by the ladar transmitter.

Detailed Description:

Figure 1 illustrates a system 100 for dynamic scanning ladar transmission in accordance with an example embodiment. The system 100 includes a system controller 102 in communication with a scanning ladar transmission system 104 and an environmental sensing system 106. The environmental sensing system 106 can be configured to sense an environmental scene 108 and provide environmental scene data 110 to the system controller 102. Based on an analysis of the environmental scene data 110, the system controller 102 can

generate control information 112 for delivery to the scanning ladar transmission system 104. The scanning ladar transmission system, in turn, can transmit ladar pulses 114 in accordance with the control information 112 received from the system controller 102. As explained in further detail below, the scanning ladar transmission system 104 can employ closed loop 5 feedback control of the scan positions for the scanning ladar transmission system 104.

Although not shown, it should be understood that a ladar receiver can be used in combination with the ladar transmission system, wherein the ladar receiver receives reflections of the ladar pulses to support the determination of range information based on the transmitted ladar pulses.

10 The environmental sensing system 106 can include a sensor that senses data about a nearby environmental scene 108 to generate environmental scene data 110 for delivery to the system controller 102. An example of a suitable sensor includes a camera such as a CCD camera, thermal camera or the like. Another example of a suitable sensor can include another ladar system. The environmental scene data 110 can include frames of image data for the 15 environmental scene generated by a camera, and the environmental sensing system 106 can be configured to generate frames of the environmental scene on a rolling basis for delivery to the system controller 102. As another example, a sensor can be a global positioning system (GPS) receiver and/or Inertial Measurement Unit (IMU) or the like that is capable of determining the geographic position and direction of the environmental sensing system 106. 20 Based on the determined geographic location, a database that includes map information such as a street map and/or a terrain map can be accessed to obtain environmental scene data 110. As such, it should be understood that the environmental scene data 110 can take any of a number of forms, including still images, video images, maps, ladar data, and others such as any accompanying “high value target data” corresponding to high value locations within the 25 environmental scene data to be queried.

30 In an example embodiment, for an initial scan, the environmental sensing system can use a sensor such as a camera to generate the environmental scene data, but additional scans can employ, as the environmental scene data 110, 3D image data generated from the data received by a laser range receiver in response to the ladar pulses sent by the scanning ladar transmission system.

The system controller 102 can include a processor 120 and memory 122. The processor 120 and memory 122 can be configured to interact with each other such that the processor 120 executes instructions stored in memory 122. The processor 120 may be any

type processor with sufficient computational capabilities to implement the processing operations described herein. It should be understood that processor 120 may comprise multiple processors, optionally distributed via a network. The programming instructions for implementing the processing logic executed by the processor 120 may be resident on a non-transitory computer-readable storage medium (e.g., memory 122) for access and execution by the processor 120. It should also be understood that the memory 122 may comprise multiple memory devices, which may be multiple distributed memory devices and/or memory devices of different types, including but not limited to one or more hard drives, random access memories (RAMs), removable storage media such as flash drives, optical media, and the like, etc. The memory 122 may also store a plurality of data structures that reflect any information computed by the processor, such as lists of selected range points, shot lists, etc. as described below. A data structure may be a physical manifestation of information organized within a computing system. Examples of data structures may include data objects, files, records, tables, arrays, trees, and the like.

15 In operation, the processor 120 can process the environmental scene data 110 received from the environmental sensing system 106 to generate control information 112 that will govern the operation of the scanning ladar transmission system 104. This control information 112 may include targeting information that defines where the scanning ladar transmission system 104 will send its ladar pulses 114, examples of which are provided in the description 20 below.

25 The scanning ladar transmission system 104 is configured to controllably transmit ladar pulses 114 to desired targets based on the control information 112 received from the system controller 102. The scanning ladar transmission system 104 can be configured to scan to a desired target via one or more movable mirrors that can direct a ladar pulse to the desired target. Examples of scanning ladar transmission systems 104 are included in the description that follows.

System Controller 102 - Configuration and Operation:

Figure 2A depicts a general process flow for execution by processor 120 to generate 30 control instructions 112 (a shot list in this example) from input environmental scene data 110. The data 110 serves as a priori data about the environmental scene 108 that will be processed by the processor 120 at step 200. Based in this processing, the processor generates a list of range points for targeting with the scanning ladar transmission system 104 (step 202). This

list can be generated by selecting a subset of possible range points, where the selected range points then serves as a sparse array or point cloud that represents salient features of the environmental scene to be targeted by the scanning ladar transmission system 104. In an example where the a priori data 110 is an image, the sparse array that serves as the list of 5 selected range points can be a subset of the pixels in the a priori image data 110.

Next, at step 204, the processor 120 translates the list of range points generated by step 202 into a shot list for the scanning ladar transmission system 104. This shot list can serve as the control information 112 for the scanning ladar transmission system 104. While the list of range points generated at step 202 can be merely a list of selected range points for 10 targeting, the shot list serves as an ordered list of the selected range points for targeting by the scanning ladar transmission system, where the ordering takes into consideration the capabilities and limitations of the scanning ladar transmission system 104 as well as a desired scan pattern for the system operation. While the example of Figure 2A shows step 204 being performed by processor 120, it should be understood that step 204 could be performed by 15 other components in the system. For example, step 204 could be performed by a beam scanner controller 308 within the scanning ladar transmission system 104. As another example, processor 120 can be configured to perform a portion of step 204 while beam scanner controller 308 could be configured to perform the remaining portion of step 204. For an example embodiment where step 204 is performed by processor 120, then the control 20 information 112 can include the shot list. However, for an example embodiment where step 204 is performed by the beam scanner controller 308 within the scanning ladar transmission system 104, then the control information 112 can include the range point list from step 202.

Figure 2B depicts an example that shows the results of step 202 for a sample image of 25 an environmental scene. In this example, the environmental scene data 110 shows a road and nearby topographical scenery. The processor at step 202 can select a plurality of intelligent range points 210 and a plurality of fill range points 212 to be included in the range point list. As explained below, intelligent range points are range points that are found by the system to exhibit a high utility for the purposes of critically sampling a scene, while fill range points are range points that provide scaffolding for the detail of the intelligent range points. Together, 30 these points 210 and 212 can define the sparse array of range points. By reducing the size of the point array used to represent the environmental scene, it is believed that a scanning ladar transmission system can support higher frame rates because it will be able to scan an environmental scene more quickly due to the reduced point load on the scanning ladar

transmission system. It is further believed that the sparse array may also support improved range for the ladar system primarily because the laser could operate with a lower repetition rate, in which case the laser can exhibit a higher amount of energy per pulse (which would in turn translate into longer ranges supported by the system). It is expected that example 5 embodiments will be capable of ranging up to distances of around 2 km or even higher (e.g., around 10 km).

The intelligent range points 210 can be selected based on any of a number of criteria. For example, areas of high contrast can be deemed to be areas of interest for the system that should include a relatively high concentration of range points. Thus, step 202 can operate to 10 intelligently select a high concentration of range points in areas of high contrast based on an analysis of the image data 110. This is shown by the example of Figure 2B where the intelligent range points 210 are concentrated in relatively high contrast areas of the image such as the shoulder boundary for the road, the break between the road and non-road terrain, and the horizon boundary between the distant mountains and sky. Additional criteria that can 15 be used to identify salient range points are images areas that exhibit lines or corners. To flesh out other portions of the image 110, the processor 202 can define a fill pattern and select fill range points 212 based on the defined fill pattern. Furthermore, a practitioner may choose to employ additional stereoscopic 3D information or structure from motion algorithms to supplement the sparse array with additional range points.

20 An example process flow for the dynamic selection of intelligent range points and fill range points can be seen in Figures 2C and 2D. It should be understood that Figures 2C and 2D generally correspond to steps 200 and 202 from Figure 2A. With reference to Figure 2C, at step 220, the processor applies a pre-filtering process to the environmental scene data 110. For this example, the environmental scene data can be an image. The pre-filtering process 25 can be designed to suppress high frequency noise or other unwanted artifacts in the image. The pre-filtering process may also include an edge detection operation to identify areas of high contrast in the image 110. The processor can apply any of a plurality of selectable filter operations to perform step 220. The selection of appropriate filters can be controlled by a filter select parameter, where the filter select parameter can be included as a set of parameters 30 250 that are used to control the range point selection . Parameters 250 can be defined based on user input or a feedback algorithm that optimizes the parameters based on data from the environmental sensing system, other sensors (such as GPS, IMU), and/or a macro operation mode set by the user.

At step 222, the processor may identify super pixels for the image 110. In doing so, the processor is able to break the image 110 into natural or smaller segments. Parameters 250 that can be used at step 222 to control the identification of super pixels can include a size parameter and a threshold parameter. Any of a number of image segmentation algorithms 5 can be used in the performance of step 222, including but not limited to simple linear iterative clustering (SLIC) segmentation, QuickShift segmentation, TurboPixels segmentation, normalized cuts segmentation, and/or graph-based segmentation. Size and threshold parameters 250 can be used to control the nature of the segmentation at step 222. By breaking the image 110 into natural or smaller segments using super pixel segmentation 10 techniques, intelligent range points can then be identified as a result of processing each natural/smaller segment which is expected to enhance and improve range point selection and ultimately 3D scene interpretation and reconstruction.

Next, at step 224, the processor selects candidates for intelligent range points to be included in the list of range points. Thus, the output of step 226 represents the list of 15 intelligent range points that have been selected for ladar scanning. Step 224 can be performed on a segment-by-segment basis with respect to the super pixel segments found as a result of step 222. Any of a number of techniques can be used in the performance of step 224. For example, techniques that are effective to identify points corresponding to edges, and corners in an image can be employed. An example of an open source method that can be 20 employed in this regard is the use of the Harris Corner Detector open source algorithm included in the OpenCV library. However, it should be understood that other techniques and tools are available for implementing step 224, such as the Shi Tomasi algorithm , the Features from Accelerated Segment Test (FAST) algorithm, the Smallest Univalue Segment Assimilating Nucleus (SUSAN) algorithm, and other corner detection algorithms.

25 Parameters 250 that can be used at step 224 to control the initial selection of intelligent range points can include distance parameters, angle parameters, and density parameters. The distance parameters define different spacing parameters between types of points such as corner points. The distance parameter can be expressed in units of pixels. Spacing for the distance parameters may also be a function of range, in which case the distance parameters 30 may change as a function of previous image frames and previous range information. The angle parameters are used to make spacing a function of azimuth and/or elevation. For example, at larger angles, it may be better to reduce spacing between points. The density

parameters are other types of spacing parameters that can mostly be used as upper or lower limits for some distance values.

At step 226, the processor refines the list of selected intelligent range points from step 224 to make a final selection of intelligent range points. As part of this operation, step 226 5 can utilize a parameter 250 that defines a point budget for the list of range points. This point budget can identify a maximum number of range points for the list of range points. The value for the point budget parameter can be any of a number of values depending upon the desires of a practitioner. As an example, the point budget can be around 0.3% to around 3.0% of the number of pixels in the image data 110. However, it should be understood that other values 10 or metrics for expressing the point budget can be used.

In a simple example embodiment, step 226 can be configured to consider the point budget parameter 250 and operate to (1) select all intelligent range point candidates for inclusion in the final range point list if the number of intelligent range point candidates is less than the point budget or a defined portion thereof (in which case the remainder relative to the 15 point budget or point budget portion is allocated for fill range points), and (2) reduce the number of intelligent range points selected at step 224 so as to comply with the point budget or defined portion thereof.

In another example embodiment, step 226 can adjust and/or augment the intelligent range point candidates when selecting the intelligent range points for inclusion in the list. For 20 example, some intelligent range point candidates might be shifted up, down, left, or right by some distance depending on predictive algorithms that may be employed during refinement. As another example, in the case of edge points, one or more additional intelligent range points might be added on either side of an intelligent range point candidate corresponding to an edge in order to better define the edge. In the case of corner points one or more additional 25 points may surround the corner points. And still another example additional range points may surround points corresponding to moving objects such as pedestrians in the case of a vehicle application.

Still further, step 226 can also be configured to take into account the configuration of the scanning lidar transmission system 104 with respect to its dynamic scan pattern. As 30 explained below, the scanning lidar transmission system 104 can be configured to perform scans of range points using any of a number of dynamic scan patterns, where each dynamic scan pattern may exhibit different characteristics where performance can be improved by altering the selection of intelligent range points. For example, for a given type of scanner, it

may be better to step down on intelligent range point to the next row if doing so would avoid a line skip and the stepping down of the intelligent range point would be compliant with one of the density parameters that controls the upper limit on how many pixels away a point can shift without impacting its selection (that is, if the pixel slightly below the originally chosen 5 pixel candidate will perform just as well, then the adjustment can be made to improve scanning performance).

At step 228, the processor generates a set of fill range points that fill out the list of range points for ladar scanning. Figure 2D illustrates an example process flow for performing step 228. As shown in Figure 2C, the point budget parameter will help govern 10 the operation of step 228.

At step 230, the processor combines the list of intelligent range points from step 226 and the list of grid range points from step 228 to create the list of range points 240 to be used for ladar scanning. This list 240 generally corresponds to the output of step 202 from Figure 2A. Each range point on list 240 can be expressed in terms of a location information such as 15 a row and column number for the location of that point within image 110.

Figure 2D describes the operation of step 228 in greater detail. At step 260, the processor determines a desired spacing between fill range points. This determination is affected by the defined point budget. For example, if the point budget is X, and the operation of step 226 results in the selection of Y intelligent range points (where $Y < X$), the process 20 flow of Figure 2D will have a budget of $X - Y$ to work with when selecting fill range points. The value of $X - Y$, in turn, will influence the determined spacing between fill range points at step 260. Additional factors that can affect the operation of step 260 include the scan pattern dynamics (such as the minimal spacing permitted between consecutive shots).

At step 262, the processor chooses a fill pattern for the fill range points. Examples of 25 fill patterns that can be chosen at step 262 include square grid patterns, diamond grid patterns, and staggered grid patterns (in which case, there are multiple square grids, but each successive grid row has an offset from the previous grid column or row depending on which one corresponds to the fast axis). Fill pattern selection can choose an optimal fill pattern for the point spacing determined at step 260. The fill pattern selection may also take into 30 consideration environmental factors as determined from the image 110. For example, if the image is an overhead view of the ground, this fact might influence the selection of a particular fill pattern, while if the image is a horizon view that includes both the ground and the sky, this fact might influence the selection of a different fill pattern. The fill pattern may

also be translated and wrapped (effectively a 3D rotation in 2D) horizontally and/or vertically from frame to frame such that after N number of frames, all addressable pixels within the space of possible fill points will be chosen. Once the fill pattern has been chosen, step 262 is able to generate a list of candidate fill points based on the chosen fill pattern and the

5 determined point spacing.

Also, it should be understood that different fill patterns can be chosen for different segments of the image 110. As noted, at step 222, the processor identifies different image segments that the image 110 can be broken into. Thus, at step 262, different fill patterns can be applied to different segments of the image 110. For example, the fill pattern for an image

10 segment above the horizon may have a lower fill density than an image segment below the horizon.

At step 264, the processor loops through the candidate fill points. At step 266, a comparison is made between each candidate fill point and the selected intelligent range points from step 226. If there is a selected intelligent range point within a defined threshold

15 distance of the candidate fill point, then that candidate fill point can be eliminated (step 268). Otherwise, the candidate fill point is retained. The defined threshold distance for this comparison operation can be a parameter that is defined in response to user input or an AI algorithm. The looping started at step 264 terminates at step 268 after each candidate fill point has been considered for retention at step 266. Thus, upon completion of the Figure 2D

20 process flow, the processor has defined the list of fill range points for ladar scanning.

Figure 9F depicts an example range point list 240 that can be generated as a result of the operation of Figures 2C and 2D. In the example of Figure 9F, each selected range point is defined by a row number (left side) and a column number (right side). It should be understood that this list can be a simple raw list of range points. If desired, a practitioner can

25 further process the range point list to impose an order to the range points with respect to the dynamic scan pattern that will be employed by the scanning ladar transmission system 104. That is, each range point on the range point list can be placed in a sequence with the other range points on the list that will define the shot order of range points for the scanning ladar transmission system 104. As explained, this translation of a range point list to a shot list can

30 be performed at step 204 by the processor. As noted, the shot list defines an order for the range points to be shot by the scanning ladar transmitter system 104. Figures 9A-9F, discussed in greater detail below, depict examples of process flows that can be used for translating a range point list 240 into a shot list.

Figure 9F also shows an example shot list 950 generated from a range point list 240. In this example, the order is defined with a top down order where the range points that are higher on the shot list will be shot prior to the range points that are lower on the shot list (e.g., the range point at row (“Srow”) 104, column (“SCol”) 19 will be shot before the range point 5 at row (“Srow”) 104, column (“SCol”) 26, and so on). The leftmost and middle columns define the row number and column number, respectively, for a given range point on the shot list. The other columns in the shot list table provide additional control information for the scanning radar transmitter system 104, as explained below in connection with Figures 9A-F. The example shot list of Figure 9F also includes fill shots that are added at step 204 due to 10 factors such as a minimum spacing parameter for the transmission laser.

The example shot list of Figure 9F can serve as the control information 112 that is provided to the scanning radar transmission system 104 to govern its operation. While the example embodiments of Figures 2C and 9F describe an arrangement where the range points on the shot list are delivered to the scanning radar transmission system 104 as a batch, it 15 should be understood that the shots in the shot list could alternatively be communicated to the scanning radar transmission system on a rolling basis where each shot is passed to the scanning radar transmission system once it is identified. Thus, the shot list can be delivered to the scanning radar transmission system 104 and processed thereby in both a batch mode and a rolling mode.

20

Scanning Radar Transmission System 104:

Figure 3 depicts an example embodiment for a scanning radar transmission system 104. The system 104 can include a laser source 300 in optical alignment with laser optics 302, a beam scanner 304, and transmission optics 306. These components can be housed in a 25 packaging that provides a suitable shape footprint for use in a desired application. For example, for embodiments where the laser source 300 is a fiber laser or fiber-coupled laser, the laser optics 302, the beam scanner 304, and any receiver components can be housed together in a first packaging that does not include the laser source 300. The laser source 300 can be housed in a second packaging, and a fiber can be used to connect the first packaging 30 with the second packaging. Such an arrangement permits the first packaging to be smaller and more compact due to the absence of the laser source 300. Moreover, because the laser source 300 can be positioned remotely from the first packaging via the fiber connection, such

an arrangement provides a practitioner with greater flexibility regarding the footprint of the system.

Based on the control information 112, such as a shot list as generated at step 204 of Figure 2A, a beam scanner controller 308 can be configured to control the nature of scanning performed by the beam scanner 304 as well as control the firing of the laser source 300. A closed loop feedback system 310 is employed with respect to the beam scanner 304 and the beam scanner controller 308 so that the scan position of the beam scanner 304 can be finely controlled, as explained below.

The laser source 300 can be any of a number of laser types suitable for ladar pulse transmissions as described herein.

For example, the laser source 300 can be a pulsed fiber laser. The pulsed fiber laser can employ pulse durations of around 1-4 ns, and energy content of around 0.1-100 μ J/pulse. The repetition rate for the pulsed laser fiber can be in the kHz range (e.g., around 1-500 kHz). Furthermore, the pulsed fiber laser can employ single pulse schemes and/or multi-pulse schemes (see Figures 12A and 12B). However, it should be understood that other values for these laser characteristics could be used. For example, lower or higher energy pulses might be employed. As another example, the repetition rate could be higher, such as in the 10's of MHz range (although it is expected that such a high repetition rate would require the use of a relatively expensive laser source under current market pricing).

As another example, the laser source 300 can be a pulsed IR diode laser (with or without fiber coupling). The pulsed IR diode laser can employ pulse durations of around 1-4 ns, and energy content of around 0.01-10 μ J/pulse. The repetition rate for the pulsed IR diode fiber can be in the kHz or MHz range (e.g., around 1 kHz - 5 MHz). Furthermore, the pulsed IR diode laser can employ single pulse schemes and/or multi-pulse schemes (see Figures 12A and 12B).

The laser optics 302 can include a telescope that functions to collimate the laser beam produced by the laser source 300. Laser optics can be configured to provide a desired beam divergence and beam quality. As example, diode to mirror coupling optics, diode to fiber coupling optics, and fiber to mirror coupling optics can be employed depending upon the desires of a practitioner.

The beam scanner 304 is the component that provides the system 104 with scanning capabilities such that desired range points can be targeted with ladar pulses. The beam scanner receives an incoming ladar pulse from the laser source 300 (by way of laser optics

302) and directs this ladar pulse to a desired downrange location (such as a range point on the shot list) via reflections from movable mirrors. Mirror movement can be controlled by a driving voltage waveform 314 received from the beam scanner controller 308. Any of a number of configurations can be employed by the beam scanner 304. For example, the beam 5 scanner can include dual microelectromechanical systems (MEMS) mirrors, a MEMS mirror in combination with a spinning polygon mirror, or other arrangements. An example of suitable MEMS mirrors are single surface tip/tilt/piston MEMS mirrors. By way of further example, in an example dual MEMS mirror embodiment, a single surface tip MEMS mirror and a single surface tilt MEMS mirror can be used. However, it should be understood that 10 arrays of these MEMS mirrors could also be employed. Also, the dual MEMS mirrors can be operated at any of a number of frequencies. For example, if a first MEMS mirror is acting as a fast axis mirror and a second MEMS mirror is acting as a slow axis mirror, the ratio of resonant frequencies between the second and first MEMS mirrors can fall in a range of around 1:5 to around 1:9. However, a practitioner may choose to employ different ratios. As 15 another example of other arrangements, a miniature galvanometer mirror can be used as a fast-axis scanning mirror. As another example, an acousto-optic deflector mirror can be used as a slow-axis scanning mirror. Furthermore, for an example embodiment that employs the spiral dynamic scan pattern discussed below, the mirrors can be resonating galvanometer mirrors. Such alternative mirrors can be obtained from any of a number of sources such as 20 Electro-Optical Products Corporation of New York. As another example, a photonic beam steering device such as one available from Vescnt Photonics of Colorado can be used as a slow-axis scanning mirror. As still another example, a phased array device such as the one being developed by the DARPA SWEEPER program could be used in place of the fast axis and/or slow axis mirrors.

25 Also, in an example embodiment where the beam scanner 304 includes dual mirrors, the beam scanner 304 may include relay imaging optics between the first and second mirrors, which would permit that two fast axis mirrors be used (e.g., two small fast mirrors as opposed to one small fast mirror and one long slower mirror).

30 The transmission optics 306 are configured to transmit the ladar pulse as targeted by the beam scanner 304 to a desired location through an aperture. The transmission optics can have any of a number of configurations depending upon the desires of a practitioner. For example, the environmental sensing system 106 and the transmitter 104 can be combined optically into one path using a dichroic beam splitter as part of the transmission optics 306.

As another example, the transmission optics can include magnification optics (an example of which is shown in Figure 5). Further still, an alignment pickoff beam splitter can be included as part of the transmission optics 306.

5 *Beam Scanning Configuration and Control:*

The beam scanner controller 308 can provide one or more voltage waveforms 314 to the beam scanner 304 that will drive the mirrors of the beam scanner to a desired scan position (e.g., scan angle). Given the high oscillation rates of the movable mirrors within the beam scanner 304, a fine degree of control over the beam scanner's scan positions is 10 desirable. With respect to an example embodiment where a first mirror of the beam scanner 304 serves to rotate over a first axis at a relatively high speed (the "fast axis") while a second mirror of the beam scanner 304 serves to rotate over a second axis orthogonal to the first axis at a relatively slower speed (the "slow axis"), slight errors in mirror positioning when the ladar pulses are incident to the mirrors can cause significant degradation in system 15 performance.

Figures 4A-4C illustrate this phenomenon. Figure 4A depicts a desired scan area 400 for the beam scanner 304. However, as shown by Figure 4B, without fine slow-axis control (the Y-axis in this example), the useable scan area 402 shrinks relative to scan area 400 as the areas 404 are required for the Y axis mirror to settle down during rotation. Furthermore, this 20 settling time may increase as a function of the number of lines to be skipped in a dynamic scan pattern, although even with no line skipping, settlement time considerations still apply. Further still, as shown by Figure 4C, with respect to the fast axis (the X-axis in this example), phase shifts in the targeted range points 406 can occur that cause waviness and other artifacts in the scan area if fine control over the scan position of the fast axis mirror is not achieved.

25 As a solution to these problems, a closed loop feedback system 310 can be employed to provide fine control over the scan position of at least one mirror employed by the beam scanner 304. The beam scanner controller 308 can then use the feedback information from the closed loop feedback system to adjust at least one of the mirror driving waveforms 314 and thereby achieve finer control over mirror positioning. In a preferred embodiment, this 30 feedback control is employed with respect to both mirrors of the beam scanner 304.

Figure 5 depicts an example embodiment for a beam scanner 304 in combination with closed loop feedback. In this example, the beam scanner 304 includes dual MEMS mirrors. A Y-axis MEMS mirror 500 is positioned to receive an incident laser pulse from the laser

source 300 by way of laser optics 302. The X-axis MEMS mirror 500 will reflect this laser pulse to the Y-axis scanning MEMS mirror 502. It should be understood that this reflection can be a direct reflection or an indirect reflection whereby the beam reflected from the X-axis MEMS mirror passes through relay imaging optics such as a unity magnification telescope on its way to the Y-axis MEMS mirror 502. The Y-axis MEMS mirror 502 is positioned to receive the reflected laser pulse from mirror 500 and further reflect this laser pulse to a location within the scan area 510 corresponding to the range point on the shot list that is being targeted by the beam scanner 304.

The MEMS mirrors 500 and 502 are controllably rotatable around their respective axes of rotation. The X-axis MEMS mirror 500 will be rotatable to control the position of the ladar pulse within the scan area 510 along the scan area's X-axis, while the Y-axis MEMS mirror 502 will be rotatable to control the position of the ladar pulse within the scan area 510 along the scan area's Y-axis. Thus, the combined positioning of mirrors 500 and 502 along their respective axes of rotation when the laser pulse strikes each mirror will be effective to direct the laser pulse to the desired location within the scan area 510. In this example embodiment the X-axis MEMS mirror 500 can be rotated at a relatively higher rate than the Y-axis MEMS mirror 502, hence the reference to the X-axis MEMS mirror as the fast axis mirror and the reference to the Y-axis MEMS mirror as the slow axis mirror.

It should be understood by a practitioner that the designation of the fast axis as the X-axis and the slow axis as the Y-axis is arbitrary as a 90 degree turn in position for the system would render the X-axis as the slow axis and the Y-axis as the fast axis. Furthermore, in an example embodiment, the fast axis mirror is smaller than the slow axis mirror in terms of mirror area and is also positioned upstream from the slow axis mirror (that is, the fast axis mirror receives the ladar pulse and reflects it to the slow axis mirror for transmission toward the targeted range point). However, this configuration could be changed for other embodiments. For example, while making the slow axis mirror larger than the fast axis mirror provides a benefit in terms of permitting a larger scan area, for embodiments where a decrease in the size of the scan area is permissible, the slow axis mirror could be the same size or even smaller than the fast axis mirror. As another example, if the fast axis mirror were downstream from the slow axis mirror, re-imaging optics, such as relay imaging optics, could be used between the two mirrors to support such an arrangement.

Furthermore, the transmission optics 306 can be configured to provide field of view magnification of the directed laser pulse.

An X-axis closed loop feedback system 504 can be used to achieve fine control over the positioning of the X-axis MEMS mirror 500. A Y-axis closed loop feedback system 506 can be used to achieve fine control over the positioning of the Y-axis MEMS mirror 502. As indicated above, while it is preferable to employ feedback control over both the X-axis and 5 Y-axis mirrors 500 and 502, it is believed that improvements in performance relative to an open loop, no feedback design can still be achieved through application of feedback control to only one of the mirrors. For example, a practitioner might choose to employ only the Y-axis feedback control system 506. As another example, a practitioner might choose to employ only the X-axis feedback control system 504.

10 Figure 6A depicts an example embodiment for how closed feedback control can be implemented for the Y-axis mirror 502. In this example, the closed loop feedback control is closed loop optical feedback control. Mirror 502 rotates around the axis of rotation 622 to direct an incident ladar pulse 620 in a desired manner via reflection off the frontside of the mirror 502. A laser 600 be targeted at a backside 606 of the mirror 502. The laser 600 can 15 be any type of laser suitable for position detection. For example, laser 600 can be a pulsed or continuous wave (CW) visible diode laser. Laser 600 can exhibit a variable pulse width and produce power in the uW to mW range.

20 The laser beam 604 produced by laser 600 will be reflected off the backside 606 of mirror 502, and a Y-axis position sensitive detector 602 can be positioned to receive this reflection. The detector 602 can be a single axis position sensing detector. The angular position of mirror 502 with respect to axis of rotation 622 will affect where the reflected laser beam 604 is received by the detector 602. Thus, the position detector 602 will be able to sense data indicative of the actual position of mirror 502. This sensed data can then be fed back via 608 for improved Y-axis mirror control.

25 Figure 6B depicts an example embodiment for how closed feedback control can be implemented for the X-axis mirror 500, and operates in the same fashion as the example of Figure 6A. Mirror 500 rotates around the axis of rotation 632 to direct an incident ladar pulse 630 in a desired manner via reflection off the frontside of the mirror 500. A laser 610 be targeted at a backside 616 of the mirror 500. Laser 610 can be a laser similar to laser 600.

30 The laser beam 614 produced by laser 610 will be reflected off the backside 616 of mirror 500, and an X-axis position sensitive detector 612 can be positioned to receive this reflection. The angular position of mirror 500 with respect to axis of rotation 632 will affect where the reflected laser beam 614 is received by the detector 612. Thus, the position

detector 612 will be able to sense data indicative of the actual position of mirror 500. This sensed data can then be fed back via 618 for improved X-axis mirror control.

Figure 6C depicts another example embodiment for closed loop feedback control of mirror positioning. While the examples of Figures 6A and 6B, if used together, employ two 5 lasers 600 and 610 and two position detectors 602 and 612 to detect mirror positions, the example of Figure 6C employs a single laser 650 and a single two-axis position sensitive detector 662.

With the example of Figure 6C, a beam splitter 654 such as a dichroic beam splitter or pick-off mirror is positioned to intercept the laser pulse emanating from the laser optics 302 10 before it strikes mirror 500. An alignment laser 650 is also positioned to direct an alignment laser beam 652 onto the beam splitter 654. The dichroic beam splitter (acting as a beam combiner) co-aligns the laser beam from laser source 300 with the alignment laser beam 652. As such, the aligned laser beams will be incident on mirror 500 such that the laser lies 15 completely within the mirrors plane of rotation i.e. perpendicular to the mirror's axis of rotation. The dichroic beam splitter 654 can be positioned to achieve such co-alignment, and a 90 degree combination angle as between the laser 300 and alignment laser 650 is typical. Laser 650 can be a visible CW or high repetition rate pulsed diode laser.

Also, a beam splitter 656 such as a pick-off beam splitter can be positioned to intercept the reflected laser light from mirror 502, which will include both the targeting ladar 20 pulse 666 generated by laser source 300 and the alignment laser beam 652 generated by laser 650. The beam splitter 656 will direct the ladar pulse 666 toward the targeted range point while also reflecting a small portion of the light onto re-imaging lens 658. The re-imaging 25 lens 658 will ultimately re-image the scan field 510 onto a two-axis position sensitive detector 662. The position detector 662 will be able to detect the position of the reflected alignment laser beam 652 along two-axes, and this detected position can serve as data indicative of the actual positions for both mirrors 500 and 502. This sensed data can then be fed back via 664 for improved X-axis and Y-axis mirror control.

Figure 7A depicts an example arrangement whereby the closed loop feedback system 310 can process the sensed position data from the position detectors to generate an error 30 signal that can be used to drive an adjustment correction to the driving waveforms for the mirror scan positions. In this example, the closed loop feedback system 310 is used to finely tune the positioning of a MEMS mirror 500/502) in the scanner 304. The beam scanner controller 308 and a MEMS driver within scanner 304 will apply MEMS drive voltages 700

to the MEMS mirror 500/502. This results in mechanical movement 702 of the mirror to a desired mirror position. However, as noted, it is expected that there may be some error in this positioning that is to be mitigated via the closed loop feedback system. As explained in connection with the example embodiments of Figures 6A-C, an optical beam deflection 704 5 can be sensed by any of the position sensors 602/612/662 described in connection with the example embodiments of Figures 6A-C. The position sensor may be accompanied by a trans- impedance amplifier (TIA) that serves to amplify the signal sensed by the position sensor for signal processing purposes. The position sensor can produce sensed mirror position data 706 that is indicative of the actual position of the MEMS mirror. Thus, if the Y-axis mirror was 10 expected to target Row 3 of the scan area, but the actual sensed position for the Y-axis mirror was effective to target Row 4 of the scan area, the feedback system can detect an error of 1 row downward. This error measurement can be fed to the beam scanner controller 308 so that the beam scanner controller can adjust the driving waveform for the Y-axis mirror to achieve an upward adjustment of 1 row.

15 The sensed mirror position data 706 can be combined with the desired mirror position data 708 that is used as an input by comparator 710 to compute a measured error 712. The measured error 712 can be a value that is indicative of the difference between the actual and expected mirror positions.

20 The beam scanner controller 308 may then use any of a number of techniques to process the desired mirror position data 708 in view of the measured error 712 to adjust the MEMS drive voltages 700 in view of this measured error 712. For example, proportional- integral-derivative (PID) control techniques may be used to perform this feedback control. As another example, device inverse response waveforms can be used, in which case a stored 25 response waveform is used to counter the natural device step response and reduce settling time.

Figure 7B depicts example driving waveforms 720 and 722 that might be used to drive the mirror positions for the X-axis mirror 500 and the Y-axis mirror 502 respectively. In this example, the fast axis X-axis mirror 500 is driven in a resonant mode while the slow axis Y-axis mirror 502 is driven in a point-to-point mode where the driving waveform 702 30 varies as a function of the shot list. These examples show the driving waveforms in an uncorrected form where no feedback is used to fine tune mirror positioning.

Figure 7C depicts examples of how mirror positioning error can be corrected by an exemplary closed loop feedback system 310.

The left frame of Figure 7C shows an example Y-axis open loop driving waveform without low pass filtering. As shown by the difference between the uncorrected actual position waveform 730 that corresponds to the actual mirror position and the waveform 732 for the commanded mirror position, there is a fairly significant error that would correspond to 5 the measured error 712 if closed loop feedback were not used to sense the actual mirror position. That is, while the driving waveform 732 seeks to drive the mirror to a desired position via a square wave, in actuality, as the mirror moves toward the desired position, the mirror will overshoot and undershoot the desired position in a fluctuating manner as shown by 732, which corresponds to the settling time for mirror positioning. This settling time 10 repeats itself as the square wave 732 transitions to a low state following the high state.

The right frame of Figure 7C shows an example Y-axis closed loop driving waveform. In this example, closed loop feedback is employed as described in connection with Figure 7A to reduce the settling time error. As shown by the similar shapes of the waveform 736 for the commanded position and the waveform 738 for the actual position, the 15 closed loop feedback is effective to effectively eliminate the large settling time error that is shown in the left frame of Figure 7C. It should be understood that the general amplitude values shown in Figure 7C are inconsequential, and the important characteristic is the comparative shape and timing of each waveform.

Thus, based on the closed loop adjustments to the driving waveforms, it is believed 20 that finer control over mirror scan positions can be achieved that will, over time, reduce the detected error signal.

While the examples of Figures 6A-C describe the use of closed loop optical feedback control, it should be understood that other modes of closed loop feedback control of the 25 mirror scan positions can be employed. For example, closed loop capacitive feedback control may be employed. With capacitive feedback, a capacitor would be formed by the edge of the mirror (serving as a first capacitor plate) and a reference metal plate (serving as a second capacitor plate), with the air/vacuum gap between the mirror edge and reference plate serving as the capacitive dielectric. As the mirror's scan position changes, the gap distance will change, thus causing a change in the capacitor's capacitance. The closed loop capacitive 30 feedback system would thus track a capacitance change (via a voltage measurement) as the mirror changes scan positions to determine the actual mirror position. Based on the determined actual mirror position, the error relative to the desired position can be computed.

As additional examples, different forms of optical feedback or capacitive feedback can be used for closed loop feedback control of mirror positioning.

Dynamic Scan Patterns:

5 To further improve performance of the scanning ladar transmission system 104, it is preferred that dynamic scan patterns be employed. With a fixed scan pattern, the beam scanner 304 will scan through the full scan area 510 and the laser source 300 is fired when the scanning mirrors are positioned to target a desired range point. Thus, with a fixed scan pattern, it is expected that the driving waveforms used to define mirror scan positions will not 10 vary as a function of the range points on the shot list 112.

By contrast, with a dynamic scan pattern, the beam scanner will not scan through the full scan area 510, and instead the mirrors will target the range points on the shot list 112 in accordance with a scan pattern that varies as a function of the ordered range points on the shot list 112. Because the shot list 112 will be varying from frame to frame captured by the 15 environmental sensing system 106, the scan pattern is dynamic as it will also vary from frame to frame.

Figures 8A-F depict examples of different dynamic scan patterns that could be employed by the system

Figure 8A describes an example base addressing scheme for a dynamic scan pattern. 20 As a general matter, the mirrors will be scanned to produce a scan pattern that generally proceeds from left to right across a top row, then downward to the next row where the scan direction is from right to left, and so on, where the scan direction alternates each row downward. However, it should be understood that alternative base patterns could be employed, such as starting from a bottom row and working upward, and/or changing the 25 alternating scan directions to start from right to left. Also, as shown by Figure 8A, a dynamic scan pattern may include line repeats, line skips, and inter-line skips, and inter-line detours, as explained below.

With a line repeat, the beam scanner maintains the Y-axis position for the transmitter 30 during successive left-to-right and right-to-left scans along the X-axis. A line repeat may be needed when the two pixels on the shot list are in the same row but are too close together to be targeted during a single pass. In such a case, the line can be repeated, and the additional pixel on the shot list can be targeted during the return scan pass. A minimum pixel spacing constraint for the dynamic scan pattern can govern the need for line repeats. The minimum

pixel spacing corresponds to the fastest rate the laser source 300 can fire back-to-back shots. It should also be understood that the minimum pixel spacing parameter can vary by position within the scan area 510 in embodiments where resonant beam steering is employed.

A sample line repeat scenario is shown by Figure 8A with respect to sample row area 5 that includes a group of 4 pixels that share the same row. In this example, the minimum pixel spacing is 5 pixels. The laser source 300 fires at pixel (1) first. Since the next pixel (2) is more than five pixels away, the laser can fire at it on the same pass. However pixel (5) is too close in time to be addressed, so the system will address it on the next pass after it performs a line repeat. Thus, during the left-to-right scan, the laser source 300 passes over pixel (5) and 10 fires at pixel (3). The scanner and laser then finish scanning the row by firing at pixel (4) and repeat the same row, this time scanning from right to left. On this following pass, pixel (5) is addressed and the scanner is allowed to move on to the next row. With a line repeat, the scanner can be configured to repeat the row until all required pixels have been interrogated.

With a line skip, the beam scanner adjusts the Y-axis position for the transmitter by 15 more than one row after completing a scan pass of a given row. A line skip may be employed when there are no pixels in the shot list for a row or a set of successive rows. An example line skip is shown in the scan timing diagram of Figure 8A.

With an interline skip, the beam scanner adjusts the Y-axis position for the transmitter before completing a full scan across a given row. An interline skip may be employed when 20 there is a large contiguous portion of a row that is empty. In such a case, the system may choose to address the next row or rows if that will result in a faster scan of the scan area with respect to the shot list. Examples of interline skips are shown in the scan timing diagram of Figure 8A.

An interline detour is a type of interline skip. With an interline detour, the beam 25 scanner adjusts the Y-axis position from the given row to a new row for the transmitter before completing a full scan across the given row, but returns to the given row before completing the scan across the new row. As explained below, an interline detour can serve as an opportunistic and valuable detour from the current row in the normal raster trajectory to address a pixel in a row or a pixel that would have to normally be skipped because it is too 30 close to another pixel in the same row. An example of an interline detour is shown in the scan timing diagram of Figure 8A.

Figure 8B depicts an example dynamic scan pattern that employs line repeats, line skips, interline skips, and interline detours as discussed in connection with Figure 8A. The

dynamic scan pattern of Figure 8B can be employed with a beam scanner that includes dual scanning mirrors where the X-axis mirror scans in two directions as a fast axis mirror at a resonant frequency and where the Y-axis mirror scans in two directions as a slow axis mirror in a non-resonant, point-to-point mode. Closed loop feedback control, such as the closed 5 loop optical feedback control described in connection with Figures 6A-C, can be employed to provide phase drift correction of the Y-axis mirror and fast settling time for the X-axis mirror. Thus, in an example embodiment, optical feedback control can mitigate Y-axis settling time and X-axis phase shift issues. As noted, with two-direction Y-axis movement and interline 10 detours, the Y-axis is capable of going back on itself during a single horizontal scan pass as shown by the interline detour example of Figure 8B. The interline skipping/detouring can increase scanner efficiency and reduce the frame time (i.e., increase the frame rate).

Figure 8C depicts an example dynamic scan pattern that also employs line repeats, line skips, interline skips, and interline detours, but where the dynamic scan pattern of Figure 15 8C can be employed with a beam scanner that includes a scanning Y-axis mirror (such as a Y-axis MEMS mirror) and an X-axis spinning polygon mirror. The X-axis spinning polygon mirror scans in one direction as a fast axis mirror in a non-resonant mode, and the Y-axis MEMS mirror scans in two directions as a slow axis mirror in a non-resonant, point-to-point mode. Closed loop feedback control, such as the closed loop optical feedback control described in connection with Figures 6A-C, can be employed to provide phase drift 20 correction of the X-axis mirror and fast settling time for the Y-axis mirror. Optionally, a closed loop position encoder can be used in place of optical feedback to finely control the positioning of the spinning polygon mirror. The primary functional difference between the dynamic scan patterns of Figures 8B and 8C is that the dynamic scan pattern of Figure 8C can only scan in one direction and does not scan in a resonant fashion.

Figure 8D depicts an example dynamic scan pattern that scans in a spiral pattern such 25 as an elliptical/oval spiral. The dynamic scan pattern of Figure 8D can support ellipse repeats, ellipse skips, interellipse skips, and interellipse detours, which are elliptical analogs to the line repeat, line skips, interline skips, and interline detours respectively discussed in connection with Figures 8A-C. The beam scanner can employ dual scanning mirrors such as 30 an X-axis MEMS mirror and a Y-axis MEMS mirror. Both the X-axis and Y-axis mirrors can scan in two directions in a resonant mode. It is expected that a scanner that employs the scan pattern shown by Figure 8D will include relay imaging optics between the two mirrors. Both mirrors can scan near a resonant frequency, which may be the first resonant frequency.

Figure 8D shows an example elliptical/oval spiral pattern where two single axis mirrors are operating near or at one of their resonant frequencies (same frequency and phase for both).

The amplitude of the spiral is controlled by the amplitude of the driving voltages on the mirrors. The same concept applies as in the dynamic scan pattern of Figure 8B, but the

5 concentric ellipses are the "rows" or the "fast axis" and the pixels lie in the rings. The "columns" or "slow axis" is addressed by the amplitude of both mirrors. The spiral pattern arises from the transition between concentric oval rings. A ring can be repeated or skipped just like in the "raster-like" dynamic scan pattern of Figure 8B, either after a full revolution (an ellipse skip) or between full revolutions (an interellipse skip or interellipse detour).

10 Closed loop feedback control, such as the closed loop optical feedback control described in connection with Figures 6A-C, can be employed to finely control the mirror scan positions.

The dynamic scan patterns of Figures 8A-C can be characterized as base scan patterns. These base scan patterns can be embedded into higher level macro dynamic scan patterns such as those depicted in connection with Figures 8E and 8F.

15 Figure 8E depicts an exemplary macro dynamic scan pattern where the scan area is divided into a plurality of blocks, and where a base dynamic scan pattern is executed within a portion of each block as the scanner proceeds from block to block. As examples, the dynamic scan patterns of Figures 8B and 8C (or other dynamic scan pattern) can be embedded within each block portion.

20 A reset jitter may arise when a large block of pixels are addressed for relatively contiguous scanning, and this reset jitter may lead to a degraded signal-to-noise ratio (SNR). To reduce this possible SNR degradation, the dynamic scan pattern can break the scan area defined by the shot list into smaller blocks. The size of these smaller blocks can be influenced by a maximum amount of background light desired for a ladar receiver. Thus, for 25 a ladar receiver that employs a block structure, the block sizes can correspond to these blocks. Each block can be re-visited by the scanner several times as shown by Figure 8E. One frame is broken up into several interlaced subframes as shown. Each subframe corresponds to a change in direction of the Y-axis/slow axis in the macro pattern. The example of Figure 8E shows a three block frame with five subframes, and where there are 30 several rows in each block.

This macro pattern essentially divides blocks by the total number of pixels that can be grouped together in one pass. As noted, that number can depend on parameters such as the SNR. Figure 8E shows an example of a dynamic macro scan pattern. In the example of

Figure 8E, the 1st and last blocks will address a few more pixels each sub-frame than the other blocks so that timing is orderly, which causes the SNR in those pixels to be a little less. However, since this is away from the center pixels of the frame this degradation in SNR may be acceptable in many applications..

5 Figure 8F depicts an exemplary macro dynamic scan pattern similar to the macro scan pattern of Figure 8E, but where the macro scan switches between the block portions of two blocks before proceeding on to the next two blocks. In other words, the scanner ping-pongs between a pair of blocks until all range points within that pair of blocks are addressed, whereupon the scanner moves on to another pair of blocks and repeats. As with Figure 8E,
10 the dynamic scan patterns of Figures 8B and 8C (or other dynamic scan pattern) can be embedded within each block portion of the Figure 8F macro scan pattern.

Translation of a Range Point List into a Shot List:

Any of a number of processing rules can be used to translate a range point list 240 into a shot list. As noted above, the translation of a range point list 240 into a shot list (see step 204 in Figure 2A) can be performed by processor 120 or by a beam scanner controller 308. The rules can be executed in software, implemented in hardware (e.g., on a field programmable gate array (FPGA) or application-specific integrated circuit (ASIC), or some combination of the two. As such, the processor used to perform the translation from the range point list to the shot list can be any processor suitable for use within processor 120 or beam scanner controller 308, including but not limited to a microprocessor, FPGA, ASIC, or the like. Figure 9A depicts an example process flow for such translation where the shot list accommodates interline skipping (but not including interline detours). Figure 9B depicts an example process flow for translating a range point list into a shot list where the shot list accommodates interline skipping, including interline detours.

As shown by Figure 9A, a range point list 240 serves as input to the process flow. At step 900, the first N rows of the range point list are loaded into a buffer 950. In this example, it is presumed that the range point list already has the range points in at least row order (e.g., starting from the top row and progressing downward). However, if this is not the case, the process flow can also sort the range points into a row order so that the first N rows can be loaded into buffer 950. In this example embodiment, the value for N is 2, in which case the buffer may hold the range points for Row Y1 and Row Y2, with each row comprising one or more range points. It should be understood that the use of a 2-row input buffer is an example

only, and a practitioner may choose to employ a large buffer that supports the consideration of N rows of range points (where $N > 2$). While such an increase in the number of rows and pixels under evaluation at a given time will require additional processing steps and additional buffer space, the practitioner can rely on guidance from the 2-row example provided by

5 Figures 9A and 9B when implementing such a process flow. Also, it should be understood that as the process flow operates to read pixels out of the N row buffer for scheduling into the shot list, step 900 will operate to keep updating buffer 950 with the next row as each row is completed.

At step 902, the processor sorts the pixels into the buffer rows and tags each pixel
10 with a scan direction. The default scan pattern for the shot list can be a scan pattern that is a left-to-right scan for each row. Another option is a default scan pattern that is a left-to-right scan direction for the first row, changes to a right-to-left scan direction for the second row, and then continues alternating scan directions for subsequent rows. In the example
15 embodiment of Figure 9A, the default scan pattern can be a left-to-right scan direction for each row.

With step 902, the pixels in each row are sorted so that they are ordered in accordance
20 with the default scan pattern. Thus, for a row having a left-to-right scan pattern, the pixels are sorted such that the leftmost pixel is first, the second leftmost pixel is next, and so on until the rightmost pixel which will be last. For a row having a right-to-left scan pattern, the pixels will be sorted in the opposite manner. Each pixel may also be tagged with control metadata
25 that identifies the scan direction for that pixel (e.g., a flag indicative of whether a left-to-right scan or a right-to-left scan will hit the pixel). It should also be understood that the range point list 240 may arrive at the process flow of Figure 9A having already been pre-sorted in this fashion, in which case step 902 would not be needed.

25 At step 904, the first two pixels from the buffer 950 are read to identify a current pixel for evaluation and a next pixel candidate. This pair of pixels can be evaluated to determine how they should be ordered in the shot list.

At step 906, the process flow computes a ΔT between the current pixel and the next
30 pixel candidate. This ΔT value is representative of the amount of time required for the scanner to scan from the current pixel to the next pixel candidate. ΔT can be computed as a function of the x-coordinates of the current pixel and next pixel candidate as well as the sinusoidal trajectory and frequency of the fast axis. Also, the processor can perform step 906 for only the current pixel and the next pixel candidate, or it can perform step 906 in a batch

mode wherein the processor computes ΔT for a number of pixel pairs before proceeding to step 908. For example, in a batch mode, the processor can compute ΔT values for each pair of neighboring pixels in the 2-row buffer 950. As another batch mode example, the processor can compute ΔT values for each possible permutation of pixel pairs for the pixels in the 2-row buffer 950.

5

Next, at step 908, the processor compares the computed ΔT for the current pixel and next pixel candidate with a parameter that corresponds to a minimum amount of time that is needed between successive ladar pulses (“Min Pulse-to-Pulse Time”). For an example embodiment, the Min Pulse-to-Pulse Time is a constant whose value is set as a function of 10 the maximum range or the minimum energy required from the laser source 300. For example, for an embodiment where a fiber laser is used, the fiber laser will have a minimum amount of energy required from it, and Min Pulse-to-Pulse Time is set so that laser recharge time is long enough to allow this minimum amount of energy to be build up. Furthermore, it should be understood that the pulse rate for the laser source affects characteristics such as 15 range and SNR. For example, by decreasing the pulse rate, the range for the system would be increased. As such, while the Min Pulse-to-Pulse Time is a constant in an example embodiment, it should be understood that this constant can be adjustable as a system level setting. Furthermore, it should be understood that the Min Pulse-to-Pulse Time need not be the same everywhere in the field of view/scan area.

20 If step 908 results in a determination that the computed ΔT is less than the Min Pulse-to-Pulse Time, this means that the next pixel candidate is too close to the current pixel, in which case the next pixel candidate is scheduled for the next pass of the scanner. Thus, at step 910, the next pixel candidate is scheduled into the shot list buffer 952 for a return scan of that row in a format where the last skipped is the first hit (i.e. a LIFO or last in first out).

25 This means a line repeat will be needed to lase the next pixel candidate, and the next pixel candidate will be placed into the shot list after any other pixels of the current row that will not need to be lased on the return scan. To flag the line repeat, the next pixel candidate can be re-tagged with the opposite scan direction. In a situation where the default scan pattern for the sorted rows is an alternating scan direction, it should also be understood that the line repeat 30 may also mean that the pixels in the next row will be hit from the opposite scan direction relative to the default scan pattern, in which case step 910 also re-tags the pixels in the next row with the opposite scan direction relative to their previous scan direction and re-sorts those re-tagged pixels in accordance with their new scan direction.

Then, at step 912, the processor increments the next pixel candidate such that the new next pixel candidate will be the pixel in the range point list buffer 950 that is immediately after the current next pixel candidate (while the current pixel remains the current pixel so that the current pixel can next be evaluated relative to the new next pixel candidate, unless the 5 new next pixel candidate is on the next row, in which case the processor will use the first pixel in the next row as the new current pixel and the pixel after the first pixel of the next row as the new next pixel candidate). It should be noted that in the situation where the next pixel is on the next row, the pixels on the next row may need to be re-sorted and re-tagged with the opposite scan direction. The processor then returns to step 906 and the process flow repeats. 10 Figure 9E shows an example of a shot list where an interline skip is present as a result of a process flow such as the one shown by Figure 9A.

If step 908 results in a determination that the computed ΔT is not less than the Min Pulse-to-Pulse Time, this means that there is a sufficient amount of time for the scanner to lase the current pixel, scan to the next pixel, and lase the next pixel. As such, the next pixel 15 candidate can be scheduled as the next pixel after the current pixel in the shot list. However, the processor will also test the next pixel to assess whether it is a candidate for an interline skip (step 914).

To test the next pixel candidate at step 914 for a possible interline skip, the processor looks for two conditions to be met: (1) the current pixel and next pixel candidate are on 20 different rows, and (2) a line repeat is not needed to hit the pixels on the current row in a return scan. If these conditions are not met, then the next pixel candidate is not an interline skip candidate, and the next pixel candidate is scheduled as the next pixel in the shot list buffer 952 at step 918 (in which case no interline skip is used). If these two conditions are met, then at step 916, the processor determines whether there is sufficient time for the 25 scanner to lase the current pixel, scan to the next pixel candidate on the new row, and lase that next pixel candidate. To make this determination, the computed ΔT is compared with a SkipTime(N) parameter. The SkipTime(N) parameter defines a minimum amount of time that is needed for the scanner to jump from the current row to the next row. The value of N can correspond to the number of rows under consideration in the buffer.

30 If ΔT is less than SkipTime(N), this means there is an insufficient amount of time for the scanner to jump to the next row and hit the next pixel candidate. In this situation, the process flow proceeds to step 918 and the next pixel candidate is scheduled as the next pixel without an interline skip. This means that the scanner will continue its scan of the current

row to the end of the row, jump to the next row and scan in the opposite direction to the next pixel candidate. As such, the next pixel may need to be re-tagged to change its scan direction in view of the scan direction that will be used by the scanner to reach that pixel.

If ΔT is greater than $\text{SkipTime}(N)$, this means there is a sufficient amount of time for 5 the scanner to jump to the next row and hit the next pixel. In this situation, the process flow proceeds to step 922. At step 922, (1) the next pixel candidate is scheduled as the next pixel in the shot list buffer 952, and (2) the current pixel is tagged with an interline skip alert to inform the scanner that the next pixel requires an interline skip.

Step 920 can be reached from either step 918 or step 922. At step 920, the processor 10 increments the current pixel and the next pixel candidate. The current next pixel candidate will become the new current pixel, and the new next pixel candidate will be drawn from buffer 950. If the next pixel in buffer 950 is on the next row, then the processor may need to re-sort the pixels of the next row (and change their scan directions) before reading the new next pixel candidate to accommodate the scan direction that will be used to target those 15 pixels. For example, assume the new current pixel will be $x5y1$ (sitting on row 1 and having a left-to-right scan direction) and the next pixel in buffer 950 is pixel $x2y2$ (sitting on row 2 and having a left-to-right scan direction), but pixel $x2y2$ shares row 2 with pixels $x6y2$ and $x9y2$ (where $x6y2$ and $x9y2$ are the remaining pixels for row 2 in buffer 950). To accommodate a desired right-to-left scan direction for row 2, the processor can re-sort the 20 pixels in row 2 so that their order in the buffer 950 is $x9y2$, $x6y2$, and $x2y2$ (rather than $x2y2$, $x6y2$, and $x9y2$) while also changing their tagged scan directions to right-to-left. Thus, $x9y2$ would serve as the new next pixel candidate rather than $x2y2$. The processor then returns to 25 step 906 and the process flow repeats.

The process flow of Figure 9A thus produces a shot list in the shot list buffer 952 that 25 supports a dynamic scan pattern with interline skips.

As noted, Figure 9B depicts an example process flow that supports interline skips that include interline detours. Steps 900-922 generally operate as described in connection with Figure 9A, although step 914 will be replaced by a step 930 that not only tests for an interline skip scenario as described for step 914 in Figure 9A but also tests for a possible interline 30 detour scenario.

To accommodate interline detours, the process flow of Figure 9B also considers a parameter that corresponds to a minimum time required for the scanner to go from its current row to another row that is N rows away, visit one or more pixels in the another row, and then

go to back to the next pixel in the current row (“DetourTime(N)”, where in the example of Figure 9B, N=2). The DetourTime(N) parameter can be a constant whose value is mostly set as a function of the electro-mechanical properties of the Y-axis.

Thus, for the process flow of Figure 9B, step 930 not only tests the current pixel-next 5 pixel candidate pair to assess whether the next pixel candidate is an interline skip candidate (see step 914 of Figure 9A), but step 930 will also test the current pixel-next pixel candidate pair to assess whether the next pixel candidate is an interline detour candidate. To evaluate for a possible interline detour, the processor checks whether the current pixel and next pixel candidate share the same row. If they share the same row, there is the possibility of an 10 interline detour, and the processor proceeds to step 934.

At step 934, the processor determines whether there is sufficient time for an interline detour. It does so by comparing the computed ΔT for the current pixel and the next pixel candidate with the DetourTime(N) parameter.

If step 934 results in a determination that the computed ΔT is not greater than 15 DetourTime(N), then the processor proceeds to step 918, which operates as described in connection with Figure 9A, from which the process flow continues as described in connection with Figure 9A.

If step 934 results in a determination that the computed ΔT is greater than 20 DetourTime(N), this means that an interline detour might be scheduled and the processor proceeds to step 936. At step 936, the processor checks whether there are range points on the range point list that can be visited during the interline detour.

To support this determination, the processor at step 932 will identify which range 25 points in the 2-row buffer are skippable due to the computed ΔT value for each pair of neighboring pixels in the 2-row buffer. That is, step 930 identifies the range points that are likely to be targeted on a return pass of the scanner rather than an initial pass due to those range points being too close to the previous range point. It would be desirable to target such skippable range points via the interline detour if possible so that a return pass of the scanner might be avoided in order to improve the scan time. It should be understood that when identifying skippable points at step 932, the processor can take into consideration the scan 30 direction that will be used by the scanner to target the range points on the row of interest. If step 906 operates in a batch mode as discussed above, step 932 may involve simply identifying the second pixel of each pixel pair for a given scan direction whose ΔT value is less than the Min Pulse-to-Pulse Time value. If step 906 does not operate in a batch mode,

then step 932 may also involve computing the ΔT values for additional pixel pairs in the 2-row input buffer so that the skippable points can be identified.

In an example embodiment, the processor performs step 932 after performing step 906 regardless of whether step 936 is ever reached so that the system is already ready to 5 perform step 936 should the process flow branch to step 936. However, this need not be the case.

At step 936, the processor evaluates pixels in the 2-row buffer to determine whether there are any pixels in the buffer that can be scheduled as the next pixel in an interline detour (such pixels can be referred to as detour pixels). The pool of pixels that are deemed 10 “visitable” for the interline detour can include those pixels in the next row whose x value falls (1) after the x value of the current pixel (giving consideration to the scan direction of the scanner) but still providing enough time for the scanner to reach such an x-coordinate given the time required for the scanner to jump to next row and (2) before the x value of the next pixel candidate (giving consideration to the scan direction of the scanner) but still providing 15 enough time for the scanner to reach the x-coordinate of the next pixel candidate.

If step 936 results in a determination that there is only one such visitable pixel for the interline detour, then that visitable pixel is scheduled as the next pixel in the shot list buffer 952 at step 938.

If step 936 results in a determination that there are multiple visitable pixels for the 20 interline detour, and the spacing between these multiple visitable pixels does not violate the ΔT constraint, then those visitable pixels in sequence are scheduled as the next pixels in the shot list buffer 952 at step 938.

If step 936 results in a determination that there are multiple visitable pixels for the 25 interline detour, but not all can be scheduled for the interline detour because of ΔT constraints, then priority is given to a visitable pixel that was identified as a skippable pixel at step 932. The visitable skippable pixel would be scheduled at step 938, and step 938 would also schedule any remaining visitable pixels if compliant with the ΔT constraints in view of the scheduling of the visitable skippable pixel.

If step 936 results in a determination that there are multiple visitable pixels for the 30 interline detour, but not all can be scheduled for the interline detour because of ΔT constraints, and none of the visitable pixels were identified as skippable pixels at step 932, then another prioritization scheme can be used to select which of the visitable pixels are scheduled for the interline detour (for example, removing from the interline detour the

visitable pixel(s) whose removal would permit the largest number of visitable pixels to be scheduled for the interline detour, and in the case of a tie simply scheduling the visitable pixel whose x-value is closest to the current pixel). A similar prioritization scheme can be used to resolve scheduling in a situation where there are multiple skippable visitable pixels 5 but those skippable visitable pixels cannot be scheduled for the same interline detour because of ΔT constraints.

At step 938, the current pixel can be tagged with an interline detour alert to inform the scan that an interline detour will be needed to scan to the next pixel in the shot list.

Furthermore, if the interline detour operates to hit all of the pixels on the next row, a new 10 scan direction may be needed to hit the pixels of the new next row. If this is the case, step 938 can also involve re-tagging and re-sorting the pixels of the new next row in buffer 950. From step 938, the processor proceeds to step 918, and the next pixel candidate is scheduled as the next pixel in shot list buffer 952 following the detour pixel(s) scheduled at step 938.

If step 936 results in a determination that there are not any visitable pixels for the 15 interline detour, then the processor proceeds to step 918 as previously described.

Furthermore, it should be understood that when a pixel is scheduled at step 938 as part of an interline detour, the processor can remove that pixel from the buffer 950 to avoid it being visited twice during the execution of the process flow.

The process flow of Figure 9B thus produces a shot list in the shot list buffer 952 that 20 supports a dynamic scan pattern with interline skips and interline detours.

Figure 9C depicts an example sequence of range points that are scheduled via a shot list in accordance with the process flow of Figure 9B. It should be understood that the pixels are labeled with an x-axis label x_i and a y-axis label y_i , where each value of i for x_i is incremented to show the sequencing of the pixels along each row, but not to identify the 25 distance between pixels. As such, the x-axis distance between pixels x_1y_1 and x_2y_1 is not the same as the x-axis distance between pixels x_2y_1 and x_3y_1 .

As can be seen in Figure 9C, the shot list sequence includes interline detours to shoot pixels x_1y_3 and x_2y_3 . The bottom line of Figure 9C shows the shot list, which identifies the sequence in which the pixels are shot, while the pixel graph of Figure 9C shows the scan 30 progressions through the rows and columns. To better understand the concept of visitable pixels with regard to step 922, it can be seen that pixel x_1y_3 is a visitable pixel for an interline detour from pixel x_2y_1 given that it was visited by an interline detour. However, when the interline detour from pixel x_2y_1 was being considered, pixel x_2y_3 did not qualify as

a visitable pixel for an interline detour from pixel x2y1 (although pixel x2y3 did qualify as a visitable pixel from pixel x3y1). The reason that pixel x2y3 did not qualify as a visitable pixel for an interline detour from pixel x2y1 is that, when the interline detour was being considered from pixel x2y1, the next pixel candidate was x3y1, and the x-axis position of pixel x2y3 falls after the x-axis position of pixel x3y1. As such, pixel x2y3 did not fall within the visitable space for an interline detour between pixels x2y1 and x3y1.

Figures 9D and 9E depict another example sequence of range points that are scheduled via a shot list in accordance with the process flow of Figure 9B. In this example, there is a pixel, x4y1, that is shot after x3y1 but on the return pass of the scanner for that row 10 rather than the initial pass of that row because of the small spacing between x3y1 and x4y1. As with Figure 9C, the bottom line of Figure 9D shows the shot list portion which identifies the sequence in which the pixels are shot, while the pixel graph of Figure 9D shows the scan progressions through the rows and columns. Figure 9E shows the shot progression for the remaining pixels, which includes an interline skip to progress from shooting pixel x1y4 to 15 shooting pixel x1y5. Thus, for the range point list and shot list of Figures 9D and 9E, three scans are required to shoot the pixels.

Figure 9F shows a sample range point list 240 and its corresponding shot list 950, where the shot list 950 is generated in accordance with the process flow of Figure 9B, where the Min Pulse-to-Pulse Time (labeled as “Shot2ShotMinTime” in Figure 9F) corresponds to 20 10 pixels and the DetourTime(N) corresponds to 50 pixels (and where N=1). Once again, it should be understood that different values could be used, and furthermore, these values could vary over the scan field.

The shot list 950 includes meta-information that accompanies each pixel on the shot list. For example, as shown by column 952, each pixel on the shot list can be associated with 25 a flag that identifies whether that pixel is to be shot by the scanner during a left to right scan (a value of “1” in this example) or during a right to left scan (a value of “0” in this example). As another example, as shown by column 954, each pixel on the shot list can be associated with a flag that identifies whether that pixel corresponds to a live waypoint or a real fire command. If a pixel is flagged as a real fire command pixel, this means that the laser source 30 will fire a ladar pulse at such pixel. If a pixel is flagged as a live waypoint, this means that the scanner will scan to that pixel to target it, but the laser source will not fire a ladar pulse toward it. The use of live waypoints can be advantageous in some situations (such as when a constant fiber laser pump source is used). In this example, a value of “1” in column 954

serves to identify a real fire command. As another example, as shown by column 956, each pixel on the shot list can be associated with a code that corresponds to a particular pulse pattern for a ladar pulse. Examples of different pulse patterns are discussed below. As yet another example, as shown by column 958, each pixel on the shot list can be identified by a 5 flag that identifies whether an interline skip (which may include an interline detour) was needed to target the next pixel on the shot list. In this example, a value of “1” would identify that an interline skip was needed to target the next pixel on the shot list.

With the example of Figure 9F, it can be seen that the use of interline skipping and interline detouring in the translation of the range point list to the shot list results in one less 10 pass being needed by the scanner to shoot the pixels on the shot list. With such a reduction in scan passes, a higher frame rate can be supported by the system.

Example Beam Scanner Controller 308:

Figure 10 depicts an example embodiment for a beam scanner controller 308 that can 15 be used in connection with driving dual MEMS mirrors 500/502 in instances where the shot list includes interline skipping and interline detours. To provide acceleration, the beam scanner controller 308 can take the form of a field programmable gate array (FPGA) with logic deployed thereon as shown in connection with Figure 10. By leveraging the parallelism that is supported by the reconfigurable hardware logic of an FPGA, the beam scanner 20 controller 308 can operate in an accelerated manner. However, other platforms could be used for the beam scanner controller, including but not limited to microprocessors, ASICs, and the like.

In the example embodiment of Figure 10, the beam scanner controller receives a range point list 240 as input via FIFO2. FIFO1 can be used to store fire commands and 25 associated pulse patterns for each fire command. The pulse patterns can be ordered within FIFO1 so as to provide a cycling function for different pulse patterns to reduce the risk of interference or ambiguity on the part of a ladar receiver that will receive the reflected ladar pulses.

Component 1000 of Figure 10 can be configured to perform step 204 of Figure 2A 30 (e.g., the process flow of Figure 9B to incorporate both interline skipping and interline detouring). Component 1000 will then output the shot list paired with the control metadata as shown by Figure 9F and a pulse pattern to be used for each pixel. However, once again, it should be understood that the translation of the range point list to the shot list could be

performed by processor 120, in which case the input to FIFO2 would be the shot list rather than the range point list.

The controller 308 will read each pixel out of the shot list in sequence (Present Col, Row) for targeting by the scanner and firing by the laser source. Lookup tables (LUTs) can 5 be used to convert each x-axis value and y-axis value for a pixel on the shot list into digital values that correspond to the mirror scan positions need to target such pixel.

For the X-axis, which in this example operates as a fast-axis in a resonant mode according to a sinusoidal trajectory, the column LUT value will be used to identify an appropriate time slot for the pixel within the scanning mirror's trajectory.

10 For the Y-axis, which in this example operates as a slow-axis in a point-to-point mode, the row LUT value will be used to identify a voltage needed to drive the Y-axis mirror to a desired scan position. As explained, closed loop feedback control can be used to finely control this Y-axis positioning. The generation of the Y-axis driving voltage would then be based on the row LUT and the closed loop feedback. This voltage value can then be fed to a 15 digital-to-analog converter (DAC) to create the Y-axis driving voltage waveform.

A clock can be used as a source for the sinusoidal X-axis waveform. As examples, the clock frequency can be in the 50-100 MHz range. However, it should be understood that other clock frequencies could be used. To track the X-axis position for the resonant X-axis mirror, a counting mechanism can be used to track the X-axis position as the clock signal 20 modulates according to the sinusoid. For example, if there X-axis space is divided into 3226 positions, the counter can cycle through values from 0 to 3225 for the sine wave half period to track X-axis position. Each counter value generally corresponds to a time slot for a give position along the Y-axis. Moreover, given the sinusoidal nature of the signal, it should be understood that these time slots will not be equally spaced.

25 This counter value can then be compared with the column LUT value (and the left-to-right (L2R) flag for the current pixel to judge whether the X-axis mirror is on target for the column position of the current pixel. A laser trigger signal can then be provided to the laser driver at an appropriate time when the X-axis position of the mirror corresponds to the X-axis position of the current pixel to be targeted and the Y-axis position of the mirror corresponds 30 to the Y-axis position of the current pixel. In an example embodiment, the laser trigger can be timed to occur in the middle of the X-axis time slot of the sinusoid for the targeted pixel.

The laser driver can respond to this laser trigger signal to drive the laser to fire a ladar pulse toward the targeted pixel in accordance with the pulse pattern that had been associated with that pixel. The laser driver can also provide any desired pump modulation for the laser.

Also, an Hsync signal can be used by the beam scanner controller to identify where

5 the zero point of each row is, which can facilitates Y-axis transitions.

Additional Beam Scanner Embodiments:

As indicated previously, additional example embodiments for the beam scanner 304 may employ a MEMS mirror in combination with a spinning polygon mirror (see Figures 10 11A-G). Such a polygon mirror may spin at rates in the range of approximately 2 kHz to approximately 10 kHz. However, this need not be the case as other values can be used. For example, in additional example embodiments, an N-sided spinning polygon mirror can spin at a rate such that its rotational frequency multiplied by N is around 10-18 times faster than a resonant frequency for the MEMS mirror. Thus, if the MEMS mirror is operating at close to 15 a full bandwidth of around 2 kHz, and the spinning polygon mirror has 4 sides, the spin rate for the polygon mirror can be in a range between around 2.5 kHz to around 4.5 kHz. It should be understood that other ratios may also be used. For ease of illustration, some of the spinning polygons are shown as circles in Figures 11A-G. An example of such an arrangement is shown by Figure 11A, which includes both a top view and a perspective view 20 of such a beam scanner 304. In this example, a single targeting laser source 300 is employed. The MEMS mirror 1100 is a Y-axis, slow axis mirror while the spinning polygon mirror 1102 is an X-axis, fast axis mirror. The spinning polygon mirror 1102 is positioned to receive an incident laser pulse from laser source 300 (as well as an alignment laser beam from alignment 25 laser 650 for feedback control purposes – see Figure 6C). The spinning polygon mirror 1102 rotates as shown by rotational direction 1104, and it directs the received laser pulse to the Y-axis MEMS mirror 1100, which in turn reflect the laser pulse to a desired location in the scan area shown by Figure 11B.

Furthermore, the general arrangement shown by Figure 11A for a single scanner can also employ two lasers 300 to serve as a double scanner as shown by Figure 11B. Figure 11B 30 depicts a perspective view and a top view of a double scanner that employs two Y-axis MEMS mirrors 1100 and a single shared spinning polygon mirror 1102. Separately positioned lasers 300 can direct laser pulses 1110 and 1112 onto the spinning polygon mirror 1102, and this results in the beam scanner generating two targeted outgoing ladar pulses.

Figure 11C depicts how this general arrangement can support additional targeting lasers, with example embodiments including a triple scanner, a quad scanner, and an N scanner, where N is effectively limited by the space availability for positioning different lasers 300 that lase the spinning polygon from different positions. As an example, N may 5 reach values of 4-16 (or larger) depending upon the desires and needs of a practitioner as discussed below.

Figure 11D depicts examples of different polygons that can be employed as the spinning polygon mirror 1102, with examples including a square and octagon in addition to the hexagon example shown by Figure 11A. Furthermore, an N-sided polygon can be 10 employed for mirror 1102, where N is constrained by parameters such as the size of the Y-axis or secondary mirror, the view angle, and the diameter of the polygon to name just a few.

Figure 11E shows a top view of a beam scanner employing a hexagonal spinning polygon mirror and 4 MEMS mirrors. This example supports 4 scan fields of around 110 degrees. However, up to N independent scan fields of around 20-180 degrees could be 15 supported. It should be understood that a 4-sided mirror spinning at 5 kHz means that a possible row rate of 20kHz may be supported, although time would be needed for the Y-axis to step down between rows, so the actual row rate may be a lower value (such as around 10 kHz). In general, increasing the number of sides for the spinning polygon mirror means smaller scan fields, where the number of scan fields is more dictated by polygon diameter and 20 Y-axis size, but the size and speed of the Y-axis will also influence the relationship between the number of polygon sides and the number of scan fields and scan field size. Further still, the scan fields can exhibit symmetric angles or non-symmetric angles as shown by Figure 11F, where the choice between symmetric or non-symmetric angles can be driven by desires for higher resolution in one scan field versus another.

Figure 11G shows different ways of tilting the vertical field of view (FOV) so that, for 25 example, a car can see the ground and the horizon as well as part of the sky. This can become an issue when there is more than one scan field per spinning polygon mirror.

Figures 12A and B show examples of laser pulse encoding patterns that may be employed by the laser source when transmitting ladar pulses. These encoding patterns are 30 types of intensity modulation schemes that can be applied to the ladar pulses targeted at individual range points. The use of such encoding patterns helps reduce interference and/or increase dynamic range to obtain better accuracy. The ladar pulses can range from a simple

no code single pulse or pulse burst to a complex N-code pulse burst to a asymmetric amplitude modulation (AM) bursts.

For example, Figure 12A examples of pulse position modulation (PPM). An example ladar pulse for PPM can have a pulselwidth of around 0.1 to around 10 ns, and pulse position modulation (PPM) can be employed between pulses. As an example, 3 to N pulses can be used, with the pulses being around 1-10 ns apart. It should be understood that these values are examples only. PPM allows multiple range requests to exist in the air simultaneously. Thus, multiple modulated pulses fired in close succession by a scanning ladar transmission system can be in the air at the same time, and a receiver can meaningfully interpret the reflections of those modulated pulses via demodulation. By way of example, a scanning ladar transmission system can employ two (or more) lasers for generating ladar pulses, where these ladar pulses are pulse modulated relative to each other via PPM. Laser 1 can fire its PPM pulses in close succession with Laser 2's firing of its PPM pulses without interfering with each other. Such an arrangement can permit the scanning ladar transmission system to use a lower effective minimum pulse-to-pulse time because Laser 1 can be recharging while Laser 2 fires (and vice versa). PPM also provides a buffer against interference from the co-location of multiple ladar systems. Thus, if Transmitter 1 (for example, deployed on Vehicle 1) is in close proximity to Transmitter 2 (for example, deployed on Vehicle 2), the two scanning ladar transmitters can fire ladar pulses in a manner with little to no optical interference between the two. Use of PPM can also reduce the signal-to-noise ratio (SNR). Figure 12A shows an example generalization of PPM, where N pulses are used. The first pulse is always there, any combination of N-1 pulses can be positioned after the first pulse. Figure 12A also shows some example basic patterns for PPM.

Intensity modulation can also be used for similar purposes as PPM. For example, intensity modulation can also allow for the transmission of multiple interrogations simultaneously because the interrogations can be separated later through demodulation techniques. Intensity modulation can also reduce or eliminate optical interference that might otherwise result from the use of multiple ladar transmitters in close proximity to each other. Furthermore, intensity modulation can increase the dynamic range of a scanning ladar transmission system, which results in improved range accuracy.

As an example of intensity modulation, Figure 12B shows examples of basic patterns for short asymmetric amplitude modulation (AM) pulse bursts. The ladar pulses can have different amplitudes in different ratios. Short asymmetric AM pulse bursts provide for an

increase in dynamic range (i.e., the signal stays within the acceptable intensity range to be properly detected so that range information can be detected more accurately). An example ladar pulse for an AM pulse burst can have a pulselwidth of around 0.1 to around 10 ns, with around 2 to around 10 pulses being included in the burst, and where the pulses are around 1
5 to around 10 ns apart. As noted, AM can be used to distinguish the individual pulses. It should be understood that these values are examples only. Moreover, it should be understood that PPM may be used in addition to AM.

Furthermore, it should be understood that additional or alternate techniques could be employed to reduce interference and resolve potential ambiguities, including but not limited
10 to polarization modulation, phase modulation with coherent combining, or even the use of additional lasers having different colors. Each additional or alternative technique can provide its own tradeoffs for use in the system. For example, the use of two lasers of different colors can provide an advantage in permitting the use of a lower Min Pulse-to-Pulse Time for the shot lists (as one laser can be re-charging while the other laser is firing or it allows two
15 simultaneous received pulses to be demodulated by a receiver).

Additional Embodiments for Range Point Down-Selection

It should be understood that the dynamic range point selection techniques described herein can also be used to effect improvements in ladar technology in other ways.

20 For example, dynamic range point selection techniques can be used as a post-scan compression tool rather than a pre-scan tool. That is, rather than using the dynamic range point selection technique described herein to limit the number of range points that are targeted by a transmitted ladar pulse, the dynamic range point selection techniques can be used as a compression tool on a high volume ladar point cloud.

25 For example, the scanning ladar transmission system could be employed to shoot a full array of range points (as opposed to the sparse array described in connection with embodiments that are disclosed above). This would result in the creation of a point cloud with a large volume of range points. Then, post-scan, a dynamic range point selection technique such as the one described in connection with Figures 2C and 2D could be
30 performed to choose which range points should be retained for a compressed point cloud. While such post-scan compression would not enjoy the improvements in frame rate or pulse energy that are exhibited by the pre-scan down-selection of range points, it should be understood that the compressed point cloud could provide its own benefits. For example, in

situations where there is a need to communicate a point cloud over a bandwidth-sensitive channel, the intelligently compressed point cloud would be advantageous.

The use of the dynamic range point selection technique as a compression tool for point clouds can be especially useful for compressing 3D point clouds, which typically have 5 very high volumes of points. As an example, the 3D point cloud can be flattened to a desired 2D perspective, and the 2D points can be analyzed to select a subset thereof as intelligent range points using techniques described herein. This subset of points can then serve as the compressed point cloud.

Similarly, a dynamic range point selection technique such as that described by Figures 10 2C and 2D can be used to compress a point cloud that would result from a flash ladar transmission system.

As another example, the scanning ladar transmission system could be employed to target range points using a classic grid scan rather than using a dynamic scan pattern, and the dynamic range point selection technique could be used to select which range points that the 15 laser source will actually fire a ladar pulse at as the transmitter scans through the grid. A classic grid scan would be a fixed scan where the scanning ladar transmission system visits all points in the scan area. However, rather than having the laser source fire at all of the targeted range points, a dynamic range point selection technique such as that described by Figures 2C and 2D can be used to select which range points will be shot at by the ladar 20 transmitter. While such a fixed scan would provide little or no improvement in terms of the system's frame rate or pulse energy relative to the dynamic scan embodiments described herein, the down-selection of range points would still provide some data bandwidth reduction and power management benefits because the transmitter can avoid firing ladar pulses at all of the possible range points.

25

While the present invention has been described above in relation to its exemplary embodiments, various modifications may be made thereto that still fall within the invention's scope. Such modifications to the invention will be recognizable upon review of the teachings herein.

30

WHAT IS CLAIMED IS:

1. A method comprising:

processing a shot list, the shot list comprising a plurality of range points for targeting

5 by a scanning ladar transmission system;

controlling a dynamic scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions based on the processed shot list using closed loop feedback control of the mirror scan positions to target the range points of the processed shot list, wherein the mirror scan positions define where the scanning ladar

10 transmission system is targeted; and

transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern.

15 2. The method of claim 1 further comprising:

receiving a priori data representative of an environmental scene;

processing the a priori data;

based on the processing, selecting a plurality of range points within the environmental scene to define a point group, the selected range points corresponding to less than all of the

20 environmental scene, and the defined point group comprising the selected range points; and

translating the point group into the shot list such that the shot list comprises less than all of the environmental scene; and

wherein the steps of processing the a priori data, selecting, and generating are performed by a processor.

25

3. The method of claim 2 wherein the a priori data comprises an image of the environmental scene, the image comprising a plurality of image points, and wherein the selecting step comprises the processor applying a range point down selection algorithm to the image points to select a subset of the image points as the range points.

30

4. The method of claim 1 wherein the closed loop feedback control comprises closed loop optical feedback control.

5. The method of claim 4 wherein the controlling step comprises:
applying a voltage waveform to the mirror to drive the mirror to the mirror scan positions;
- 5 the method further comprising:
implementing the closed loop optical feedback control by:
targeting a feedback laser on the mirror as the mirror scans in response to the applied voltage waveform;
detecting reflections of the feedback laser via a sensor;
10 determining an error for the mirror scan positions based on the detected reflections; and
adjusting the applied voltage waveform based on the determined error.
- 15 6. The method of claim 5 wherein the targeting step comprises targeting the feedback laser on a backside of the mirror.
7. The method of claim 5 wherein the targeting step comprises targeting the feedback laser on a frontside of the mirror via a first beam combiner positioned between a ladar pulse source and an incoming path to the mirror; and
20 wherein the detecting step comprises directing the reflections to the sensor via a beam splitter positioned between an outgoing path from the mirror and the sensor.
8. The method of any of claims 4-7 wherein the mirror comprises a slow axis mirror that scans in a point-to-point mode based on the processed shot list.
- 25 9. The method of any of claims 1-3 wherein the closed loop feedback control comprises closed loop capacitive feedback control.
10. The method of any of claims 1-9 wherein the scanning ladar transmission system
30 comprises a first mirror and a second mirror;
wherein the controlling step comprises scanning the first and second mirrors to a plurality of mirror scan positions based on the processed shot list using closed loop feedback control of the mirror scan positions for the first and second mirrors to target the range points

of the processed shot list, wherein the scan positions for the first and second mirrors define where the scanning ladar transmission system is targeted.

11. The method of any of claims 1-10 wherein the mirror comprises a first mirror and a

5 second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission

10 system is targeted.

12. The method of claim 11 wherein the first and second mirrors comprise microelectromechanical systems (MEMS) mirrors.

15 13. The method of claim 11 wherein the first mirror comprises a spinning polygon mirror, and wherein the second mirror comprises a microelectromechanical systems (MEMS) mirror.

14. The method of claim 13 wherein the scanning ladar transmission system further comprises a plurality of laser sources and at least one additional MEMS mirror that scans

20 along the first axis, the method further comprising:

operating the scanning ladar transmission system as a multi-beam scanner using the plurality of laser sources.

15. The method of any of claims 1-14 wherein the dynamic scan pattern includes interline

25 skipping based on the processed shot list.

16. The method of claim 15 further comprising;

generating the shot list to define the dynamic scan pattern.

30 17. The method of any of claims 15-16 wherein the mirror comprises a first mirror and a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission

system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the controlling step comprises:

5 scanning the first mirror in a plurality of directions a plurality of directions in a resonant mode; and

 scanning the second mirror in a plurality of directions in a point-to-point mode based on the processed shot list.

10 18. The method of any of claims 15-16 wherein the mirror comprises a first mirror and a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the

15 first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the controlling step comprises:

 scanning the first mirror in one direction in a non-resonant mode; and

 scanning the second mirror in a plurality of directions in a point-to-point mode

20 based on the processed shot list.

19. The method of claim 18 wherein the first mirror comprises a spinning polygon mirror.

20. The method of any of claims 1-19 wherein the dynamic scan pattern includes interline

25 detouring based on the processed shot list.

21. The method of claim 20 wherein the mirror comprises a first mirror and a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the controlling step comprises:

scanning the first mirror in a plurality of directions a plurality of directions in a resonant mode; and

scanning the second mirror in a plurality of directions in a point-to-point mode based on the processed shot list.

22. The method of claim 20 wherein the mirror comprises a first mirror and a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the controlling step comprises:

15 scanning the first mirror in one direction in a non-resonant mode; and

scanning the second mirror in a plurality of directions in a point-to-point mode based on the processed shot list.

23. The method of claim 22 wherein the first mirror comprises a spinning polygon mirror.

20

24. The method of any of claims 1-23 wherein the dynamic scan pattern comprises an elliptical spiral dynamic scan pattern.

25. The method of claim 24 wherein the elliptical spiral dynamic scan pattern includes a member of the group consisting of interellipse skipping and interellipse detouring.

26. The method of any of claims 24-25 wherein the mirror comprises a first mirror and a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the controlling step comprises:

scanning the first mirror in two directions in a resonant mode based on the processed shot list; and

scanning the second mirror in a plurality of directions in a resonant mode based on the processed shot list.

27. The method of any of claims 1-26 wherein the dynamic scan pattern comprises a macro dynamic scan pattern and a base dynamic scan pattern embedded within the macro dynamic scan pattern, wherein the macro dynamic scan pattern segments a scan area for the 10 processed shot list into a plurality of blocks and wherein the scanning of range points on the processed shot list proceeds from block portion to block portion such that a plurality of the consecutively scanned block portions are for block portions of different blocks.

28. The method of claim 27 wherein the macro dynamic scan pattern operates to proceed 15 from block portion to block portion consecutively for each of the blocks before returning to a block for which a block portion has already been scanned.

29. The method of claim 27 wherein the macro dynamic scan pattern operates to switch 20 between the scanning of the block portions of two blocks successively until all of the block portions of the two blocks have been scanned before proceeding to additional blocks.

30. The method of any of claims 1-29 wherein the scan positions comprise scan angles.

31. An apparatus comprising:

25 a scanning ladar transmission system, wherein the scanning ladar transmission system comprises:

30 a beam scanner, the beam scanner including a mirror, wherein the beam scanner is configured to (1) scan the mirror to a plurality of mirror scan positions in response to a control signal, and (2) direct a plurality of incoming ladar pulses onto the scanning mirror for transmitting the ladar pulses toward a plurality of range points;

a beam scanner controller, wherein the beam scanner controller is configured to generate the control signal for the beam scanner such that the control signal defines

a dynamic scan pattern for the scanning ladar transmission system with respect to the range points; and

5 a closed loop feedback system in operative communication with the beam scanner and the beam scanner controller, wherein the closed loop feedback control system is configured to (1) sense a plurality of actual mirror scan positions for the mirror and (2) provide a feedback signal to the beam scanner controller indicative of the actual mirror scan positions for the mirror, the feedback signal for use by the beam scanner controller to adjust the control signal in order to keep the transmitted ladar pulses on target toward the range points.

10

32. The apparatus of claim 31 wherein the closed loop feedback system comprises a closed loop optical feedback system.

15 33. The apparatus of claim 32 wherein the closed loop optical feedback system comprises:

a feedback light source configured to direct light onto the scanning mirror; and
a position detector configured to (1) sense a reflection of the directed light, and (2) generate data indicative of the actual scan positions for the mirror based on the sensed deflection.

20

34. The apparatus of claim 33 wherein the feedback light source is positioned to direct light onto a backside of the scanning mirror.

25 35. The apparatus of claim 33 wherein the closed loop optical feedback system further comprises a beam combiner and a beam splitter, the beam combiner positioned optically between a ladar pulse source and an incoming path to the scanning mirror, the beam splitter positioned optically between an outgoing path from the scanning mirror and the position detector;

30 wherein the feedback light source is positioned to direct light onto a frontside of the scanning mirror via the beam combiner; and

wherein the position detector is positioned to sense the reflection of the directed light via the beam splitter.

36. The apparatus of any of claims 31-35 wherein the mirror comprises a first mirror and a second mirror, wherein the beam scanner is further configured to, in response to the control signal, (1) scan the first mirror with respect to a first axis for targeting the scanning ladar transmission system along the first axis, and (2) scan the second mirror with respect to a

5 second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted.

10 37. The apparatus of claim 36 wherein the first and second mirrors comprise microelectromechanical systems (MEMS) mirrors.

15 38. The apparatus of claim 36 wherein the first mirror comprises a spinning polygon mirror, and wherein the second mirror comprises a microelectromechanical systems (MEMS) mirror.

20 39. The apparatus of any of claims 36-38 wherein the control signal comprises a first control signal and a second control signal, and wherein the beam scanner controller is further configured to (1) generate the first control signal in order to define the mirror scan positions for the first mirror, and (2) generate the second control signal in order to define the mirror scan positions for the second mirror.

25 40. The apparatus of claim 39 wherein the beam scanner controller is further configured to generate the first control signal to cause the first mirror to scan in a plurality of directions in a resonant mode.

41. The apparatus of claim 40 wherein the beam scanner controller is further configured to generate the second control signal to cause the second mirror to scan in a plurality of directions in a point-to-point mode.

30

42. The apparatus of claim 39 wherein the beam scanner controller is further configured to generate one of the control signals to cause the mirror controlled by that control signal to scan in a plurality of directions in a point-to-point mode.

43. The apparatus of claim 39 wherein the beam scanner controller is further configured to generate the first control signal to cause the first mirror to scan in one direction in a non-resonant mode.

5

44. The apparatus of claim 43 wherein the beam scanner controller is further configured to generate the second control signal to cause the second mirror to scan in a plurality of directions in a point-to-point mode.

10 45. The apparatus of any of claims 39-44 wherein the closed loop optical feedback system is further configured to (1) sense a plurality of actual mirror scan positions for the first and second mirrors, (2) provide a first feedback signal to the beam scanner controller indicative of the actual mirror scan positions for the first mirror, and (3) provide a second feedback signal to the beam scanner controller indicative of the actual mirror scan positions for the 15 second mirror, the first and second feedback signals for use by the beam scanner controller to adjust, respectively, the first and second control signals in order to keep the transmitted ladar pulses on target toward the range points.

20 46. The apparatus of claim 45 wherein the beam scanner controller is further configured to adjust the first and second control signals via proportional-integral-derivative (PID) control.

47. The apparatus of claim 45 wherein the beam scanner controller is further configured to adjust the first and second control signals via inverse response waveforms.

25

48. The apparatus of any of claims 45-47 wherein the closed loop optical feedback system comprises:

30 a single light source configured to direct light onto a frontside of the first mirror for use in detecting the mirror scan positions of both the first mirror and the second mirror, whereupon the directed light will be reflected to a frontside of the second mirror for further reflection therefrom;

a beam splitter positioned to optically receive reflected light from the frontside of the second mirror, the beam splitter configured to direct a portion of the received light corresponding to the single light source onto a lens;

5 the lens positioned to receive the receive the directed light portion from the beam splitter; and

a two-axis position detector positioned to receive light from the lens, the two-axis position detector configured to, in response to the received light from the lens, generate data indicative of the actual mirror scan positions for the first and second mirrors.

10 49. The apparatus of claim 48 further comprising:

a light source for the ladar pulse; and

a beam combiner positioned optically between both (1) the ladar pulse light source and the first mirror, and (2) the single light source and the first mirror, wherein the beam combiner is configured to coalign the light from the ladar pulse light source and the single light source; and

15 wherein the first beam splitter is configured to split a portion of the received reflected light corresponding to the ladar pulse from the portion of received reflected light corresponding to the single light source.

20 50. The apparatus of any of claims 39-44 wherein the closed loop optical feedback system is further configured to provide a feedback signal for adjusting only one of the control signals.

25 51. The apparatus of any of claims 39-50 wherein the beam scanner controller is further configured to (1) generate the first control signal to operate the first mirror as a fast axis mirror, and (2) generate the second control signal to operate the second mirror as a slow axis mirror.

30 52. The apparatus of claim 51 wherein the second mirror has a larger mirror area than the first mirror.

53. The apparatus of any of claims 31-52 wherein the control signal defines a dynamic scan pattern that includes interline skipping.

54. The apparatus of any of claims 31-53 wherein the control signal defines a dynamic scan pattern that includes interline detouring.

5 55. The apparatus of any of claims 31-54 wherein the closed loop feedback system comprises a closed loop capacitive feedback system.

56. The apparatus of any of claims 31-55 further comprising:
a light source configured to create the ladar pulses in response to a plurality of firing
10 commands;

light optics positioned between the light source and the beam scanner, the light optics configured to direct the ladar pulses onto the mirror of the beam scanner;
transmission optics positioned optically downstream from the beam scanner, the transmission optics configured to transmit the ladar pulses toward the range points; and
15 wherein the beam scanner controller is further configured to provide a plurality of firing commands to the light source in coordination with the control signal for the beam scanner to define the dynamic scan pattern.

57. A method comprising:

20 targeting a scanning ladar transmission system to a plurality of range points in accordance with a dynamic scan pattern by (1) scanning a first mirror on a first axis based on a first voltage waveform, and (2) scanning a second mirror on a second axis based on a second voltage waveform, wherein the second voltage waveform is a function of the targeted range points;

25 transmitting a plurality of ladar pulses to the targeted range points in accordance with the dynamic scan pattern via the scanning mirror; and

adjusting at least one of the first and second voltage waveforms based on closed loop feedback control with respect to at least one of the scanning mirrors.

30 58. The method of claim 57 wherein the adjusting step comprises adjusting the first voltage waveform based on closed loop feedback control with respect to the first mirror.

59. The method of any of claims 57-58 wherein the adjusting step comprises adjusting the second voltage waveform based on closed loop feedback control with respect to the second mirror.

5 60. The method of any of claims 57-59 wherein the closed loop feedback control comprises closed loop optical feedback control.

61. The method of claim 60 further comprising:

10 directing light onto the first mirror;

sensing a reflection of the directed light;

based on the sensed reflection, determining a position error for the first mirror; and

wherein the adjusting step comprises adjusting the first voltage waveform based on the determined position error.

15 62. An apparatus comprising:

a beam scanner, the beam scanner including a first scanable mirror and a second scanable mirror, wherein the beam scanner is configured to (1) scan the first scanable mirror on a first axis to a plurality of mirror scan positions in response to a first voltage waveform, (2) scan the second scanable mirror on a second axis to a plurality of mirror scan positions in response to a second voltage waveform, and (3) direct a plurality of incoming ladar pulses toward a plurality of range points via reflections of the ladar pulses from the first scanable mirror to the second scanable mirror an onward toward the range points; and

20 a beam scanner controller, wherein the beam scanner controller is configured to (1) generate the first and second voltage waveforms for the beam scanner such that the combination of the first and second voltage waveforms defines a dynamic scan pattern for the beam scanner with respect to the range points, and (2) adjust at least one of the first and second waveforms based on closed loop feedback control with respect to at least one of the first and second scanable mirrors.

25 63. The apparatus of claim 62 wherein the beam scanner further comprises relay imaging optics between the first and second scanable mirrors

30 64. A method comprising:

receiving frame data representative of an environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area;

5 performing corner detection on the frame data to identify a corner feature within the environmental scene; and

selecting a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning ladar transmission system, wherein the subset includes a plurality of points corresponding to the identified corner feature within the environmental scene; and

wherein the method steps are performed by a processor.

10

65. The method of claim 64 further comprising:

the scanning ladar transmission system transmitting a plurality of ladar pulses toward the range points of the selected subset.

15 66. The method of claim 65 wherein the transmitting step comprises the scanning ladar transmission system transmitting the ladar pulses toward the range points of the selected subset according to a dynamic scan pattern.

67. The method of any of claims 65-66 further comprising:

20 the processor repeating the receiving, performing, and selecting step for each of a plurality of frames representative of the environmental scene; and

the scanning ladar transmission system transmitting the ladar pulses toward the range points of the selected subset for each frame.

25 68. The method of any of claims 65-67 wherein the selecting step comprises the processor selecting a relatively higher concentration of range points within an area of the environmental scene corresponding to the identified corner feature than within another area of the environmental scene.

30 69. The method of claim 68 further comprising:

the processor identifying a plurality of frame data segments corresponding to different segments of the environmental scene; and

wherein the selecting step comprises the processor selecting the subset of range points on a segment-by-segment basis.

70. The method of claim 69 further comprising the processor controlling the segmentation according to a size parameter and a threshold parameter.

71. The method of any of claims 69-70 wherein the performing step comprises the processor performing the corner detection separately for each of a plurality of the identified frame data segments.

10

72. The method of claim 71 further comprising:

the processor performing the segment-by-segment selecting according to at least one member of the group consisting of (1) a distance parameter, (2) an angle parameter, and (3) a density parameter.

15

73. The method of any of claims 64-72 wherein the selecting step further comprises:

the processor selecting a plurality of points within the frame data as range point candidates for retention in the subset; and

20 the processor refining the range point candidates for retention in the subset based on a defined point budget parameter.

74. The method of claim 73 wherein the selecting step further comprises:

the processor defining a fill pattern for the environmental scene; and

25 the processor selecting a plurality of range points candidates in accordance with the defined fill pattern.

75. The method of any of claims 73-74 wherein the selecting step further comprises the processor refining the range point candidates for retention in the subset based on a distance parameter to eliminate a plurality of range point candidates that are deemed too close to each other in view of the distance parameter.

76. The method of any of claims 64-75 wherein the frame data comprises image data representative of the environmental scene.

77. The method of an of claims 64-75 wherein the frame data is derived from a ladar point cloud representative of the environmental scene.

5 78. A method comprising:

receiving frame data representative of an environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area;

10 identifying a plurality of frame data segments corresponding to different segments of the environmental scene;

analyzing each of a plurality of the identified frame data segments separately to identify high contrast areas within such frame data segments; and

selecting a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning ladar transmission system, wherein the subset includes a

15 relatively higher concentration of range points within an area of the environmental scene corresponding to identified high contrast areas than within another area of the environmental scene; and

wherein the method steps are performed by a processor.

20 79. The method of claim 78 further comprising:

the scanning ladar transmission system transmitting a plurality of ladar pulses toward the range points of the selected subset.

80. The method of any of claims 78-79 wherein the analyzing step comprises the

25 processor performing a member of the group consisting of edge detection and corner detection.

81. The method of any of claims 78-80 further comprising the processor controlling the segmentation according to a size parameter and a threshold parameter.

30

82. The method of any of claims 78-81 wherein the frame data comprises image data representative of the environmental scene.

83. The method of any of claims 78-81 wherein the frame data is derived from a ladar point cloud representative of the environmental scene.

84. An apparatus comprising:

5 a processor configured to (1) receive frame data representative of an environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area, (2) perform corner detection on the frame data to identify a corner feature within the environmental scene, and (3) select a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning 10 ladar transmission system, wherein the subset includes a plurality of points corresponding to the identified corner feature within the environmental scene.

85. The apparatus of claim 84 further comprising:

15 the scanning ladar transmission system, wherein the scanning ladar transmission system is configured to transmit a plurality of ladar pulses toward the range points of the selected subset.

86. The apparatus of claim 85 wherein the scanning ladar transmission system is further configured to transmit the ladar pulses toward the range points of the selected subset 20 according to a dynamic scan pattern.

87. The apparatus of any of claims 85-86 wherein the processor is further configured to repeat the receive operation, the corner detection performance operation, and the subset selection operation for each of a plurality of frames representative of the environmental 25 scene; and

wherein the scanning ladar transmission system is further configured to transmit the ladar pulses toward the range points of the selected subset for each frame.

88. The apparatus of any of claims 85-87 wherein the processor is further configured to 30 select the subset such that a relatively higher concentration of range points within an area of the environmental scene corresponding to the identified corner feature are selected than within another area of the environmental scene.

89. The apparatus of claim 88 wherein the processor is further configured to (1) identify a plurality of frame data segments corresponding to different segments of the environmental scene, and (2) select the range points for inclusion in the subset on a segment-by-segment basis.

5

90. The apparatus of claim 89 wherein the processor is further configured to control the segmentation according to a size parameter and a threshold parameter.

91. The apparatus of claim 89 wherein the processor is further configured to perform the corner detection separately for each of a plurality of the identified frame data segments.

92. The apparatus of any of claims 89-91 wherein the processor is further configured to perform the segment-by-segment selection of range points for inclusion in the subset according to at least one member of the group consisting of (1) a distance parameter, (2) an angle parameter, and (3) a density parameter.

93. The apparatus of any of claims 84-92 wherein the processor is further configured to (1) select a plurality of points within the frame data as range point candidates for retention in the subset, and (2) refine the range point candidates for retention in the subset based on a defined point budget parameter.

94. The apparatus of claim 93 wherein the processor is further configured to (1) define a fill pattern for the environmental scene, and (2) select a plurality of range points candidates in accordance with the defined fill pattern.

25

95. The apparatus of any of claims 93-94 wherein the processor is further configured to refine the range point candidates for retention in the subset based on a distance parameter to eliminate a plurality of range point candidates that are deemed too close to each other in view of the distance parameter.

30

96. The apparatus of any of claims 84-95 wherein the frame data comprises image data representative of the environmental scene.

97. The apparatus of any of claims 84-95 wherein the frame data is derived from a ladar point cloud representative of the environmental scene.

98. An apparatus comprising:

5 a processor configured to (1) receive frame data representative of an environmental scene that serves as a scan area for a scanning ladar transmission system, the frame data comprising a plurality of points that define the scan area, (2) identify a plurality of frame data segments corresponding to different segments of the environmental scene, (3) analyze each of a plurality of the identified frame data segments separately to identify high contrast areas
10 within such frame data segments, and (4) select a subset of the points to use as range points for targeting by ladar pulses transmitted by the scanning ladar transmission system, wherein the subset includes a relatively higher concentration of range points within an area of the environmental scene corresponding to identified high contrast areas than within another area of the environmental scene.

15

99. The apparatus of claim 98 further comprising:

the scanning ladar transmission system, wherein the scanning ladar transmission system is configured to transmit a plurality of ladar pulses toward the range points of the selected subset.

20

100. The apparatus of any of claims 98-99 wherein the processor is further configured to perform a member of the group consisting of edge detection and corner detection as part of the analysis operation.

25 101. The apparatus of any of claims 98-100 wherein the processor is further configured to control the segmentation according to a size parameter and a threshold parameter.

102. The apparatus of any of claims 98-101 wherein the frame data comprises image data representative of the environmental scene.

30

103. The apparatus of any of claims 98-101 wherein the frame data is derived from a ladar point cloud representative of the environmental scene.

104. A method comprising:

generating a point cloud via lidar, the point cloud being representative of an environmental scene and comprising a plurality of range points; and

compressing the point cloud by (1) processing data representative of the

5 environmental scene, and (2) based on the processing, selecting a plurality of the range points in the point cloud for retention in a compressed point cloud, the compressed point cloud comprising fewer range points than the generated point cloud; and

wherein the compressing step is performed by a processor.

10 105. The method of claim 104 wherein the lidar is scanning lidar.

106. The method of claim 104 wherein the lidar is flash lidar.

107. The method of any of claims 104-106 wherein the point cloud comprises a 3D point 15 cloud.

108. The method of claim 107 wherein the compressing step comprises flattening the 3D point cloud into a 2D intensity map from a selected perspective from among a plurality of perspectives, wherein the 2D intensity map serves as the environmental scene data.

20

109. The method of any of claims 104-108 wherein the processing step comprises the processor analyzing the data representative of the environmental scene to identify areas of contrast within the environmental scene that exceed a threshold, and wherein the selecting step comprises the processor selecting a relatively higher concentration of range points within 25 the identified area than within another area of the environmental scene.

110. The method of any of claims 104-109 wherein the processing step further comprises the processor identifying a fill portion of the environmental scene, and wherein the selecting step comprises the processor (1) defining a fill pattern for the fill portion, and (2) selecting a 30 plurality of range points within the fill portion in accordance with the defined fill pattern.

111. The method of any of claims 104-110 wherein the processing step comprises the processor analyzing the data representative of the environmental scene to identify areas

within the environmental scene corresponding to a line or corner, and wherein the selecting step comprises the processor selecting a relatively higher concentration of range points within the identified area than within another area of the environmental scene.

5 112. The method of any of claims 104-111 wherein the processing step comprises;
the processor pre-filtering the data representative of the environmental scene to
reduce noise according to a filter;
the processor analyzing the pre-filtered data to identify a plurality of segments of the
environmental scene; and
10 wherein the selecting step comprises the processor selecting the range points on a
segment-by-segment basis.

113. The method of claim 112 wherein the processing step further comprises the processor
selecting the filter for the pre-filtering step based on a filter select parameter, wherein the
15 selected filter is configured to perform an edge detection operation.

114. The method of any of claims 112-113 wherein the step of analyzing the pre-filtered
data to identify the segments comprises the processor controlling the segmentation according
to a size parameter and a threshold parameter.

20 115. The method of any of claims 112-114 wherein the selecting step further comprises:
for each of a plurality of the identified segments, the processor analyzing an identified
segment to identify a plurality of range points that correspond to at least one member of the
group consisting of an edge, a face, and a corner within the environmental scene.

25 116. The method of claim 115 wherein the step of analyzing the identified segments
comprises the processor controlling the segment analysis according to at least one member of
the group consisting of (1) a distance parameter, (2) an angle parameter, and (3) a density
parameter.

30 117. The method of any of claims 104-116 wherein the selecting step further comprises:
the processor selecting the identified range points as range point candidates for
retention in the compressed point cloud; and

the processor refining the range point candidates for retention in the compressed point cloud based on a defined point budget parameter.

118. The method of claim 117 wherein the selecting step further comprises:

5 the processor defining a fill pattern for the environmental scene; and
 the processor selecting a plurality of range points candidates in accordance with the defined fill pattern.

119. The method of any of claims 117-118 wherein the selecting step further comprises the

10 processor refining the range point candidates for retention in the compressed point cloud based on a distance parameter to eliminate a plurality of range point candidates that are deemed too close to each other in view of the distance parameter.

120. The method of any of claims 104-119 further comprising electronically communicating

15 the compressed point cloud over a channel to a destination.

121. The method of any of claims 104-120 wherein the processed data comprises an image of the environmental scene.

20 122. An apparatus comprising:

 a ladar system, the ladar system configured to generate a point cloud via ladar, the point cloud being representative of an environmental scene and comprising a plurality of range points; and

25 a processor, the processor configured to compress the point cloud by (1) processing data representative of the environmental scene, and (2) based on the processing, selecting a plurality of the range points in the point cloud for retention in a compressed point cloud, the compressed point cloud comprising fewer range points than the generated point cloud.

123. The apparatus of claim 122 wherein the ladar system is a scanning ladar system.

30

124. The apparatus of claim 122 wherein the ladar system is a flash ladar system.

125. The apparatus of any of claims 122-124 wherein the point cloud comprises a 3D point cloud.

126. The apparatus of claim 125 wherein the processor is further configured to flatten the 5 3D point cloud into a 2D intensity map from a selected perspective from among a plurality of perspectives, wherein the 2D intensity map serves as the environmental scene data.

127. The apparatus of any of claims 122-126 wherein the processor is further configured to 10 (1) analyze the data representative of the environmental scene to identify areas of contrast within the environmental scene that exceed a threshold, and (2) select a relatively higher concentration of range points within the identified area than within another area of the environmental scene.

128. The apparatus of any of claims 122-127 wherein the processor is further configured to 15 (1) identify a fill portion of the environmental scene, (2) define a fill pattern for the fill portion, and (3) select a plurality of range points within the fill portion in accordance with the defined fill pattern.

129. The apparatus of any of claims 122-128 wherein the processor is further configured to 20 (1) analyze the data representative of the environmental scene to identify areas within the environmental scene corresponding to a line or corner, and (2) select a relatively higher concentration of range points within the identified area than within another area of the environmental scene.

25 130. The apparatus of any of claims 122-129 wherein the processor is further configured to;

pre-filter the data representative of the environmental scene to reduce noise according to a filter;

30 analyze the pre-filtered data to identify a plurality of segments of the environmental scene; and

select the range points on a segment-by-segment basis.

131. The apparatus of claim 130 wherein the processor is further configured to select the filter for the pre-filtering operation based on a filter select parameter, and wherein the selected filter is configured to perform an edge detection operation.

5 132. The apparatus of any of claims 130-131 wherein the processor is further configured to control the segmentation according to a size parameter and a threshold parameter.

10 133. The apparatus of any of claims 130-132 wherein processor is further configured to, for each of a plurality of the identified segments, analyze an identified segment to identify a plurality of range points that correspond to at least one member of the group consisting of an edge, a face, and a corner within the environmental scene.

15 134. The apparatus of claim 133 wherein the processor is further configured to control the segment analysis according to at least one member of the group consisting of (1) a distance parameter, (2) an angle parameter, and (3) a density parameter.

20 135. The apparatus of any of claims 122-134 wherein the processor is further configured to (1) select the identified range points as range point candidates for retention in the compressed point cloud, and (2) refine the range point candidates for retention in the compressed point cloud based on a defined point budget parameter.

136. The apparatus of claim 135 wherein the processor is further configured to (1) define a fill pattern for the environmental scene, and (2) select a plurality of range points candidates in accordance with the defined fill pattern.

25

137. The apparatus of any of claims 135-136 wherein the processor is further configured to refine the range point candidates for retention in the compressed point cloud based on a distance parameter to eliminate a plurality of range point candidates that are deemed too close to each other in view of the distance parameter.

30

138. The apparatus of any of claims 122-137 wherein the processor is further configured to communicate the compressed point cloud over a channel to a destination.

139. The apparatus of any of claims 122-138 further comprising:

an environmental sensing system comprising a camera, the camera configured to generate image data of the environmental scene, and wherein the environmental sensing system is configured to communicate the image data to the processor for processing thereby.

5

140. A method comprising:

processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system, wherein the scanning ladar transmission system comprises (1) a first mirror that is scannable with respect to a first axis, and (2) a second mirror that is scannable with respect to second axis that is orthogonal to the first axis, wherein the first mirror comprises a spinning polygon mirror;

controlling a dynamic scan pattern for the scanning ladar transmission system by scanning the spinning polygon mirror and the second mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list, wherein the combination of the mirror scan positions for the spinning polygon mirror and the second mirror define the range points to which the scanning ladar transmission system is targeted; and

transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern.

20 141. The method of claim 140 wherein the second mirror comprises a microelectromechanical systems (MEMS) mirror.

25 142. The method of claim 141 wherein the controlling step comprises:

scanning the spinning polygon mirror in one direction in a non-resonant mode; and

scanning the MEMS mirror in a plurality of directions in a non-resonant, point-to-point mode.

30 143. The method of claim 142 wherein the controlling step further comprises:

scanning the spinning polygon mirror as a fast axis mirror; and

scanning the MEMS mirror as a slow axis mirror.

144. The method of any of claims 140-143 wherein the spinning polygon mirror comprises an N-sided spinning polygon mirror, and wherein the controlling step comprises spinning the spinning polygon mirror at a spin rate such that N multiplied by the spin rate exhibits a ratio in the range of 10:1 to 18:1 relative to a resonant frequency for the second mirror.

5

145. The method of any of claims 140-144 further comprising:

a light source directing a plurality of ladar pulses onto the spinning polygon mirror; the spinning polygon mirror reflecting the ladar pulses onto the second mirror; and the second mirror reflecting the ladar pulses for transmission toward the targeted

10 range points, the targeted range points being defined by the combination of mirror scan positions for the spinning polygon mirror and the second mirror when the ladar pulses are incident thereon.

146. The method of any of claims 140-145 wherein the spinning polygon mirror has a

15 polygon shape with a number of sides within a range between 3-8 sides.

147. The method of any of claims 140-146 wherein the scanning ladar transmission system further comprises a plurality of laser sources and at least one additional mirror that is positioned to receive ladar pulses reflected by the spinning polygon mirror, the method

20 further comprising:

operating the scanning ladar transmission system as a multi-beam scanner using the plurality of laser sources.

148. The method of claim 147 wherein the plurality of laser sources provide a plurality of

25 fields of view for the scanning ladar transmission system, the method further comprising:

tilting the fields of view using a wedge or mirror.

149. An apparatus comprising:

a scanning ladar transmission system configured to direct a plurality of ladar pulses

30 toward a plurality of range points via a plurality of scanable mirrors, wherein the scanning ladar transmission system comprises:

a beam scanner, the beam scanner including a first mirror and a second mirror, wherein the first mirror comprises a spinning polygon mirror, wherein the beam

scanner is configured to (1) scan the first mirror to a plurality of mirror scan positions in response to a first control signal to target the scanning ladar transmission system along a first axis, and (2) scan the second mirror to a plurality of mirror scan positions in response to a second control signal to target the scanning ladar transmission system along a second axis, and wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

10 a beam scanner controller, wherein the beam scanner controller is configured to generate the first and second control signals for use by the beam scanner such that the first and second control signals define a dynamic scan pattern for the scanning ladar transmission system with respect to the range points.

150. The apparatus of claim 149 wherein the scanning ladar transmission system further comprises:

15 a light source positioned and configured to direct a plurality of ladar pulses onto the spinning polygon mirror, whereupon the spinning polygon mirror is configured to reflect the ladar pulses onto the second mirror, whereupon the second mirror is configured to reflect the ladar pulses for transmission toward the targeted range points, the targeted range points being defined by the combination of mirror scan positions for the spinning polygon mirror and the second mirror when the ladar pulses are incident thereon.

151. The apparatus of any of claims 149-150 wherein the second mirror comprises a microelectromechanical systems (MEMS) mirror.

25 152. The apparatus of claim 151 wherein the beam scanner is further configured to (1) scan the spinning polygon mirror in one direction in a non-resonant mode in response to the first control signal, and (2) scan the MEMS mirror in a plurality of directions in a non-resonant, point-to-point mode in response to the second control signal.

30 153. The apparatus of claim 152 wherein the beam scanner is further configured to (1) scan the spinning polygon mirror as a fast axis mirror, and (2) scan the MEMS mirror as a slow axis mirror.

154. The apparatus of any of claims 151-153 wherein the spinning polygon mirror comprises an N-sided spinning polygon mirror, and wherein the beam scanner is further configured to spin the spinning polygon mirror at a spin rate such that N multiplied by the spin rate exhibits a ratio in the range of 10:1 to 18:1 relative to a resonant frequency for the
5 MEMS mirror.

155. The apparatus of any of claims 150-154 wherein the scanning ladar transmission system further comprises a plurality N of the light sources, each light source positioned to render the scanning ladar transmission system as a multi-beam scanner.

10

156. The apparatus of claim 155 wherein the beam scanner further comprises an additional mirror positioned to receive ladar pulses reflected by the spinning polygon mirror.

157. The apparatus of claim 156 wherein the value of N is a member of the group
15 consisting of 2-16, and wherein the additional mirror comprises N-1 additional mirrors positioned to receive ladar pulses reflected by the spinning polygon mirror.

158. The apparatus of any of claims 155-157 wherein the beam scanner further comprises a wedge or mirror positioned to tilt a field of view for the multi-beam scanner.

20

159. The apparatus of any of claims 149-158 wherein the spinning polygon mirror has a polygon shape with a number of sides within a range between 3-8 sides.

160. The apparatus of any of claims 149-159 wherein the beam scanner is further
25 configured to spin the spinning polygon mirror at a spin rate in a range between 2 kHz to 10 kHz.

161. A method comprising:
30 processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system;
controlling a dynamic scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list, wherein the mirror scan positions define

where the scanning ladar transmission system is targeted, wherein the dynamic scan pattern includes at least one member of the group consisting of interline skipping and interline detouring; and

5 transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern.

162. The method of claim 161 wherein the at least one member comprises interline skipping.

10

163. The method of any of claims 161-162 wherein the at least one member comprises interline detouring.

164. The method of any of claims 161-163 wherein the mirror comprises a first mirror and 15 a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission 20 system is targeted; and

wherein the controlling step comprises:

scanning the first mirror in a plurality of directions in a resonant mode; and

scanning the second mirror in a plurality of directions in a point-to-point mode based on the processed shot list.

25

165. The method of any of claims 161-63 wherein the mirror comprises a first mirror and a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission 30 system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the controlling step comprises:

scanning the first mirror in one direction in a non-resonant mode; and
scanning the second mirror in a plurality of directions in a point-to-point mode
based on the processed shot list.

5 166. The method of claim 165 wherein the first mirror comprises a spinning polygon
mirror.

167. The method of any of claims 161-166 further comprising;
generating the shot list to define the dynamic scan pattern.

10 168. The method of claim 167 wherein the generating step comprises;
a processor sorting a plurality of the range points into a sort order to create the shot
list, wherein the sorting comprises the processor identifying a plurality of interline skips
within the dynamic scan pattern based on a parameter indicative of an amount of time needed
15 by the scanning ladar transmission system to scan from a current row to another row.

169. The method of claim 168 wherein the sorting further comprises the processor
computing a plurality of data values between a plurality of pairs of range points, the
computed data values being indicative of an amount of time needed by the scanning ladar
20 transmission system to scan from the first range point of the pair to the second range point of
the pair, and wherein the identifying step further comprises the processor identifying a
plurality of the interline skips within the dynamic scan pattern based on a comparison
between the computed data values and the parameter indicative of the amount of time needed
by the scanning ladar transmission system to scan from the current row to another row.

25 170. The method of any of claims 168-169 wherein the sorting further comprises the
processor identifying a plurality of line repeats within the dynamic scan pattern based on a
parameter indicative of an amount of time needed between successive ladar pulses.

30 171. The method of claim 170 wherein each range point has an associated row identifier
and an associated column identifier, and wherein the sorting step comprises:

the processor sorting the range points into row/column order according to their associated row and column identifiers such that the range points are grouped in row order, and within rows by column order;

5 the processor computing a plurality of data values between successive sorted range points in the row/column order, the computed data values being indicative of an amount of time needed by the scanning ladar transmission system to scan from a first of the successive range points to a second of the successive range points;

10 for each of a plurality of successive sorted range points in the row/column order that share the same row, the processor (1) performing a first comparison between the computed data value for those successive range points and the parameter indicative of the amount of time needed between successive ladar pulses, and (2) in response to the first comparison resulting in a determination that those successive range points sharing the same row are too close together to target with successive ladar pulses, identifying a line repeat and relegating the second of the successive range points for that first comparison to the line repeat;

15 for each of a plurality of successive sorted range points in the row/column order that do not share the same row, (1) identifying whether those successive sorted range points are eligible for an interline skip based on line repeat status, (2) performing a second comparison between the computed data value for those successive range points and the parameter indicative of the amount of time needed by the scanning ladar transmission system to scan 20 from a current row to another row, and (3) in response to the second comparison resulting in a determination that those successive range points are sufficiently far apart to target with successive ladar pulses via an interline skip, identifying an interline skip for scanning from the first of those successive range points to the second of those successive range points.

25 172. The method of any of claims 161-171 further comprising a processor identifying a plurality of interline detours for the shot list based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to (i) scan from a current row to another row, (ii) scan to a range point in the another row, and (iii) return to the current row, whether any interline detours are to be used for the scanning ladar transmission system to 30 target the range points.

173. An apparatus comprising:

a scanning ladar transmission system configured to transmit a plurality of ladar pulses toward a plurality of range points in accordance with a dynamic scan pattern that includes at least one member of the group consisting of interline skipping and interline detouring.

5 174. The apparatus of claim 173 wherein the scanning ladar transmission system comprises a beam scanner, the beam scanner comprising a first mirror and a second mirror, wherein the beam scanner is configured to (1) scan the first mirror to a plurality of mirror scan positions with respect to a first axis for targeting the scanning ladar transmission system along the first axis, and (2) scan the second mirror to a plurality of mirror scan positions with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted, and wherein the beam scanner is further configured to scan at least one of the first and second mirrors as a function of a shot list.

15

175. The apparatus of any of claims 173-174 further comprising:

20 a processor configured to process a plurality of range points to create an ordered set of range points, each range point having an associated row identifier and an associated column identifier that together define a mirror scan position, the ordered set serving as a shot list for the scanning ladar transmission system, wherein the processor, as part of the processing operation, is further configured to:

25 determine, based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to scan from a current row to another row, whether any interline skips are to be used by the scanning ladar transmission system to target the range points;

sort the range points into the ordered set based on the interline skip determinations; and

30 in response to a determination that an interline skip is to be used, tag the shot list with interline skip identifier within the ordered set at a location where the interline skip is to be performed; and

a beam scanner of the scanning ladar transmission system, the beam scanner comprising a mirror, the beam scanner configured to scan the mirror to a plurality of mirror scan positions in accordance with the shot list including any interline skip identifiers present

therein to target the range points via the dynamic scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted; and

wherein the scanning ladar transmission system is further configured to transmit, via the scanning mirror, a plurality of ladar pulses toward the range points of the shot list in

5 accordance with the dynamic scan pattern.

176. The apparatus of claim 175 wherein the processor, as part of the processing operation, is further configured to:

for each of a plurality of pairs of range points, (1) compute a data value as a function 10 of the row and column identifiers associated with the range points of the pair such that the computed data value is indicative of an amount of time needed by the scanning ladar transmission system to scan from a first range point of the pair to a second range point of the pair, and (2) perform the interline skip determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar 15 transmission system to scan from a current row to another row.

177. The apparatus of any of claims 175-176 wherein the processor, as part of the processing operation, is further configured to

determine, based on a parameter indicative of an amount of time needed by the 20 scanning ladar transmission system between successive ladar pulses, whether any line repeats are to be used for the scanning ladar transmission system to target the range points;

sort the range points into the ordered set based on the line repeat determinations and the interline skip determinations; and

25 in response to a determination that a line repeat is to be used, tag the shot list with a line repeat identifier within the ordered set at a location where the line repeat is to be performed; and

30 wherein the beam scanner is further configured to scan the mirror to a plurality of mirror scan positions in accordance with the shot list including any interline skip identifiers and any line repeat identifiers present therein to target the range points via the dynamic scan pattern.

178. The apparatus of claim 177 wherein the processor, as part of the processing operation, is further configured to:

for each of a plurality of pairs of range points, (1) compute a data value as a function of the row and column identifiers associated with the range points of the pair such that the computed data value is indicative of an amount of time needed by the scanning ladar transmission system to scan from a first range point of the pair to a second range point of the pair, (2) perform the line repeat determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system between successive ladar pulses, and (3) perform the interline skip determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system to scan from a current row to another row.

179. The apparatus of any of claims 177-178 wherein the processor, as part of the processing operation, is further configured to

determine, based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to (i) scan from a current row to another row, (ii) scan to a range point in the another row, and (iii) return to the current row, whether any interline detours are to be used for the scanning ladar transmission system to target the range points; sort the range points into the ordered set based on the interline detour determinations, the line repeat determinations, and the interline skip determinations; and

20 in response to a determination that an interline detour is to be used, tag the shot list with an interline detour identifier within the ordered set at a location where the interline detour is to be performed; and

25 wherein the beam scanner is further configured to scan the mirror to a plurality of mirror scan positions in accordance with the shot list including any interline skip identifiers, any line repeat identifiers, and any interline detour identifiers present therein to target the range points via the dynamic scan pattern.

180. The apparatus of claim 179 wherein the processor, as part of the processing operation, is further configured to:

30 for each of a plurality of pairs of range points, (1) compute a data value as a function of the row and column identifiers associated with the range points of the pair such that the computed data value is indicative of an amount of time needed by the scanning ladar transmission system to scan from a first range point of the pair to a second range point of the

pair, (2) perform the line repeat determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system between successive ladar pulses, (3) perform the interline skip determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system to scan from a current row to another row, and (4) perform the interline detour determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system to (i) scan from a current row to another row, (ii) scan to a range point in the another row, and (iii) return to the current row.

10

181. The apparatus of any of claims 173-174 further comprising:

a processor configured to process a plurality of range points to create an ordered set of range points, each range point having an associated row identifier and an associated column identifier that together define a mirror scan position, the ordered set serving as a shot list for the scanning ladar transmission system, wherein the processor, as part of the processing operation, is further configured to:

20

determine, based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to (i) scan from a current row to another row, (ii) scan to a range point in the another row, and (iii) return to the current row, whether any interline detours are to be used for the scanning ladar transmission system to target the range points;

sort the range points into the ordered set based on the interline detour determinations; and

25

in response to a determination that an interline detour is to be used, tag the shot list with interline detour identifier within the ordered set at a location where the interline detour is to be performed; and

30

a beam scanner of the scanning ladar transmission system, the beam scanner comprising a mirror, the beam scanner configured to scan the mirror to a plurality of mirror scan positions in accordance with the shot list including any interline detour identifiers present therein to target the range points via the dynamic scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted; and

wherein the scanning ladar transmission system is further configured to transmit, via the scanning mirror, a plurality of ladar pulses toward the range points of the shot list in accordance with the dynamic scan pattern.

5 182. The apparatus of claim 181 wherein the processor, as part of the processing operation, is further configured to:

for each of a plurality of pairs of range points, (1) compute a data value as a function of the row and column identifiers associated with the range points of the pair such that the computed data value is indicative of an amount of time needed by the scanning ladar transmission system to scan from a first range point of the pair to a second range point of the pair, and (2) perform the interline detour determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system to (i) scan from a current row to another row, (ii) scan to a range point in the another row, and (iii) return to the current row.

15

183. The apparatus of claim 182 further comprising;

wherein the mirror comprises a first mirror and a second mirror, wherein the beam scanner is further configured to (1) scan the first mirror with respect to a first axis for targeting the scanning ladar transmission system along the first axis, and (2) scan the second mirror with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted, and wherein the beam scanner is further configured to scan at least one of the first and second mirrors as a function of the shot list.

25

184. The apparatus of any of claims 181-183 wherein the processor, as part of the processing operation, is further configured to

determine, based on a parameter indicative of an amount of time needed by the scanning ladar transmission system between successive ladar pulses, whether any line repeats are to be used for the scanning ladar transmission system to target the range points;

sort the range points into the ordered set based on the line repeat determinations and the interline detour determinations; and

in response to a determination that a line repeat is to be used, tag the shot list with a line repeat identifier within the ordered set at a location where the line repeat is to be performed; and

5 wherein the beam scanner is further configured to scan the mirror to a plurality of mirror scan positions in accordance with the shot list including any interline detour identifiers and any line repeat identifiers present therein to target the range points via the dynamic scan pattern.

185. The apparatus of claim 184 wherein the processor, as part of the processing operation, 10 is further configured to:

for each of a plurality of pairs of range points, (1) compute a data value as a function of the row and column identifiers associated with the range points of the pair such that the computed data value is indicative of an amount of time needed by the scanning ladar transmission system to scan from a first range point of the pair to a second range point of the 15 pair, (2) perform the line repeat determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system between successive ladar pulses, and (3) perform the interline detour determinations based on the computed data values as compared to the parameter indicative of the amount of time needed by the scanning ladar transmission system to (i) scan from a 20 current row to another row, (ii) scan to a range point in the another row, and (iii) return to the current row.

186. The apparatus of any of claims 175-185 further comprising:

25 a beam scanner controller of the scanning ladar transmission system, wherein the processor is part of the beam scanner controller, and wherein the beam scanner controller is further configured to (1) generate a control signal as a function of the shot list, and (2) provide the control signal the beam scanner; and

wherein the beam scanner is configured to scan the mirror in response to the control signal.

30

187. The apparatus of claim 186 wherein the mirror comprises a first mirror and a second mirror, wherein the beam scanner is further configured to (1) in response to a first control signal from the beam scanner controller, scan the first mirror with respect to a first axis for

targeting the scanning ladar transmission system along the first axis, and (2) in response to a second control signal from the beam scanner controller, scan the second mirror with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan

5 positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the beam scanner is further controller is further configured (1) generate the first control signal as a function of the shot list, (2) generate the second control signal, and (3) provide the first and second control signals to the beam scanner.

10

188. The apparatus of claim 187 wherein the beam scanner controller is further configured to generate the second control signal as a function of the shot list.

189. The apparatus of any of claims 175-185 further comprising:

15 a beam scanner controller of the scanning ladar transmission system, the beam scanner controller in communication with the processor and the beam scanner, wherein the beam scanner controller is configured to (1) receive the shot list from the processor, (2) generate a control signal as a function of the received shot list, and (3) provide the control signal the beam scanner; and

20 wherein the beam scanner is configured to scan the mirror in response to the control signal.

190. The apparatus of claim 189 wherein the mirror comprises a first mirror and a second mirror, wherein the beam scanner is further configured to (1) in response to a first control

25 signal from the beam scanner controller, scan the first mirror with respect to a first axis for targeting the scanning ladar transmission system along the first axis, and (2) in response to a second control signal from the beam scanner controller, scan the second mirror with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan

30 positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

wherein the beam scanner is further controller is further configured (1) generate the first control signal as a function of the shot list, (2) generate the second control signal, and (3) provide the first and second control signals to the beam scanner.

5 191. The apparatus of claim 190 wherein the beam scanner controller is further configured to generate the second control signal as a function of the shot list.

192. The apparatus of any of claims 173-191 further comprising:

10 a light source of the scanning ladar transmission system, wherein the light source is configured to generate a plurality of ladar pulses in response to a plurality of firing commands that are coordinated with a shot list, and wherein the light source is positioned to direct its ladar pulses onto a scanning mirror.

193. A method comprising:

15 translating by a processor a range point list for ladar scanner targeting into a shot list for ladar scanner targeting in a manner whereby the shot list supports a dynamic scan pattern which includes at least one member of the group consisting of interline skipping and interline detouring, wherein the range point list comprises a plurality of range points, and wherein the shot list comprises a plurality of ordered range points from the range point list.

20

194. The method of claim 193 wherein the at least one member comprises interline skipping.

195. The method of claim 194 wherein the translating step further comprises the processor 25 re-ordering range points from the range point list based on a parameter indicative of an amount of time needed by the ladar scanner to scan from a current row to another row.

196. The method of any of claims 194-195 wherein the translating step comprises the processor re-ordering range points from the range point list based on a parameter indicative 30 of a minimum amount of time required between successive ladar pulses.

197. The method of any of claims 193-196 wherein the at least one member comprises interline detouring.

198. The method of claim 197 wherein the translating step further comprises the processor re-ordering range points from the range point list based on a parameter indicative of a detour time needed by the ladar scanner to accommodate an interline detour.

5

199. A method comprising:

processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system;

controlling a spiral dynamic scan pattern for the scanning ladar transmission system

10 by scanning a mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list according to the spiral dynamic scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted; and

15 transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the spiral dynamic scan pattern.

200. The method of claim 199 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern.

20

201. The method of claim 200 wherein the elliptical spiral dynamic scan pattern includes a member of the group consisting of interellipse skipping and interellipse detouring.

202. The method of any of claims 199-201 wherein the mirror comprises a first mirror and 25 a second mirror, the first mirror scanning with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror scanning with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission 30 system is targeted; and

wherein the controlling step comprises:

scanning the first mirror in a plurality of directions in a resonant mode based on the processed shot list; and

scanning the second mirror in a plurality of directions in a resonant mode based on the processed shot list.

203. The method of claim 202 further comprising:

5 controlling the scanning steps by applying a first driving voltage to the first mirror and applying a second driving voltage to the second mirror, each driving voltage having an amplitude.

204. The method of claim 203 further comprising:

10 controlling an amplitude of the spiral for the spiral dynamic scan pattern by varying the amplitudes of the first and second driving voltages.

205. The method of claim 204 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern, the method further comprising:

15 varying the amplitudes of the first and second driving voltages to perform an interellipse skip for the elliptical spiral dynamic scan pattern.

206. The method of any of claims 204-205 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern, the method further comprising:

20 varying the amplitudes of the first and second driving voltages to perform an interellipse detour for the elliptical spiral dynamic scan pattern.

207. The method of any of claims 204-206 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern, the method further comprising:

25 varying the amplitudes of the first and second driving voltages to perform an ellipse skip for the elliptical spiral dynamic scan pattern.

208. The method of any of claims 204-207 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern, the method further comprising:

30 varying the amplitudes of the first and second driving voltages to perform an ellipse repeat for the elliptical spiral dynamic scan pattern.

209. The method of any of claims 202-208 wherein the first and second mirrors comprise microelectromechanical systems (MEMS) mirrors.

210. The method of any of claims 202-209 further comprising:

5 a light source directing a plurality of ladar pulses onto the first mirror;
the first mirror reflecting the ladar pulses onto the second mirror; and
the second mirror reflecting the ladar pulses for transmission toward the targeted range points, the targeted range points being defined by the combination of mirror scan positions for the first and second mirrors when the ladar pulses are incident thereon.

10

211. The method of claim 210 wherein the step of the first mirror reflecting the ladar pulses onto the second mirror comprises the first mirror reflecting the ladar pulses through relay imaging optics onto the second mirror.

15 212. The method of any of claims 199-211 further comprising;

generating the shot list to define the spiral dynamic scan pattern.

213. The method of claim 212 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern, and wherein the generating step comprises;

20 a processor sorting a plurality of the range points into a sort order to create the shot list, wherein the sorting comprises the processor identifying a plurality of interellipse skips within the elliptical spiral dynamic scan pattern based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to scan from a current ring of the spiral to another ring of the spiral.

25

214. The method of any of claims 212-213 wherein the generating step comprises;

30 a processor sorting a plurality of the range points into a sort order to create the shot list, wherein the sorting comprises the processor identifying a plurality of ellipse repeats within the elliptical spiral dynamic scan pattern based on a parameter indicative of an amount of time needed between successive ladar pulses.

215. The method of any of claims 212-214 wherein the generating step comprises;

a processor sorting a plurality of the range points into a sort order to create the shot list, wherein the sorting comprises the processor identifying a plurality of interellipse detours within the elliptical spiral dynamic scan pattern based on a parameter indicative of an amount of time needed by the scanning ladar transmission system to (i) scan from a current ring of 5 the spiral to another ring of the spiral, (ii) scan to a range point in the another ring, and (iii) return to the current ring.

216. A method comprising:

translating by a processor a range point list for ladar scanner targeting into a shot list 10 for ladar scanner targeting in a manner whereby the shot list supports a spiral dynamic scan pattern, wherein the range point list comprises a plurality of range points, and wherein the shot list comprises a plurality of ordered range points from the range point list.

217. An apparatus comprising:

15 a scanning ladar transmission system configured to direct a plurality of ladar pulses toward a plurality of range points via a plurality of scanable mirrors, wherein the scanning ladar transmission system comprises:

20 a beam scanner, the beam scanner including a first mirror and a second mirror, wherein the beam scanner is configured to (1) scan the first mirror to a plurality of mirror scan positions in response to a first driving voltage to target the scanning ladar transmission system along a first axis, and (2) scan the second mirror to a plurality of mirror scan positions in response to a second driving voltage to target the scanning ladar transmission system along a second axis, and wherein the combination of the 25 mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

30 a beam scanner controller, wherein the beam scanner controller is configured to generate the first and second driving voltages for use by the beam scanner such that the first and second driving voltages define a spiral dynamic scan pattern for the scanning ladar transmission system with respect to the range points.

218. The apparatus of claim 217 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern.

219. The apparatus of any of claims 217-218 wherein the scanning ladar transmission system further comprises:

a light source positioned and configured to direct a plurality of ladar pulses onto the first mirror, whereupon the first mirror is configured to reflect the ladar pulses onto the second mirror, whereupon the second mirror is configured to reflect the ladar pulses for transmission toward the targeted range points, the targeted range points being defined by the combination of mirror scan positions for the first mirror and the second mirror when the ladar pulses are incident thereon.

10 220. The apparatus of any of claims 217-219 wherein the first and second mirrors comprise a microelectromechanical systems (MEMS) mirrors.

221. The apparatus of any of claims 217-220 wherein the beam scanner is further configured to (1) scan the first mirror in plurality of directions in a resonant mode in response to the first driving voltage, and (2) scan the second mirror in a plurality of directions in a resonant mode in response to the second driving voltage.

222. The apparatus of claim 221 wherein the spiral dynamic scan pattern comprises an elliptical spiral dynamic scan pattern, and wherein the beam scanner controller is configured to vary an amplitude of the first driving voltage and an amplitude of the second driving voltage to control an amplitude of the spiral for the elliptical spiral dynamic scan pattern.

223. The apparatus of claim 222 wherein the beam scanner controller is further configured to vary the amplitudes of the first and second driving voltages to cause the beam scanner to scan the first the second mirrors in a fashion that defines an interellipse skip for the elliptical spiral dynamic scan pattern.

224. The apparatus of claim 223 wherein the beam scanner controller is further configured to generate the first and second driving voltages based on a shot list that defines a targeting order for the range points, the apparatus further comprising:

a processor configured to identify a plurality of interellipse skips within the elliptical spiral dynamic scan pattern for the shot list based on a parameter indicative of an amount of

time needed by the scanning ladar transmission system to scan from a current ring of the spiral to another ring of the spiral.

225. The apparatus of claim 224 wherein the processor is part of the beam scanner
5 controller.

226. The apparatus of any of claims 222-225 wherein the beam scanner controller is
further configured to vary the amplitudes of the first and second driving voltages to cause the
beam scanner to scan the first the second mirrors in a fashion that defines an interellipse
10 detour for the elliptical spiral dynamic scan pattern.

227. The apparatus of claim 226 wherein the beam scanner controller is further configured
to generate the first and second driving voltages based on a shot list that defines a targeting
order for the range points, the apparatus further comprising:

15 a processor configured to identify a plurality of interellipse detours within the
elliptical spiral dynamic scan pattern for the shot list based on a parameter indicative of an
amount of time needed by the scanning ladar transmission system to (i) scan from a current
ring of the spiral to another ring of the spiral, (ii) scan to a range point in the another ring, and
(iii) return to the current ring.

20 228. The apparatus of claim 227 wherein the processor is part of the beam scanner
controller.

229. The apparatus of any of claims 222-228 wherein the beam scanner controller is
25 further configured to vary the amplitudes of the first and second driving voltages to cause the
beam scanner to scan the first the second mirrors in a fashion that defines an ellipse repeat for
the elliptical spiral dynamic scan pattern.

230. The apparatus of claim 229 wherein the beam scanner controller is further configured
30 to generate the first and second driving voltages based on a shot list that defines a targeting
order for the range points, the apparatus further comprising:

a processor configured to identify a plurality of ellipse repeats within the elliptical spiral dynamic scan pattern for the shot list based on a parameter indicative of an amount of time needed between successive ladar pulses.

5 231. The apparatus of claim 230 wherein the processor is part of the beam scanner controller.

232. The apparatus of any of claims 222-231 wherein the beam scanner controller is further configured to vary the amplitudes of the first and second driving voltages to cause the 10 beam scanner to scan the first the second mirrors in a fashion that defines an ellipse skip for the elliptical spiral dynamic scan pattern.

233. The apparatus of any of claims 219-232 wherein the beam scanner further comprises relay imaging optics between the first and second mirrors.

15

234. A method comprising:

processing a shot list, the shot list comprising a plurality of range points for targeting by a scanning ladar transmission system;

20 controlling a dynamic scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions based on the processed shot list to target the range points of the processed shot list, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, wherein the dynamic scan pattern comprises a macro scan pattern and a base dynamic scan pattern embedded within the macro scan pattern; and

25 transmitting, by the controlled scanning ladar transmission system, a plurality of ladar pulses toward the range points of the processed shot list in accordance with the dynamic scan pattern.

235. The method of claim 234 wherein the macro scan pattern segments a scan area into a 30 plurality of blocks, and wherein the controlling step comprises scanning the mirror to target the range points on the processed shot list in a manner that proceeds from block portion to block portion such that a plurality of the consecutively scanned block portions are for block portions of different blocks.

236. The method of claim 235 wherein the controlling step further comprises scanning the mirror to target the range points such that the base dynamic scan pattern is embedded within each block portion.

5

237. The method of claim 236 wherein the macro scan pattern operates to proceed from block portion to block portion consecutively for each of the blocks before returning to a block for which a block portion has already been scanned.

10 238. The method of claim 236 wherein the macro scan pattern operates to switch between the scanning of the block portions of two blocks successively until all of the block portions of the two blocks have been scanned before proceeding to additional blocks.

15 239. The method of any of claims 236-238 wherein the base dynamic scan pattern includes a member selected from the group consisting of (1) an interline skip, (2) an interline detour, (3) a line repeat, and (4) a line skip within at least one of the block portions.

240. The method of any of claims 234-239 wherein the mirror comprises a first mirror and a second mirror, the first mirror being scanable with respect to a first axis for targeting the 20 scanning ladar transmission system along the first axis, the second mirror being scanable with respect to a second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

25 wherein the controlling step comprises:

scanning the first mirror in a plurality of directions in a resonant mode; and
scanning the second mirror in a plurality of directions in a non-resonant mode
based on the processed shot list.

30 241. The method of any of claims 234-239 wherein the mirror comprises a first mirror and a second mirror,
the first mirror being scanable with respect to a first axis for targeting the scanning ladar transmission system along the first axis, the second mirror being scanable with respect to a

second axis that is orthogonal to the first axis for targeting the scanning ladar transmission system along the second axis, wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and

5 wherein the controlling step comprises:

- scanning the first mirror in one direction in a non-resonant mode based on the processed shot list; and
- scanning the second mirror in a plurality of directions in a non-resonant mode based on the processed shot list.

10

242. The method of claim 241 wherein the first mirror comprises a spinning polygon mirror.

15 243. The method of any of claims 234-242 further comprising;
generating the shot list to define the dynamic scan pattern.

20 244. An apparatus comprising:
a scanning ladar transmission system configured to direct a plurality of ladar pulses toward a plurality of range points via a plurality of scanable mirrors, wherein the scanning ladar transmission system comprises:
a beam scanner, the beam scanner including a first mirror and a second mirror, wherein the beam scanner is configured to (1) scan the first mirror to a plurality of mirror scan positions in response to a first control signal to target the scanning ladar transmission system along a first axis, and (2) scan the second mirror to a plurality of mirror scan positions in response to a second control signal to target the scanning ladar transmission system along a second axis, and wherein the combination of the mirror scan positions for the first and second mirrors defines the range points to which the scanning ladar transmission system is targeted; and
a beam scanner controller, wherein the beam scanner controller is configured to generate the first and second control signals for use by the beam scanner such that the first and second control signals define a dynamic scan pattern for the scanning ladar transmission system with respect to the range points, the dynamic scan pattern

comprises a macro scan pattern with and a base dynamic scan pattern embedded within the macro scan pattern.

245. The apparatus of claim 244 wherein the scanning ladar transmission system further 5 comprises:

a light source positioned and configured to direct a plurality of ladar pulses onto the first mirror, whereupon the first mirror is configured to reflect the ladar pulses onto the second mirror, whereupon the second mirror is configured to reflect the ladar pulses for transmission toward the targeted range points, the targeted range points being defined by the 10 combination of mirror scan positions for the first mirror and the second mirror when the ladar pulses are incident thereon.

246. The apparatus of any of claims 244-245 wherein the macro scan pattern segments a scan area into a plurality of blocks, and wherein the beam scanner is further configured to 15 scan the first and second mirrors in response to the first and second control signals to target range points in a manner that proceeds from block portion to block portion such that a plurality of the consecutively scanned block portions are for block portions of different blocks.

247. The apparatus of claim 246 wherein the beam scanner is further configured to scan the first and second mirrors in response to the first and second control signals such that the base dynamic scan pattern is embedded within each block portion.

248. The apparatus of claim 247 wherein the beam scanner is further configured to scan the first and second mirrors in response to the first and second control signals such that the macro scan pattern operates to proceed from block portion to block portion consecutively for each of the blocks before returning to a block for which a block portion has already been scanned.

249. The apparatus of claim 247 wherein the beam scanner is further configured to scan the first and second mirrors in response to the first and second control signals such that the macro scan pattern operates to switch between the scanning of the block portions of two blocks successively until all of the block portions of the two blocks have been scanned before proceeding to additional blocks.

250. The apparatus of any of claims 244-249 wherein the beam scanner is further configured to:

scan the first mirror in a plurality of directions in a resonant mode in response to the

5 first control signal; and

scan the second mirror in a plurality of directions in a non-resonant mode based on the processed shot list in response to the second control signal.

251. The apparatus of any of claims 244-249 wherein the beam scanner is further

10 configured to:

scan the first mirror in one direction in a non-resonant mode based on the processed shot list in response to the first control signal; and

scan the second mirror in a plurality of directions in a non-resonant mode based on the processed shot list in response to the second control signal.

15

252. The apparatus of claim 251 wherein the first mirror comprises a spinning polygon mirror.

253. The apparatus of any of claims 244-252 wherein the base dynamic scan pattern

20 includes a member selected from the group consisting of (1) an interline skip, (2) an interline detour, (3) a line repeat, and (4) a line skip within at least one of the block portions.

254. A method comprising:

25 controlling a scan pattern for the scanning ladar transmission system by scanning a mirror to a plurality of mirror scan positions to target a plurality of range points according to the scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted; and

transmitting, by the controlled scanning ladar transmission system, a plurality of modulated ladar pulses toward the range points in accordance with the scan pattern.

30

255. The method of claim 254 wherein the transmitting step further comprises transmitting the modulated ladar pulses such that a plurality of the modulated ladar pulses are traveling to and/or from a plurality of the targeted range points at the same time.

256. The method of claim 255 wherein the scanning ladar transmission system comprises a first light source and a second light source, each light source configured to generate the modulated ladar pulses, the method further comprising providing a plurality of firing commands to the first and second light sources to cause the transmitting.

5

257. The method of any of claims 254-256 wherein the transmitting step employs pulse position modulation of the ladar pulses.

10 258. The method of any of claims 254-257 wherein the transmitting step employs intensity modulation of the ladar pulses.

259. The method of any of claims 254-258 wherein the transmitting step employs short asymmetric amplitude modulation (AM) ladar pulse bursts.

15

260. The method of any of claims 254-259 wherein the transmitting step employs polarization modulation of the ladar pulses.

20 261. The method of any of claims 254-260 wherein the transmitting step employs phase modulation of the ladar pulses with coherent combining.

25 262. The method of any of claims 254-261 wherein the controlling step comprises (1) scanning a first mirror of the scanning ladar transmission system to a plurality of first mirror scan positions to target the scanning ladar transmission system along a first axis based on a first control signal, and (2) scanning a second mirror of the scanning ladar transmission system to a plurality of second mirror scan positions to target the scanning ladar transmission system along a second axis based on a second control signal, wherein the first and second axes are orthogonal to each other, and wherein the combination of the first and second mirror scan positions define where the scanning ladar transmission system is targeted; and

30 wherein the transmitting step comprises (1) firing a light source of the scanning ladar transmission system to transmit a modulated ladar pulse toward the scanning first mirror, whereupon the modulated ladar pulse is reflected toward the scanning second mirror, whereupon the modulated ladar pulse is reflected toward a targeted range point, and (2)

repeating the firing step for a plurality of the targeted range points as the first and second mirrors continue to scan.

263. The method of any of claims 254-262 wherein the scan pattern comprises a dynamic
5 scan pattern based on an ordered set of range points.

264. An apparatus comprising:

a scanning ladar transmission system comprising a mirror, the scanning ladar transmission system configured to (1) scan the mirror to a plurality of mirror scan positions to 10 control a scan pattern for the scanning ladar transmission system and target a plurality of range points according to the scan pattern, wherein the mirror scan positions define where the scanning ladar transmission system is targeted, and (2) transmit, via the scanned mirror, a plurality of modulated ladar pulses toward the range points in accordance with the scan pattern.

15

265. The apparatus of claim 264 wherein the scanning ladar transmission system is further configured to transmit the modulated ladar pulses such that a plurality of the modulated ladar pulses are traveling to and/or from a plurality of the targeted range points at the same time.

20 266. The apparatus of claim 265 wherein the scanning ladar transmission system further comprises a first light source and a second light source, each light source configured to generate the modulated ladar pulses, the wherein the scanning ladar transmission system is further configured to provide a plurality of firing commands to the first and second light sources to cause the transmissions of the modulated ladar pulses.

25

267. The apparatus of any of claims 264-266 wherein the scanning ladar transmission system is further configured to apply pulse position modulation to the ladar pulses.

268. The apparatus of any of claims 264-267 wherein the scanning ladar transmission
30 system is further configured to apply intensity modulation to the ladar pulses.

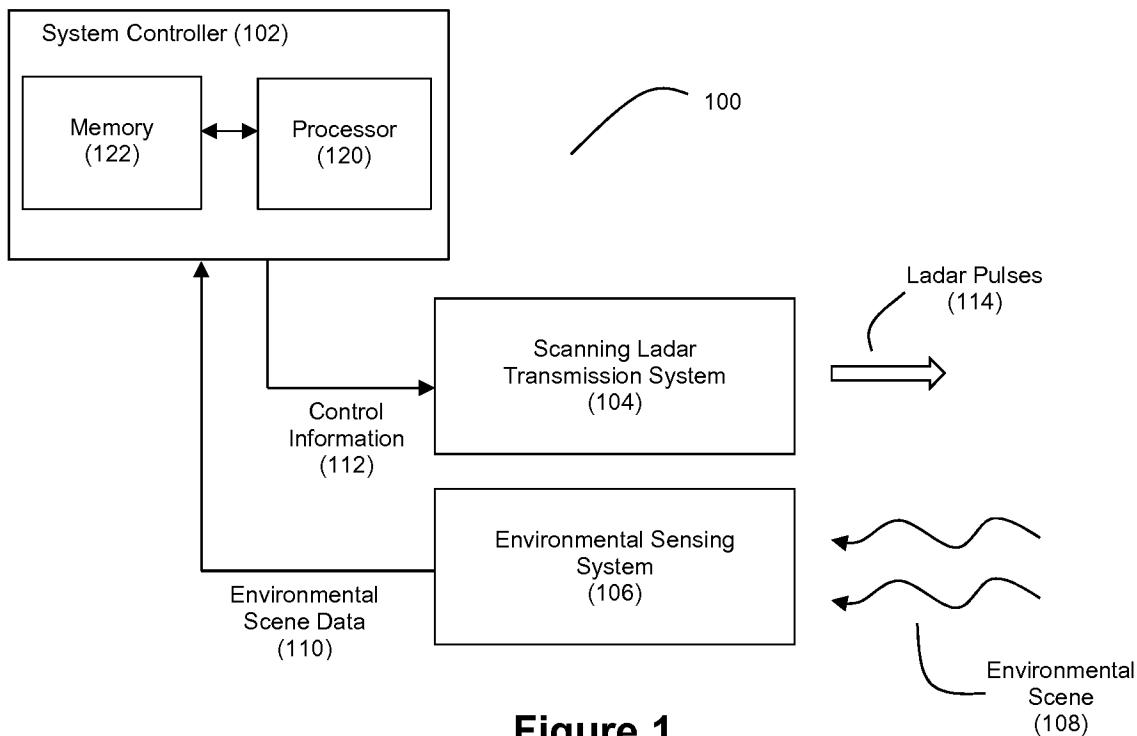
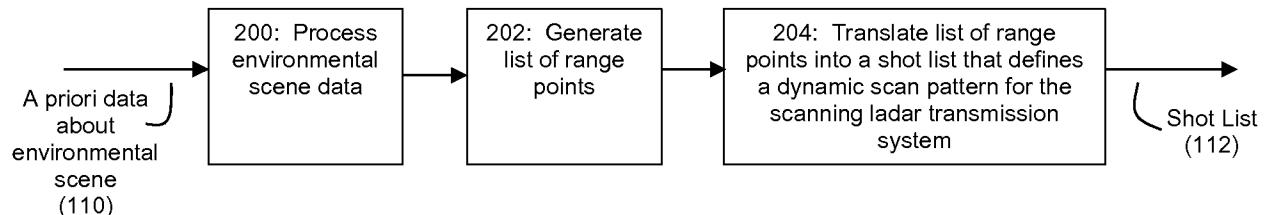
269. The apparatus of any of claims 264-268 wherein the scanning ladar transmission system is further configured to apply short asymmetric amplitude modulation (AM) bursts to the ladar pulses.

5 270. The apparatus of any of claims 264-269 wherein the scanning ladar transmission system is further configured to apply polarization modulation to the ladar pulses.

271. The apparatus of any of claims 264-270 wherein the scanning ladar transmission system is further configured to apply phase modulation to the ladar pulses with coherent 10 combining.

272. The apparatus of any of claims 264-271 wherein the mirror comprises a first mirror and a second mirror, wherein the scanning ladar transmission system further comprises a light source configured to generate a plurality of the ladar pulses, and wherein the scanning ladar 15 transmission system is further configured to (1) scan the first mirror to a plurality of first mirror scan positions to target the scanning ladar transmission system along a first axis based on a first control signal, (2) scan the second mirror to a plurality of second mirror scan positions to target the scanning ladar transmission system along a second axis based on a second control signal, wherein the first and second axes are orthogonal to each other, and 20 wherein the combination of the first and second mirror scan positions define where the scanning ladar transmission system is targeted, (3) fire the light source to transmit a modulated ladar pulse toward the scanning first mirror, whereupon the modulated ladar pulse is reflected toward the scanning second mirror, whereupon the modulated ladar pulse is reflected toward a targeted range point, and (4) repeat the fire operation for a plurality of the 25 targeted range points as the first and second mirrors continue to scan.

273. The apparatus of any of claims 264-272 wherein the scan pattern comprises a dynamic scan pattern based on an ordered set of range points.

**Figure 1****Figure 2A**

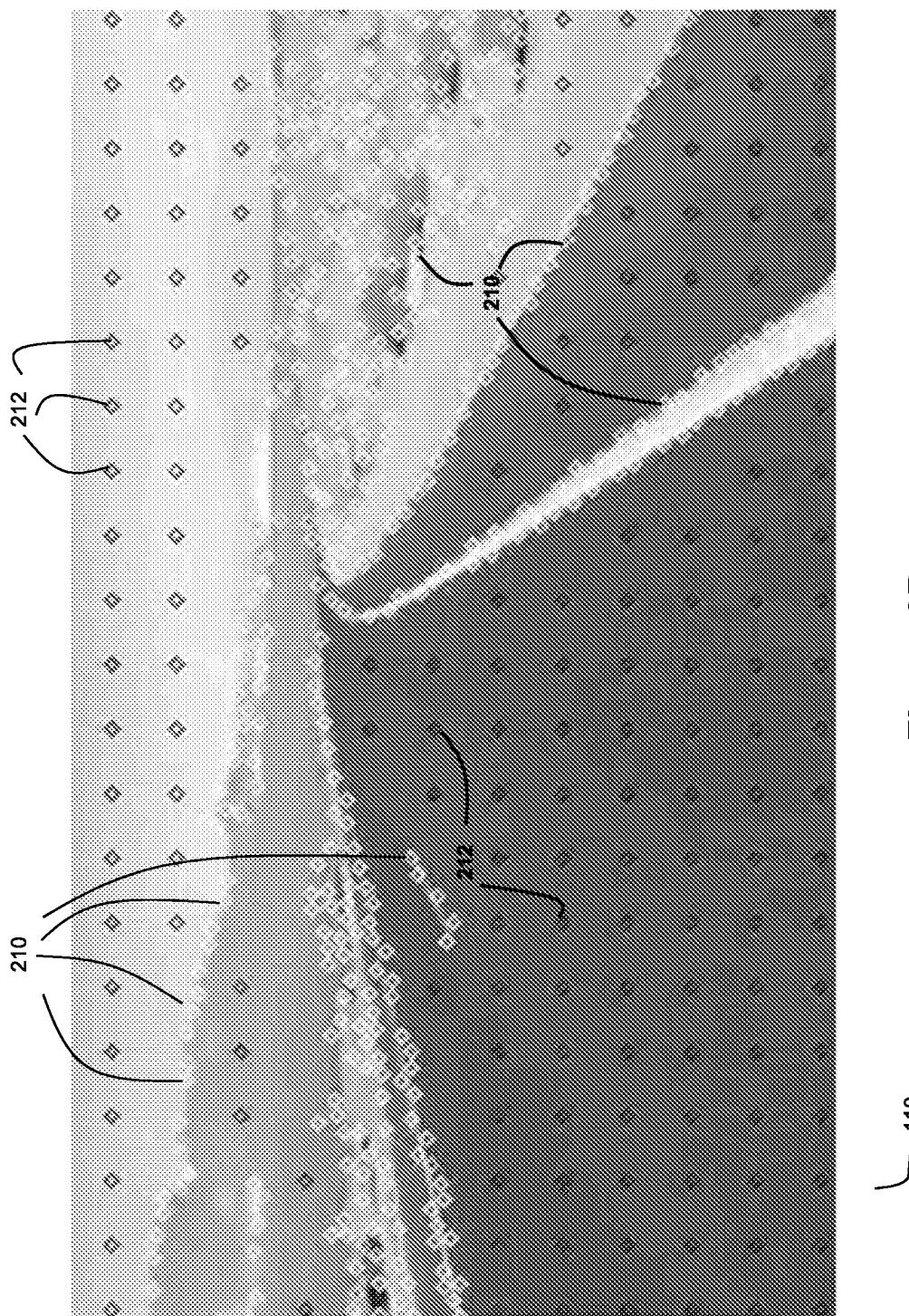
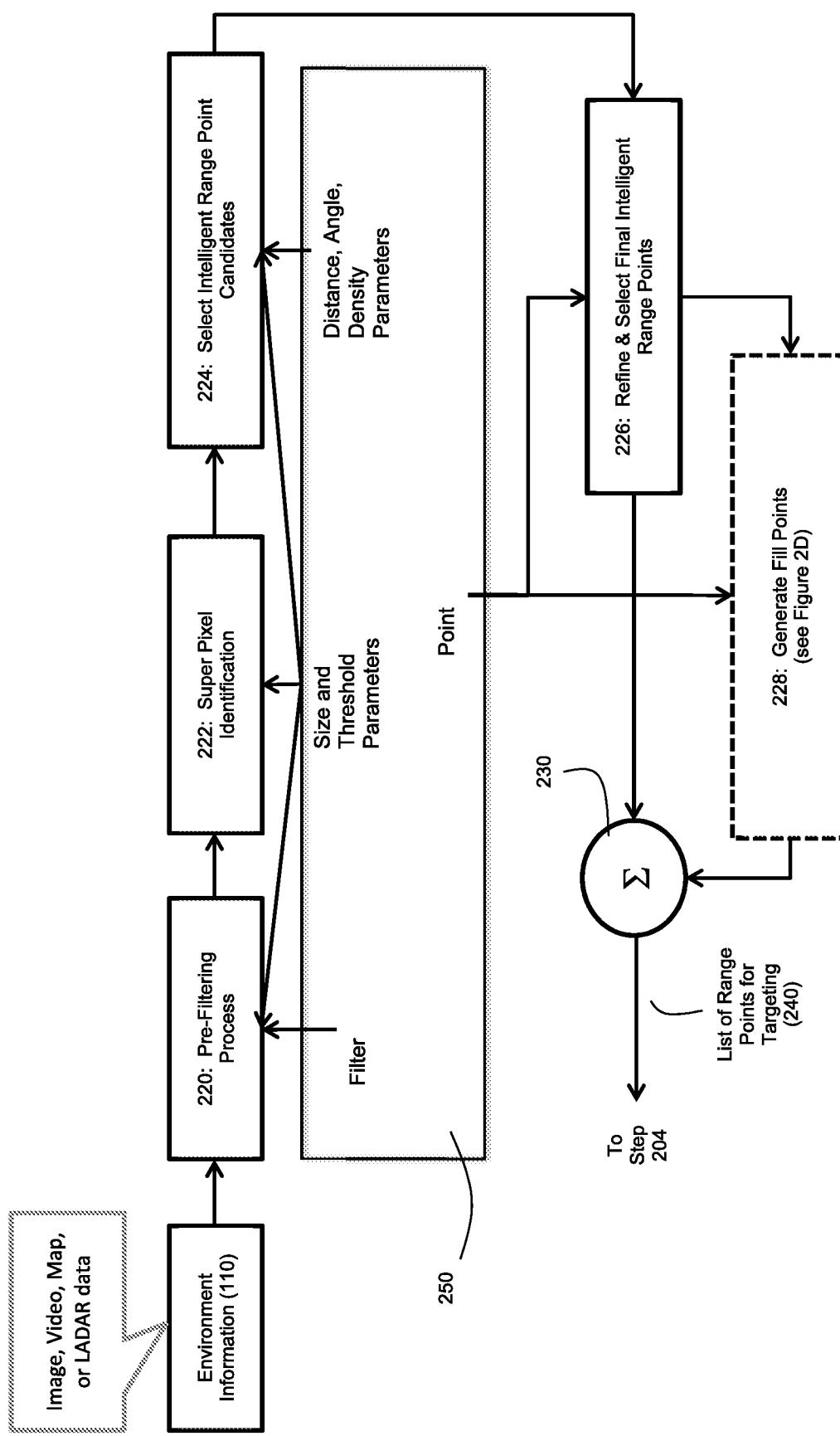


Figure 2B

**Figure 2C**

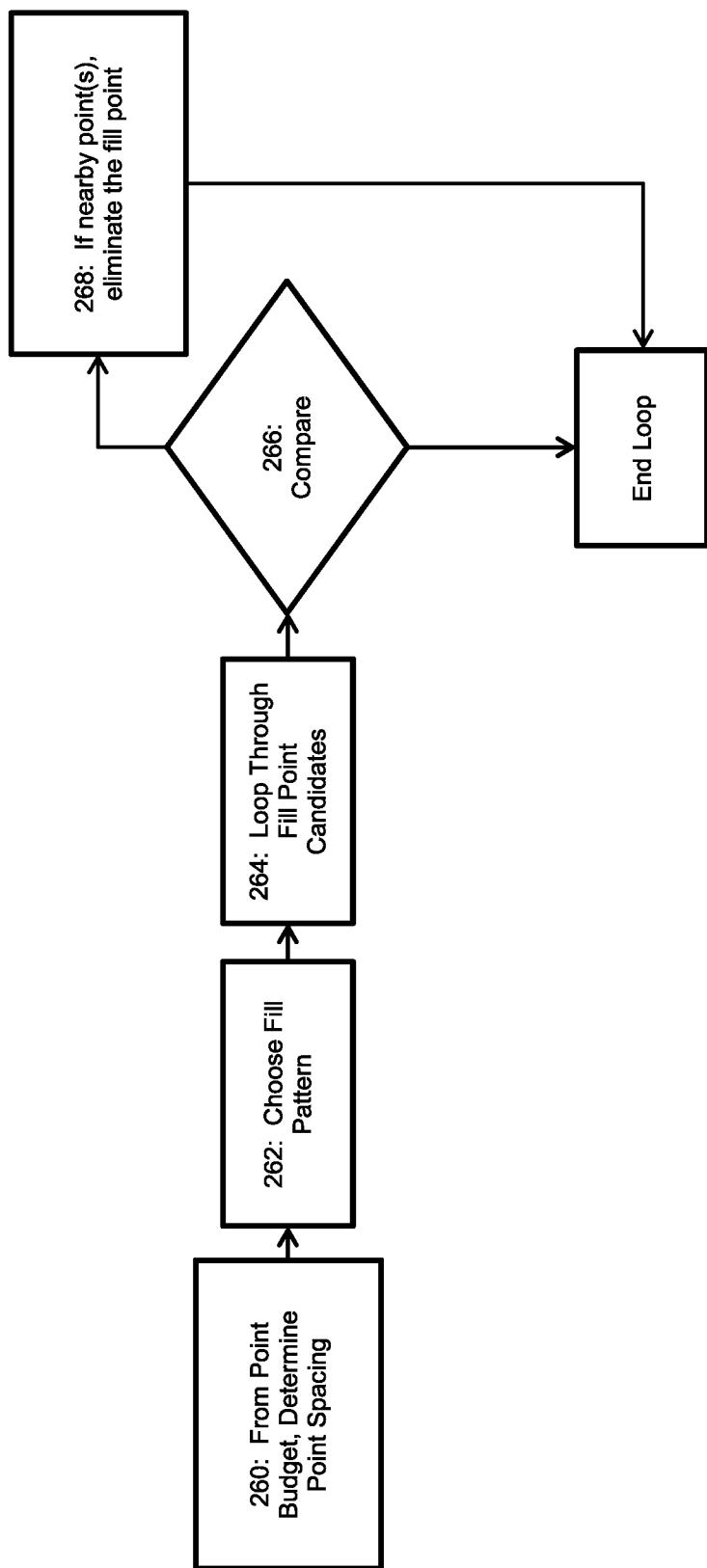


Figure 2D

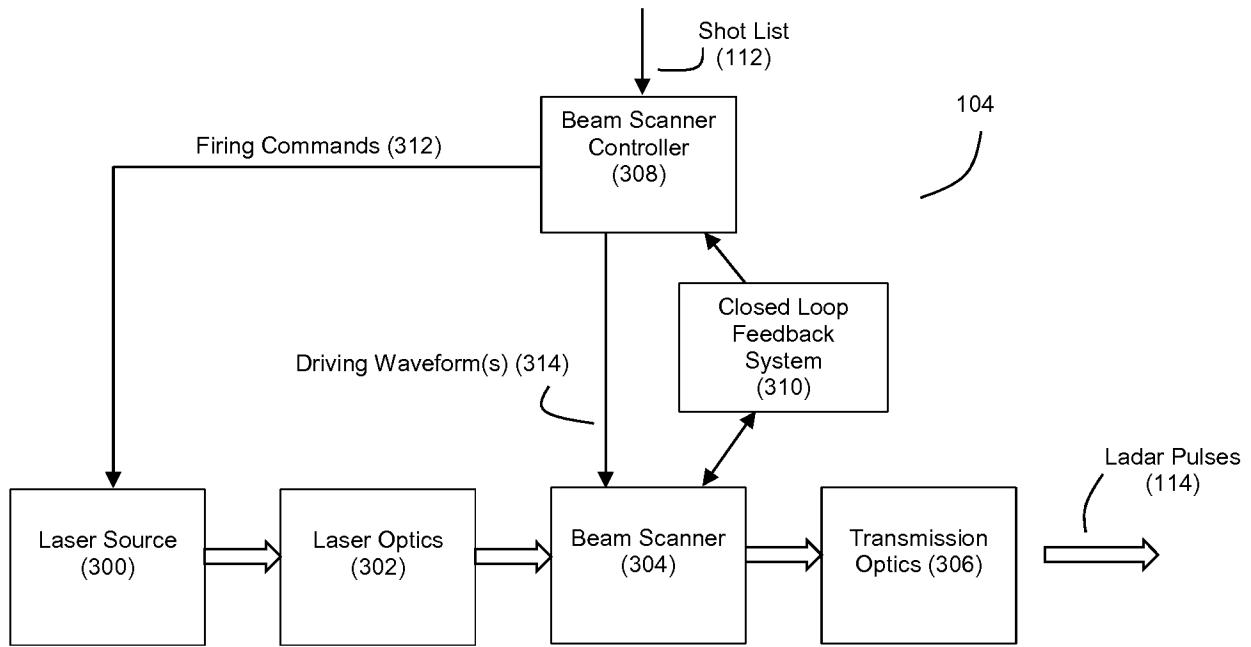


Figure 3

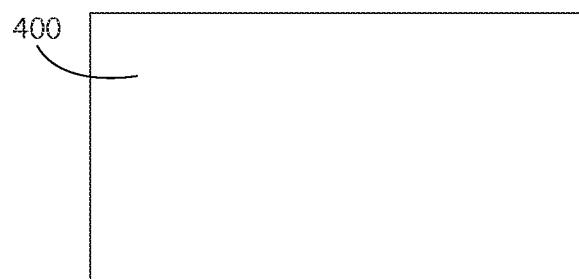


Figure 4A

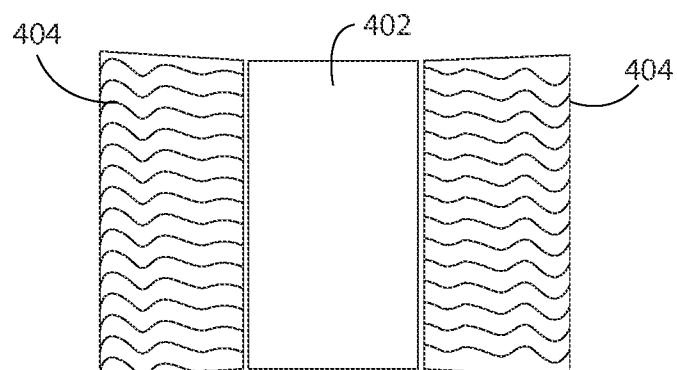


Figure 4B

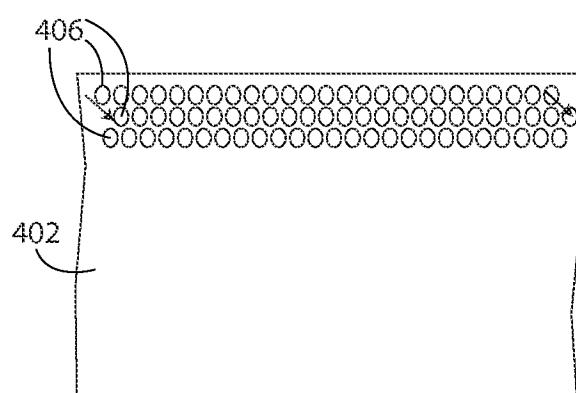


Figure 4C

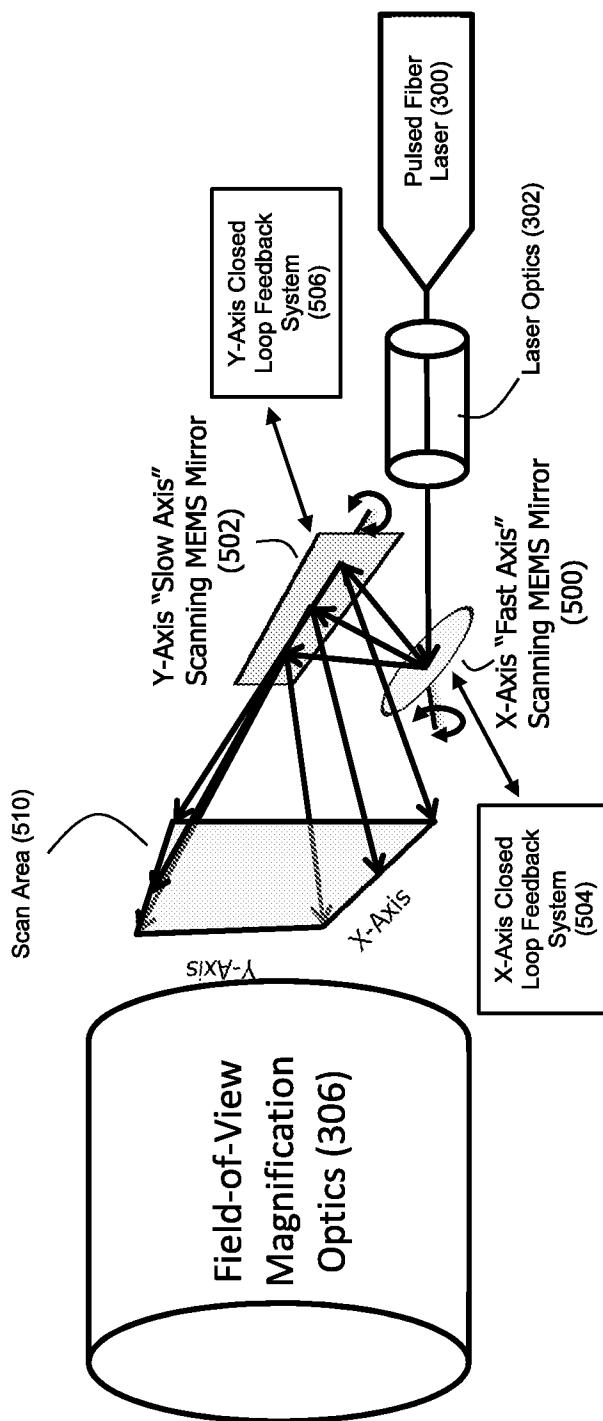


Figure 5

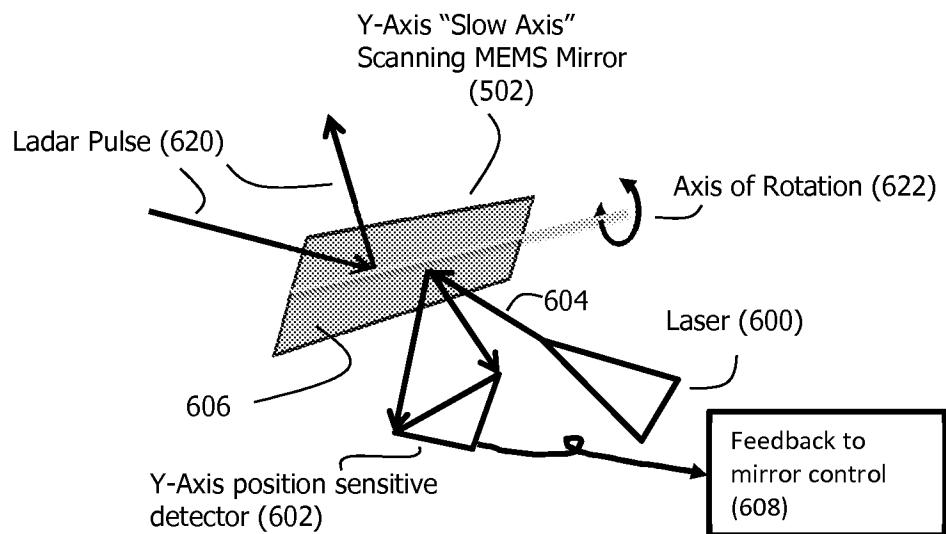


Figure 6A

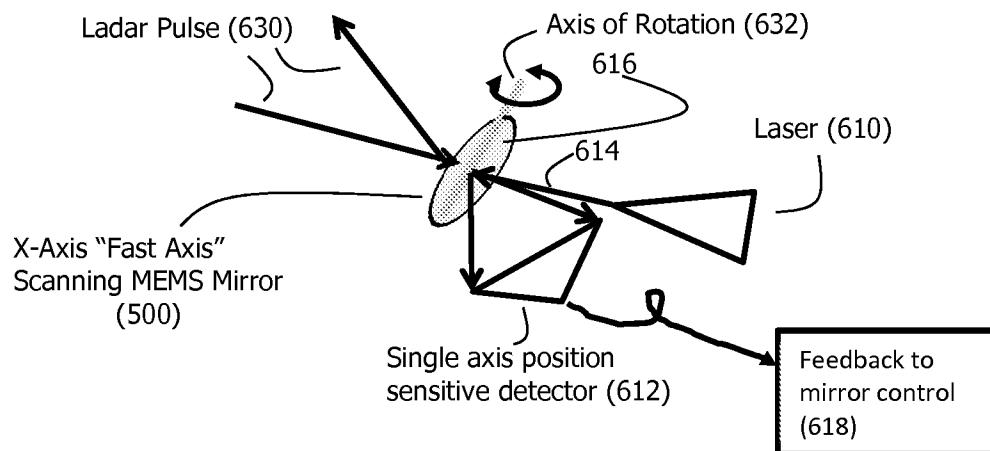


Figure 6B

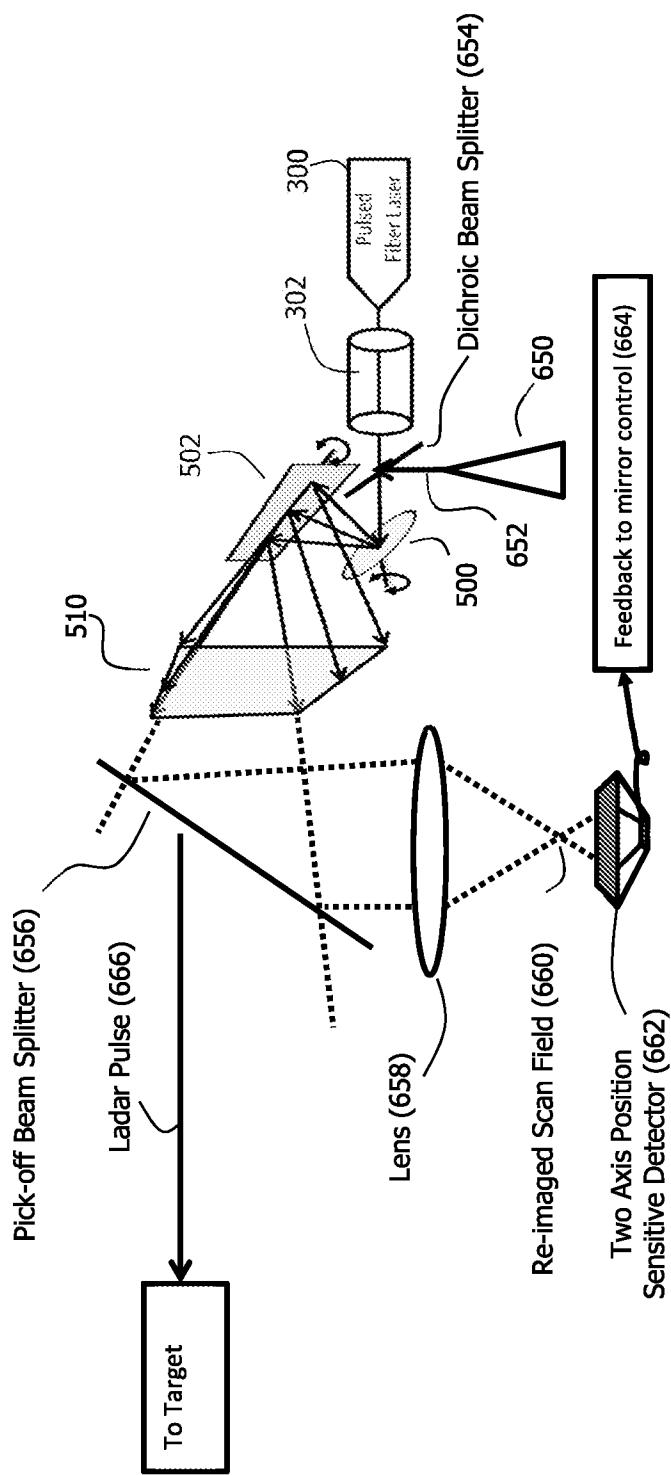
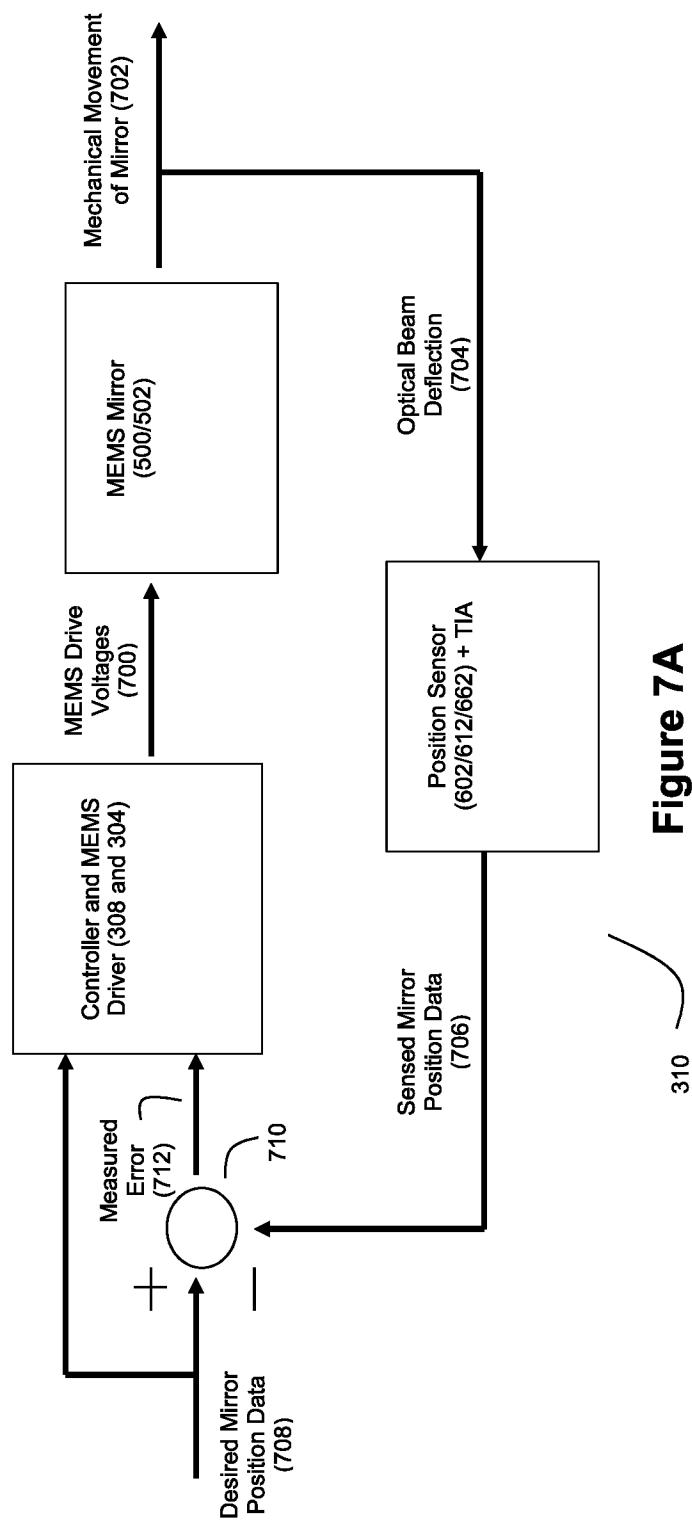


Figure 6C

**Figure 7A**

310

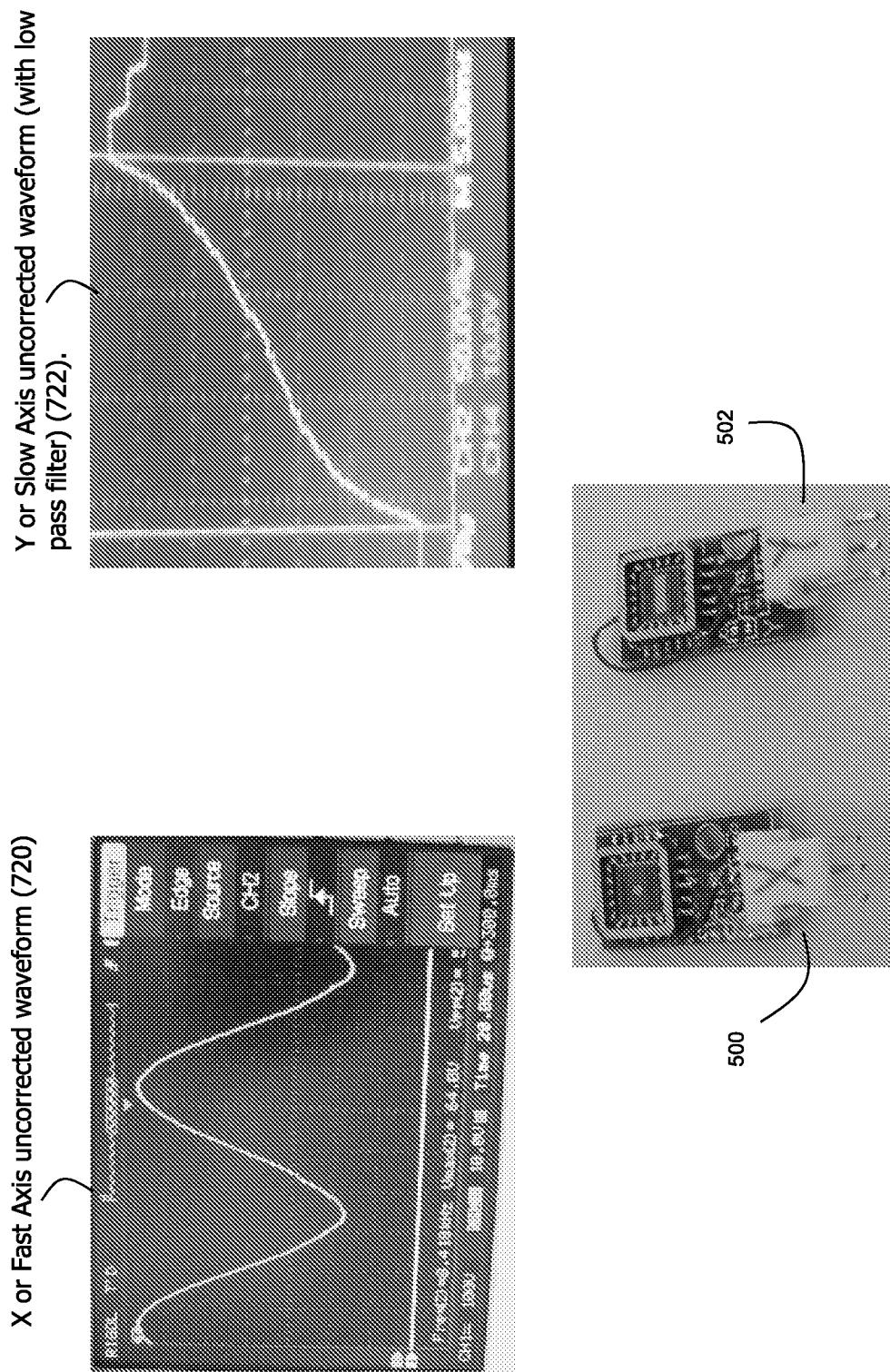


Figure 7B

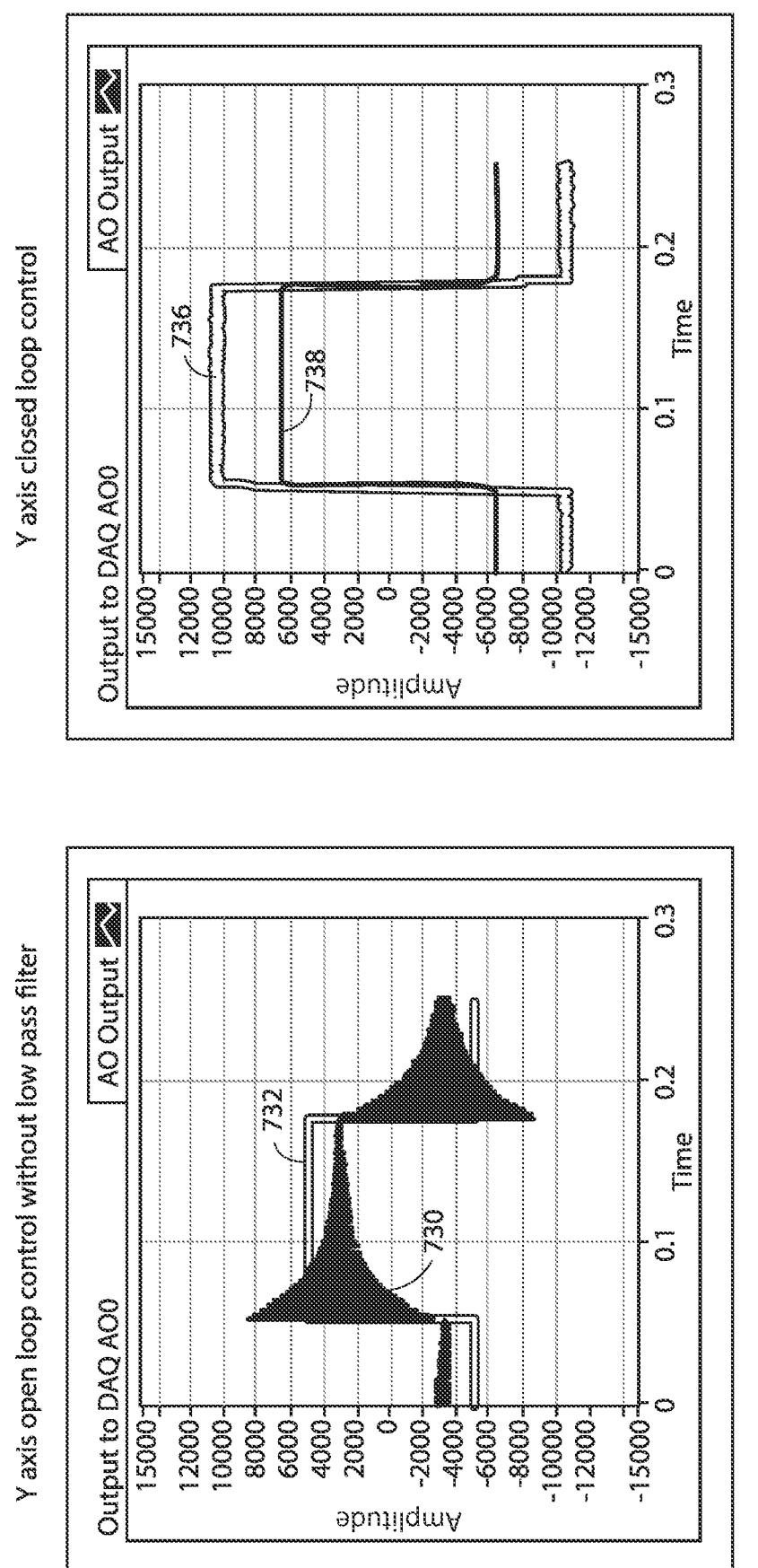


Figure 7C

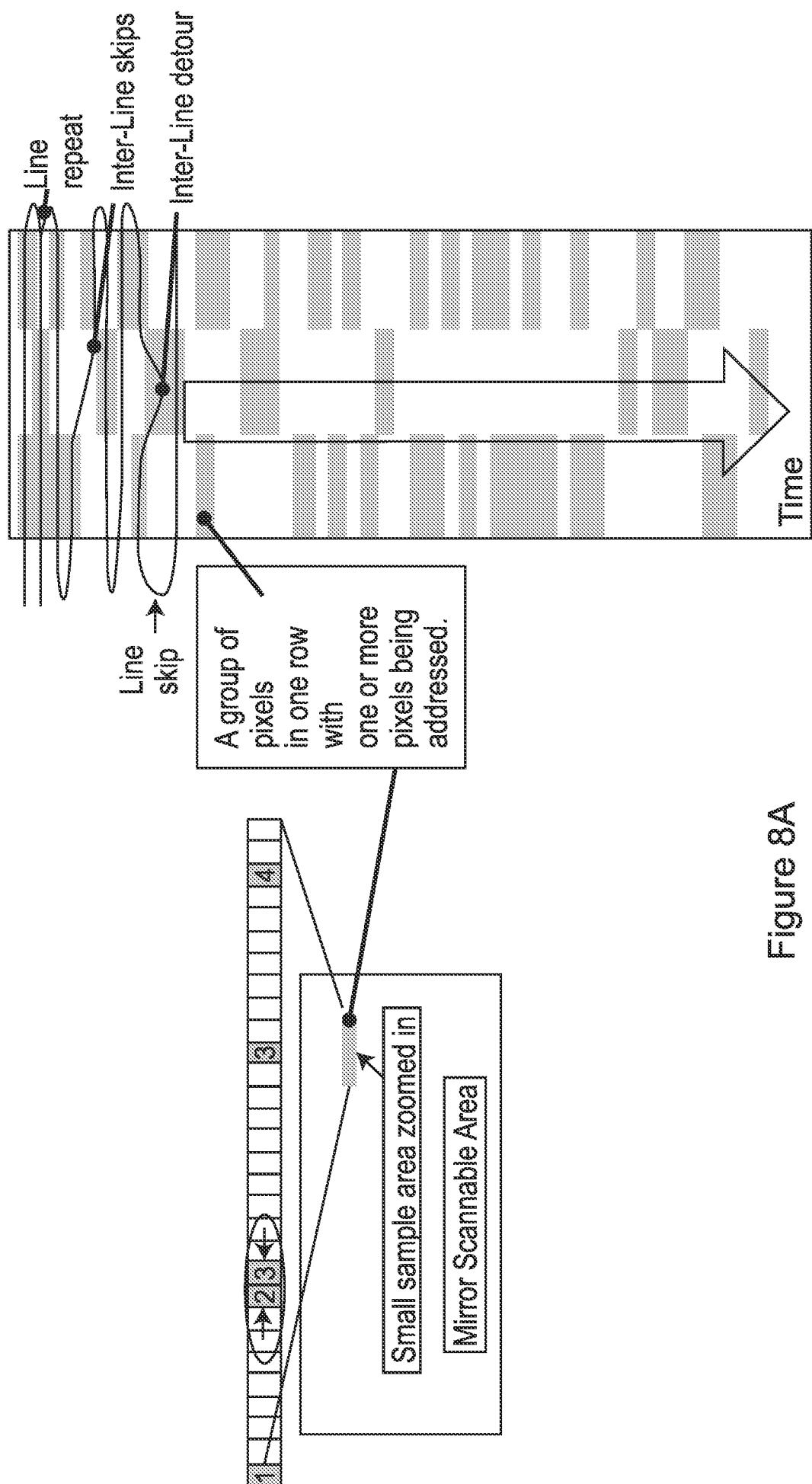


Figure 8A

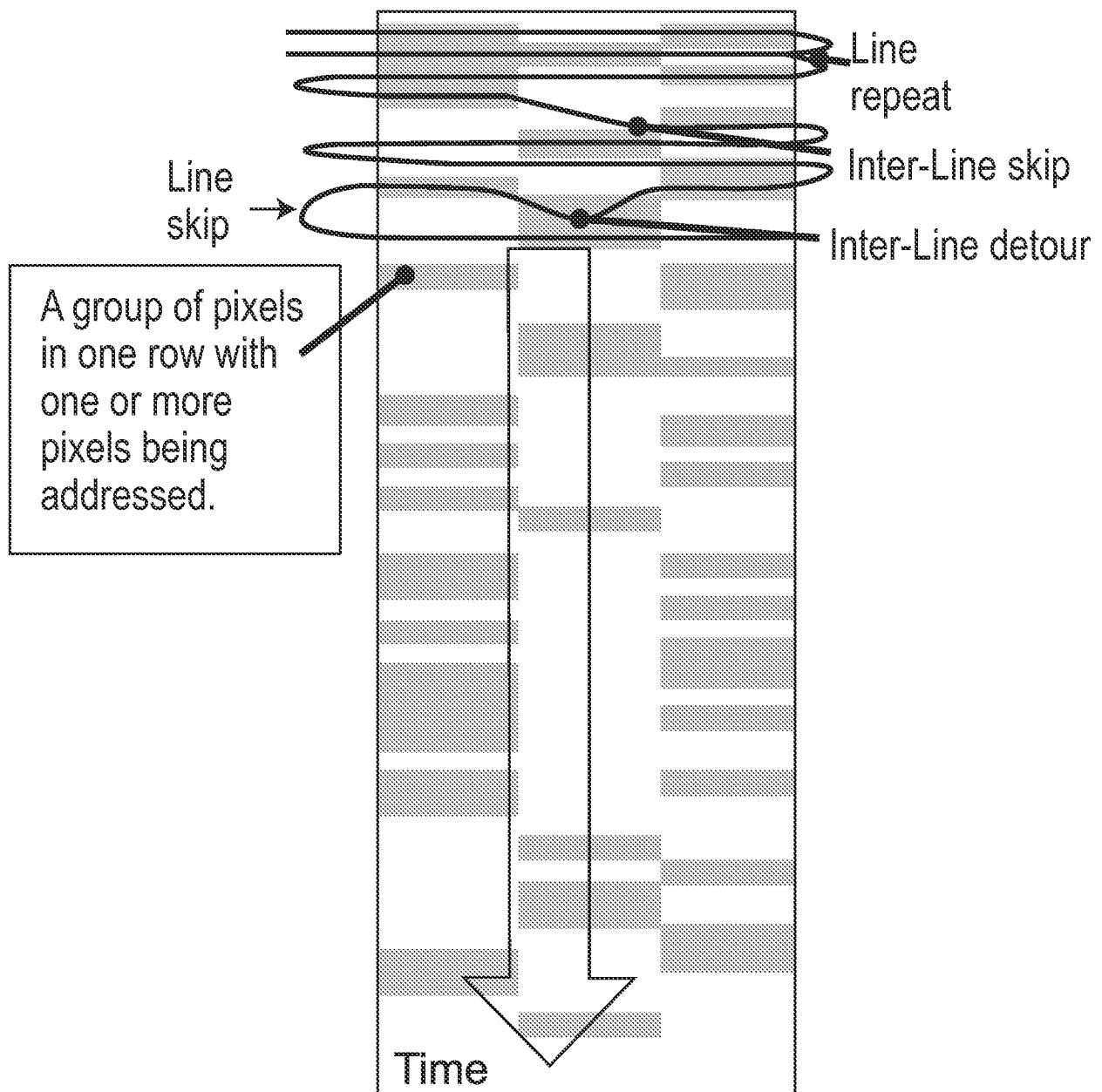


Figure 8B

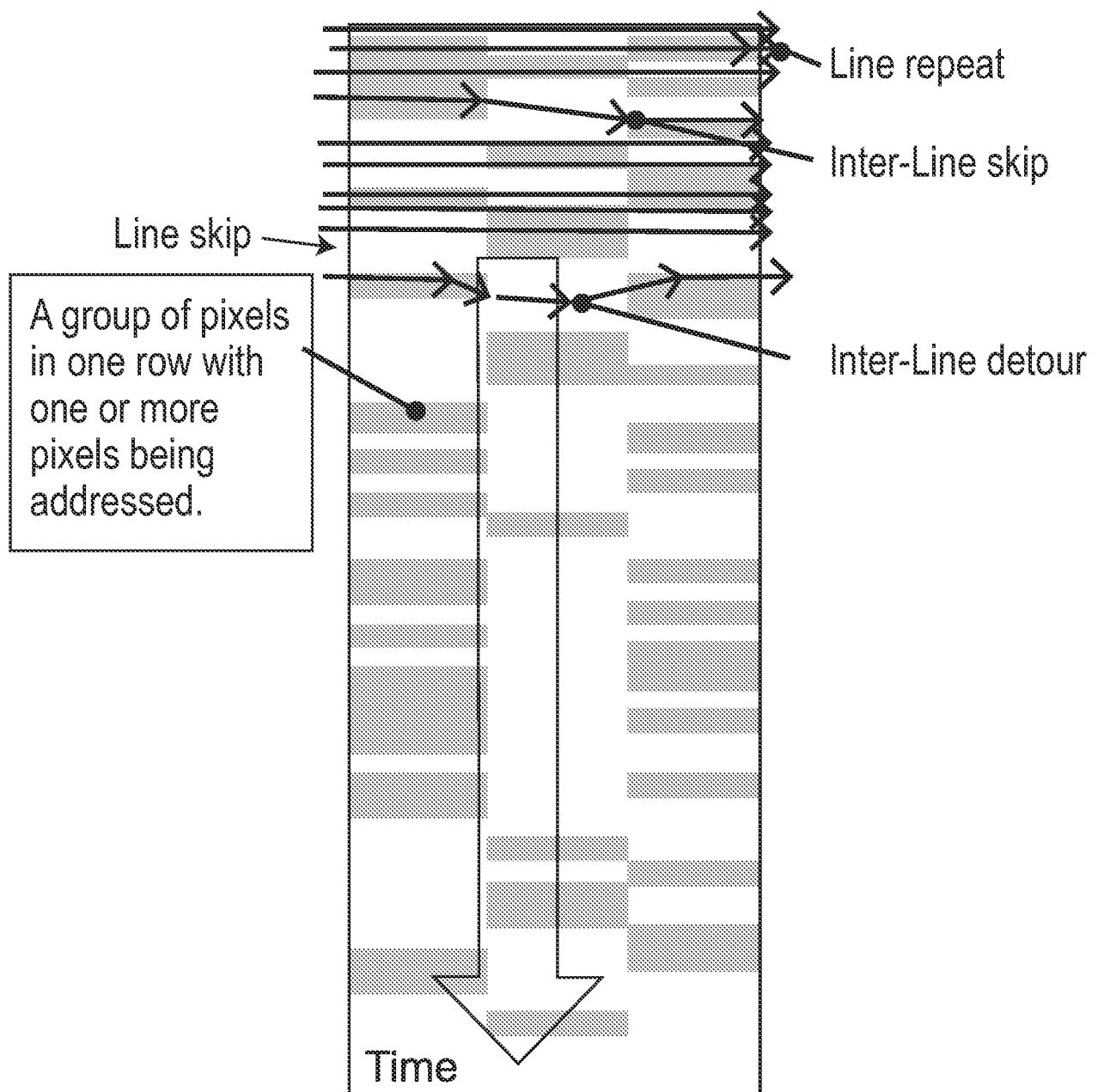


Figure 8C

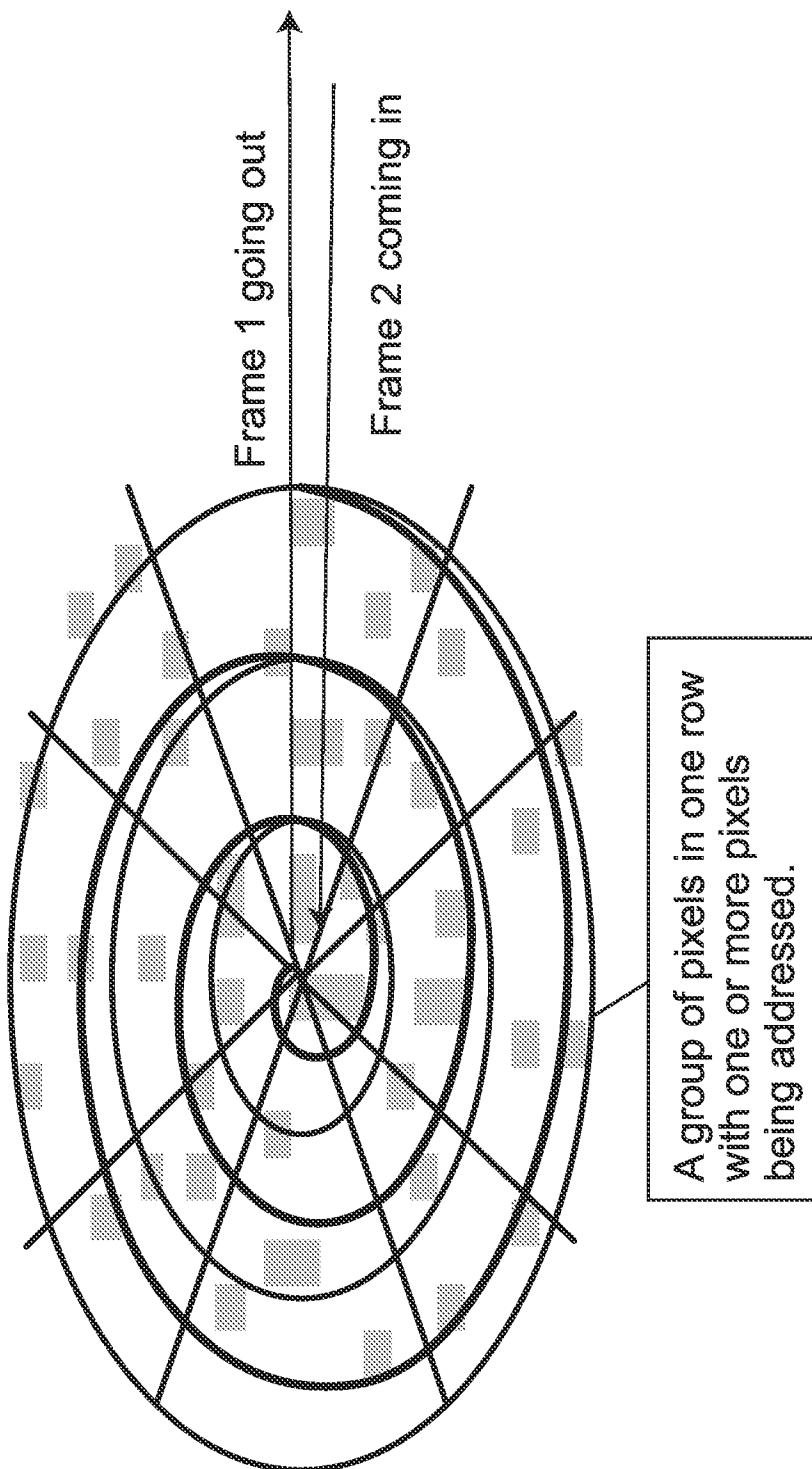


Figure 8D

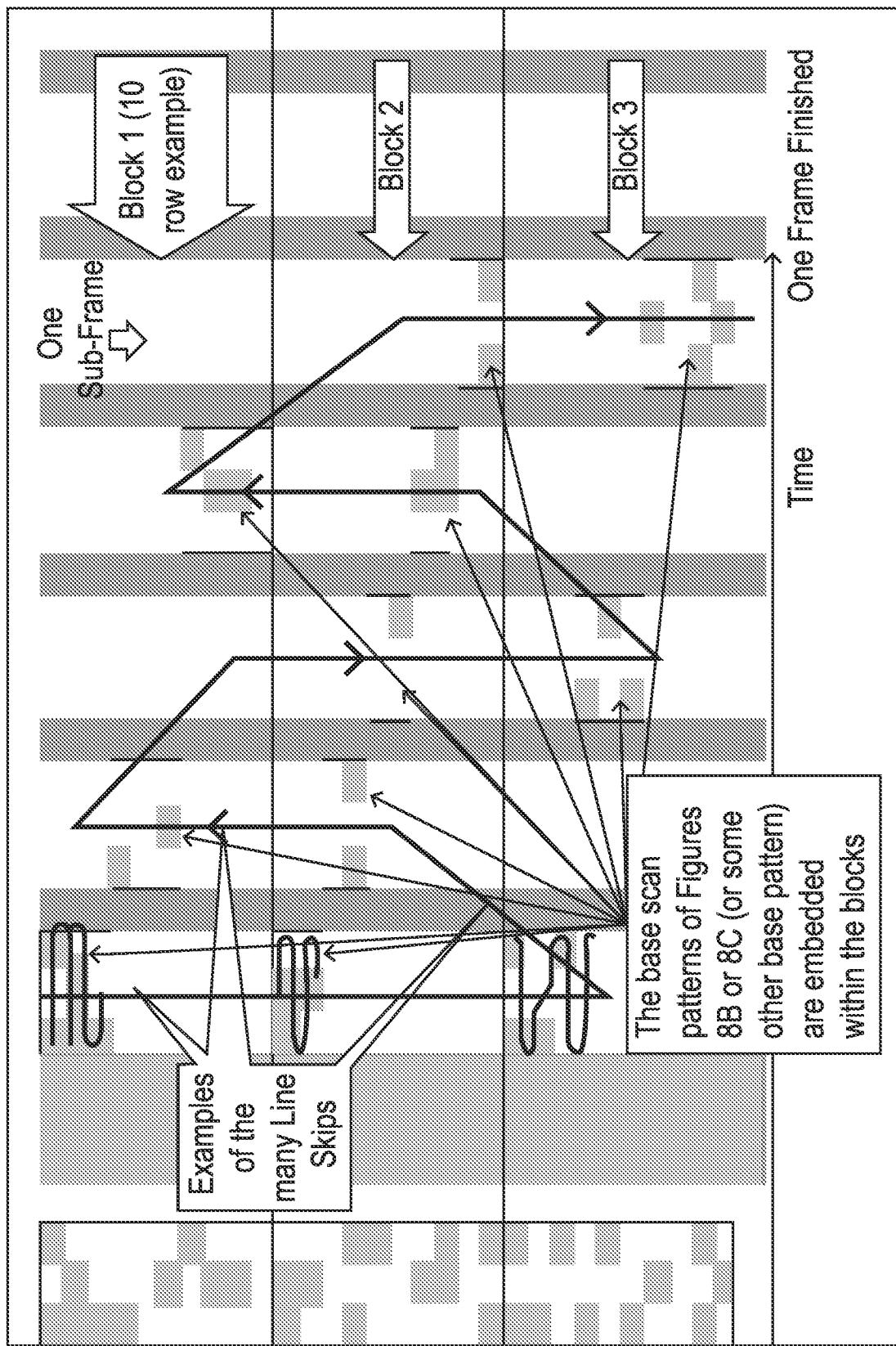


Figure 8E

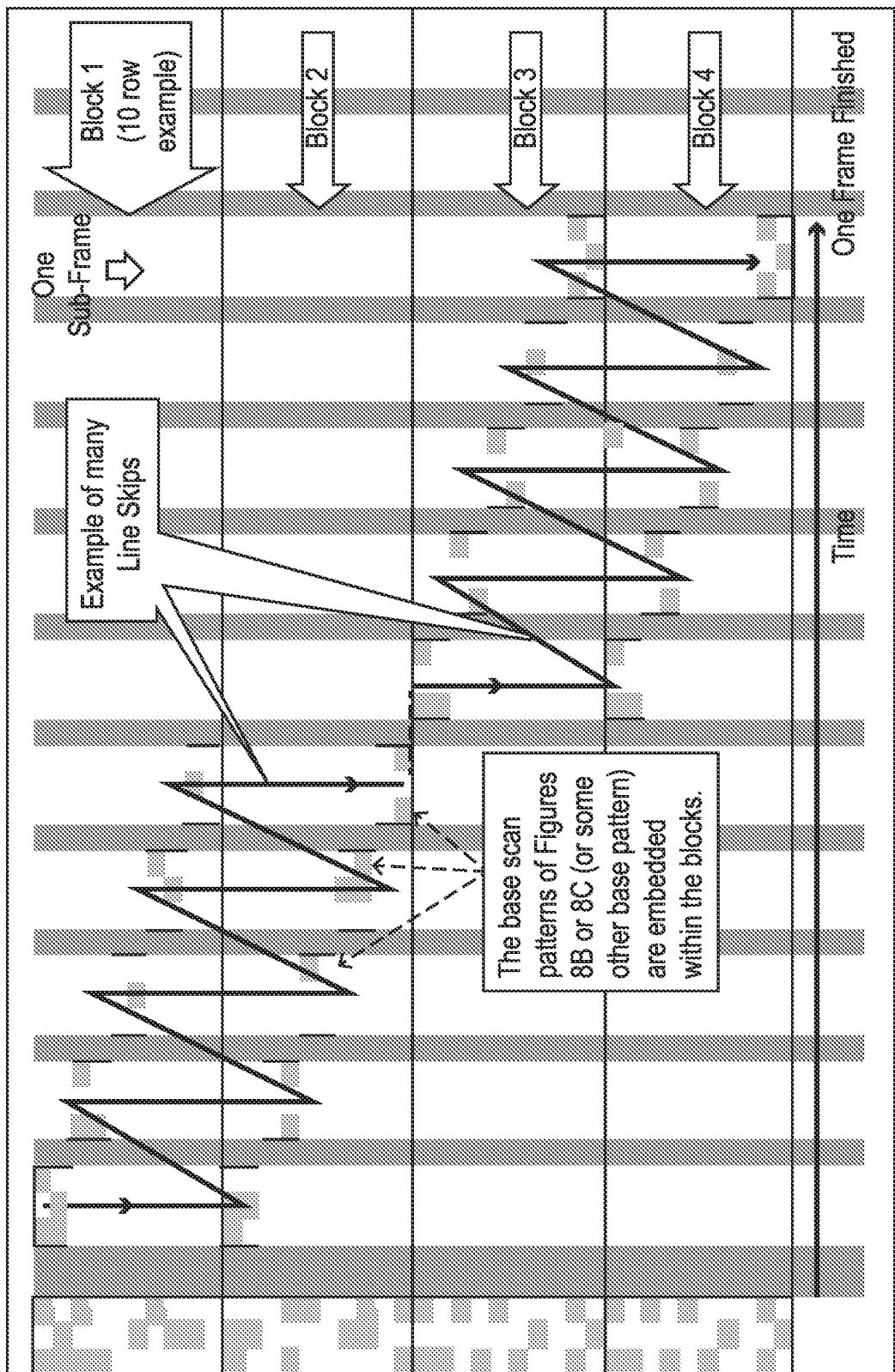


Figure 8F

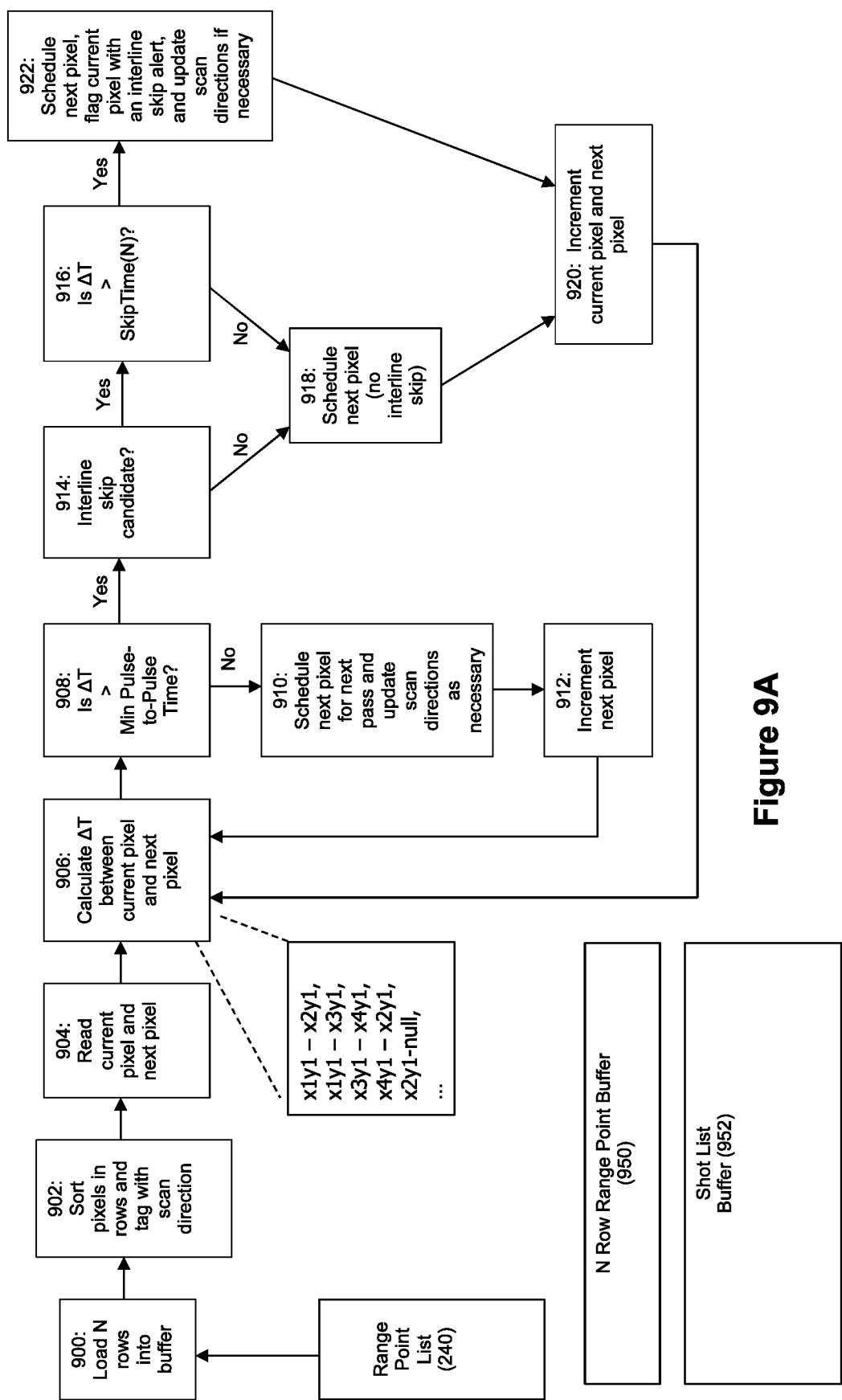


Figure 9A

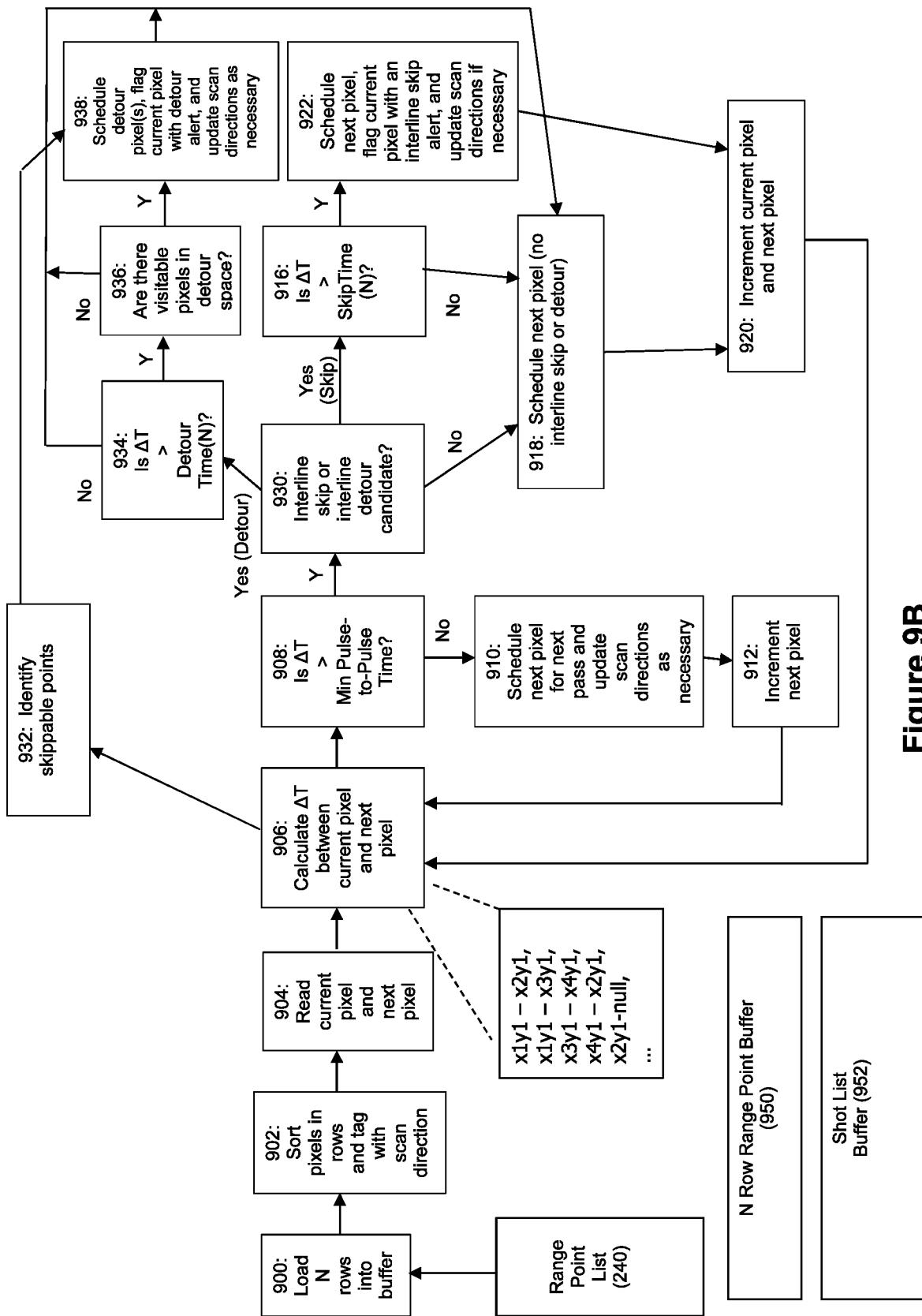


Figure 9B

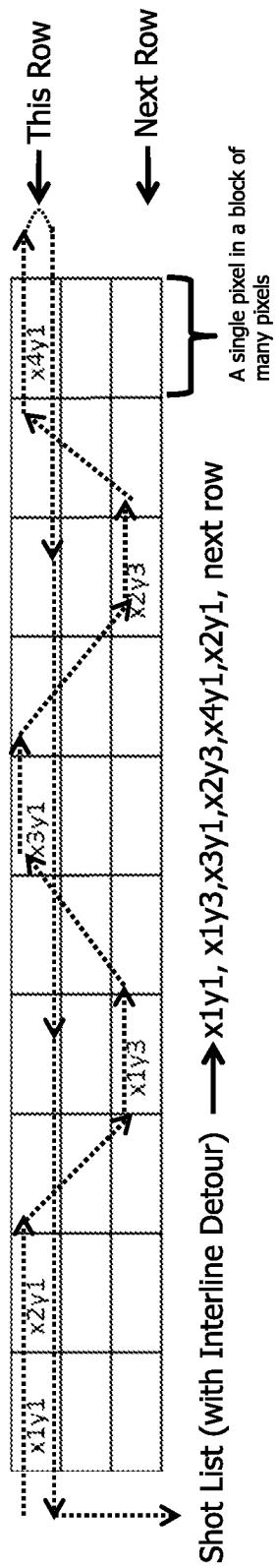
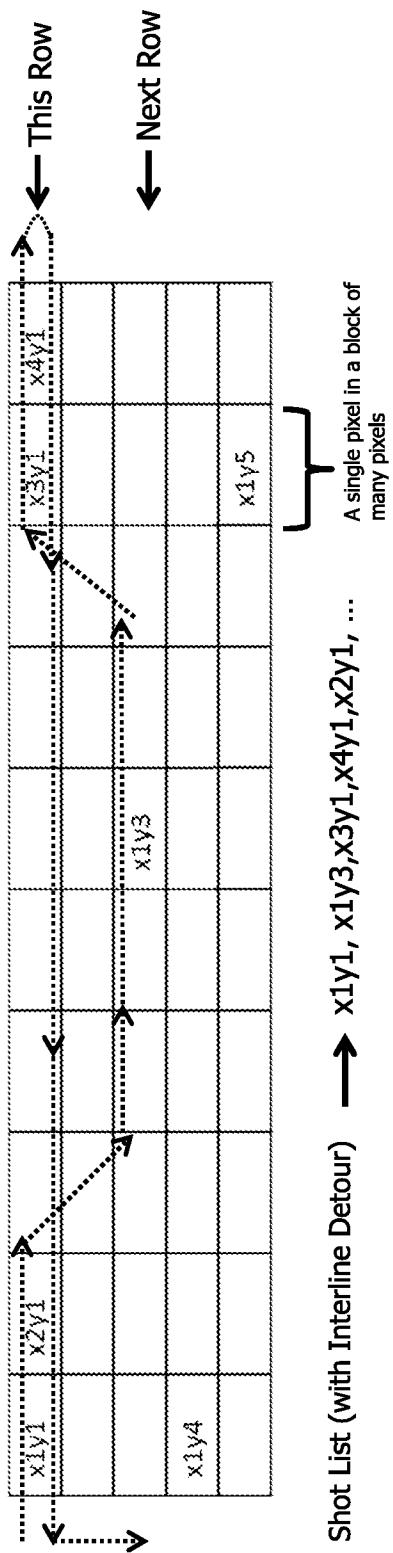
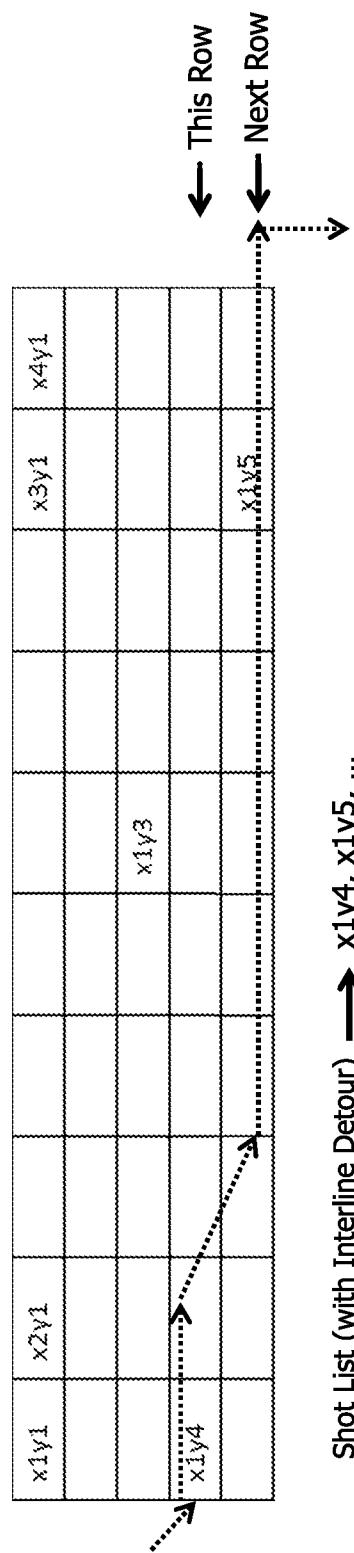


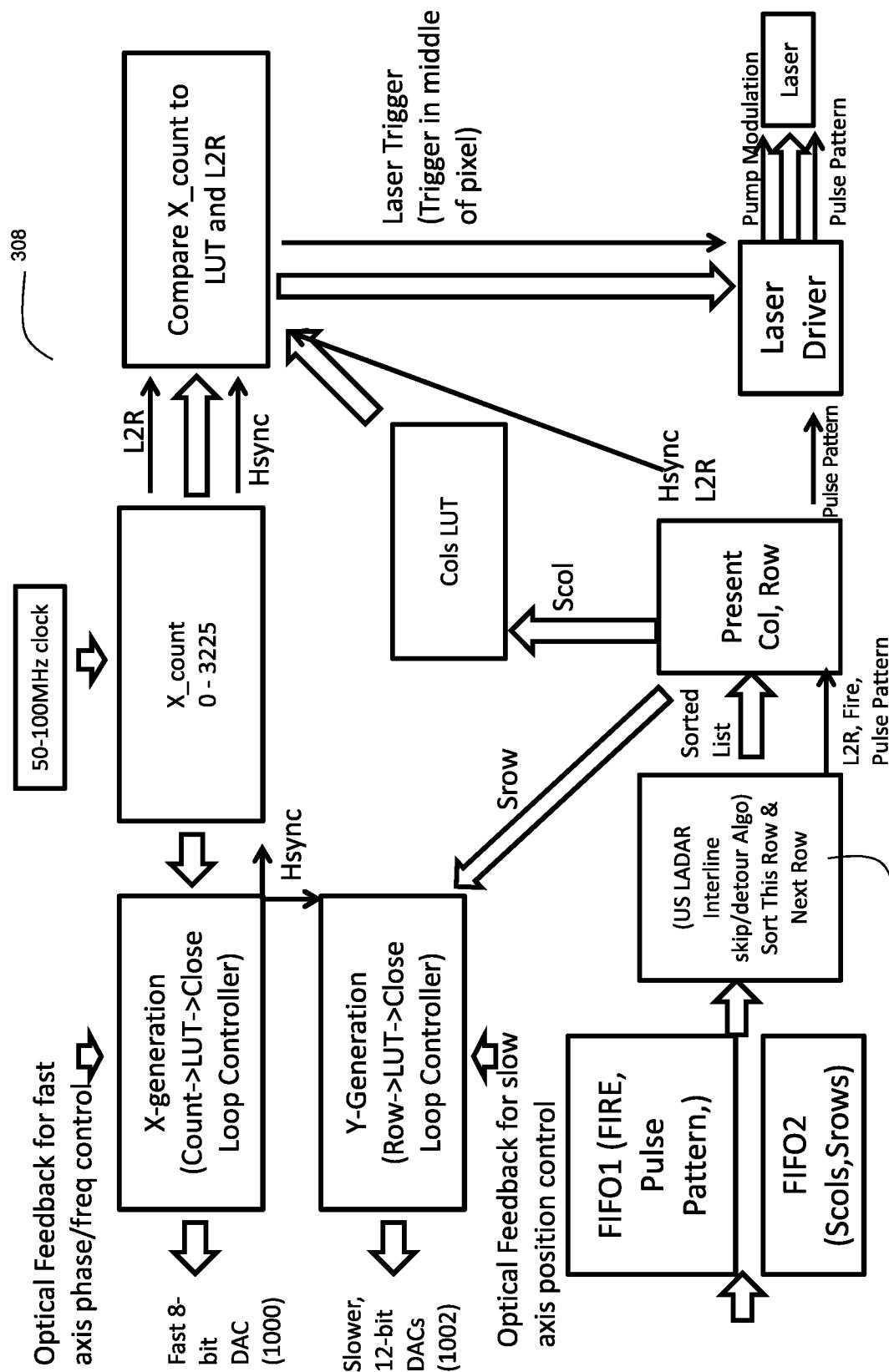
Figure 9C

**Figure 9D****Figure 9E**

Rangepoint List		Shot List		952		954		956	
row / column	240	950		Left to right or right to left		Is it a live viewpoint or a real fire command		One of several intensity modulated codes	
		10 bits	10 bits	SCol	L2R	Fire	Pulse Pattern	Inter Skip	
104	19	104	104	19	26	0	1	1	0
104	26	104	105	4	1	1	1	1	0
105	4	105	105	13	1	1	1	1	0
105	13	105	105	31	1	1	1	1	0
105	22	105	105	48	0	1	1	1	0
105	31	105	105	40	0	1	1	1	0
105	40	105	105	22	0	1	1	1	0
105	49	105	110	18	1	1	1	1	0
110	15	110	111	95	1	1	1	1	1
110	158	111	110	158	1	1	1	1	1
111	95	111	223	223	1	1	1	1	1
111	223								

The implementation of interline skipping and interline detour here results in one less pass by scanner and a faster frame

Figure 9F



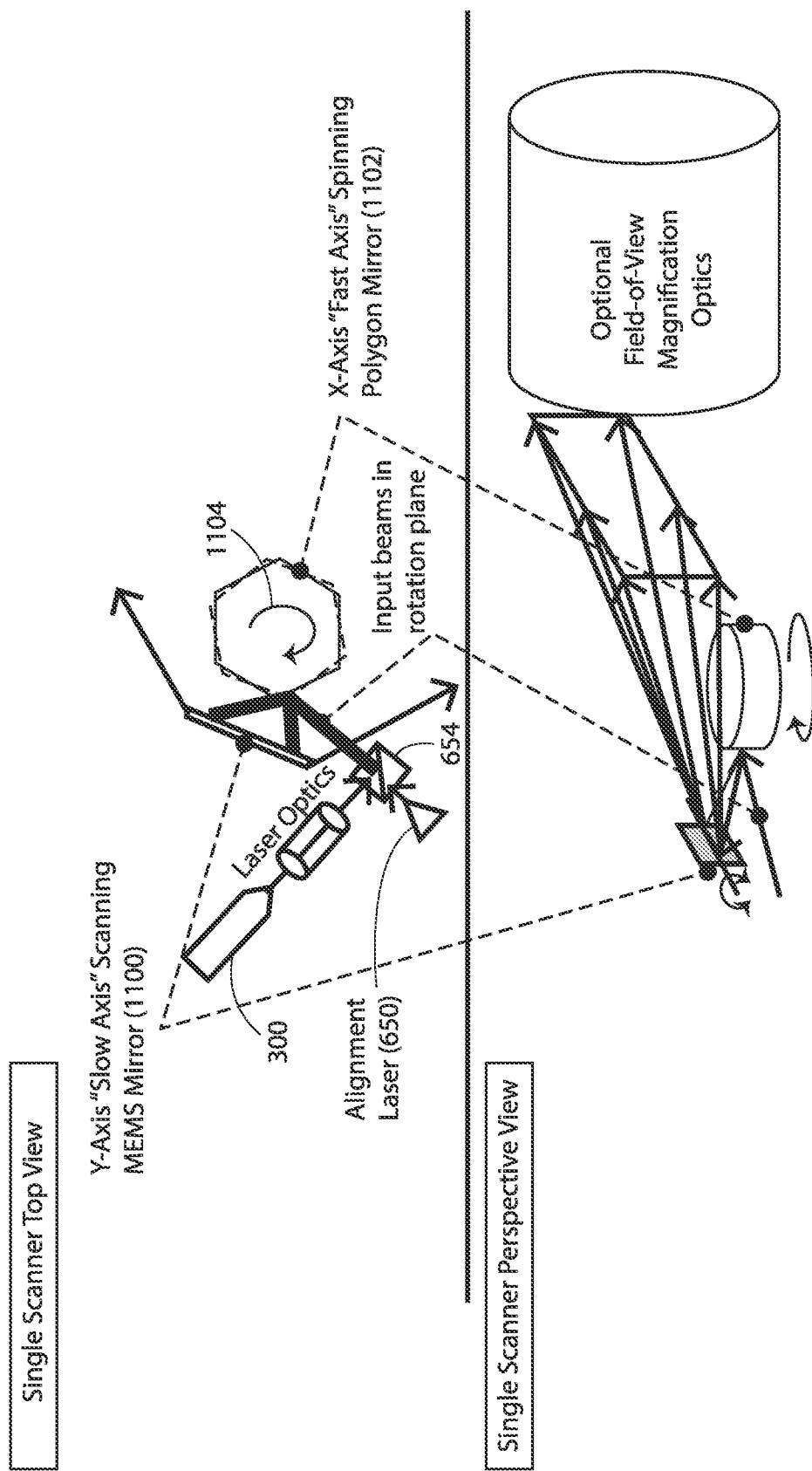


Figure 11A

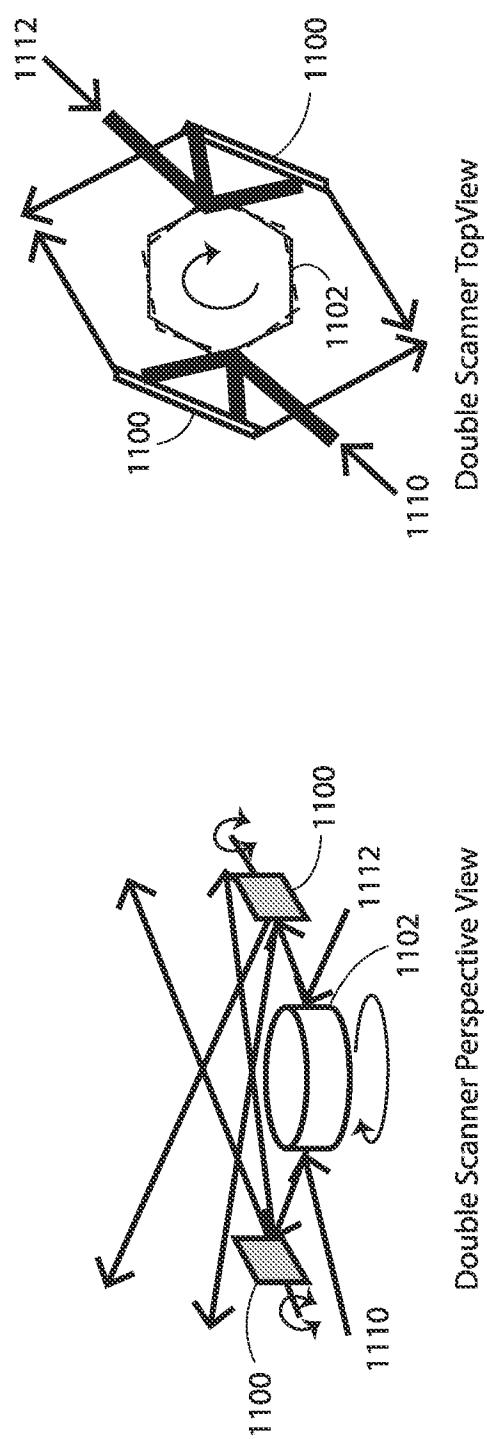
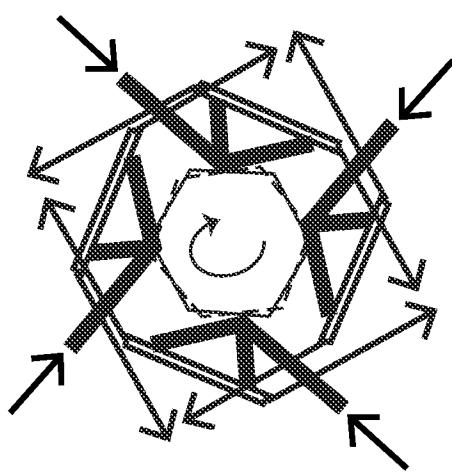
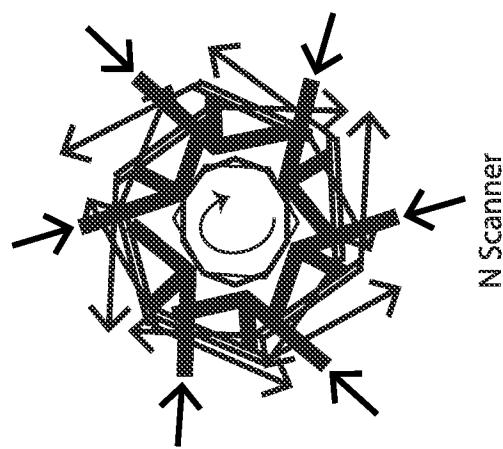
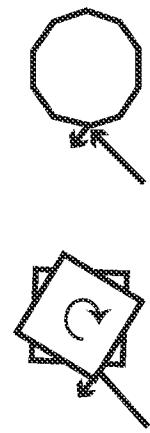
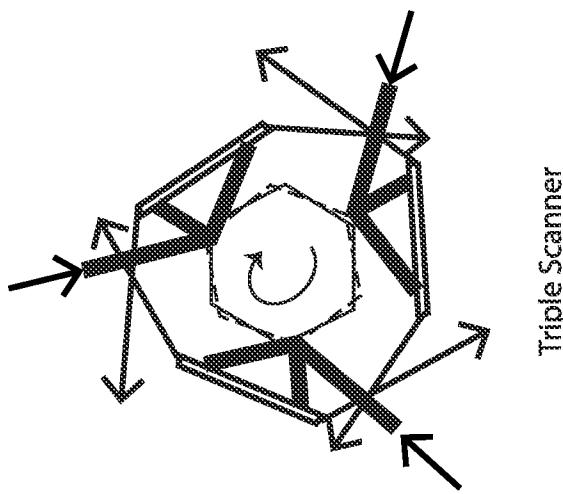


Figure 11B



Quad Scanner
Figure 11C



Different Polygon Types

Figure 11D

Top View:
 N independent scan fields of 20-180 degrees.
(In this example there are 4 scan field of about
110 degrees.)

Figure 11E

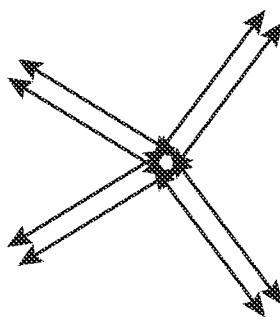
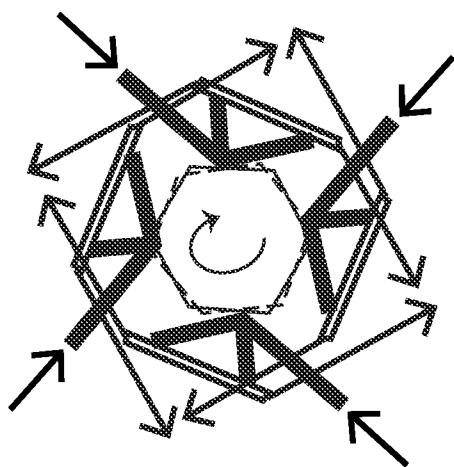
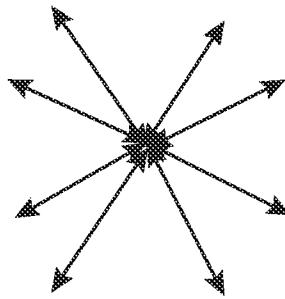
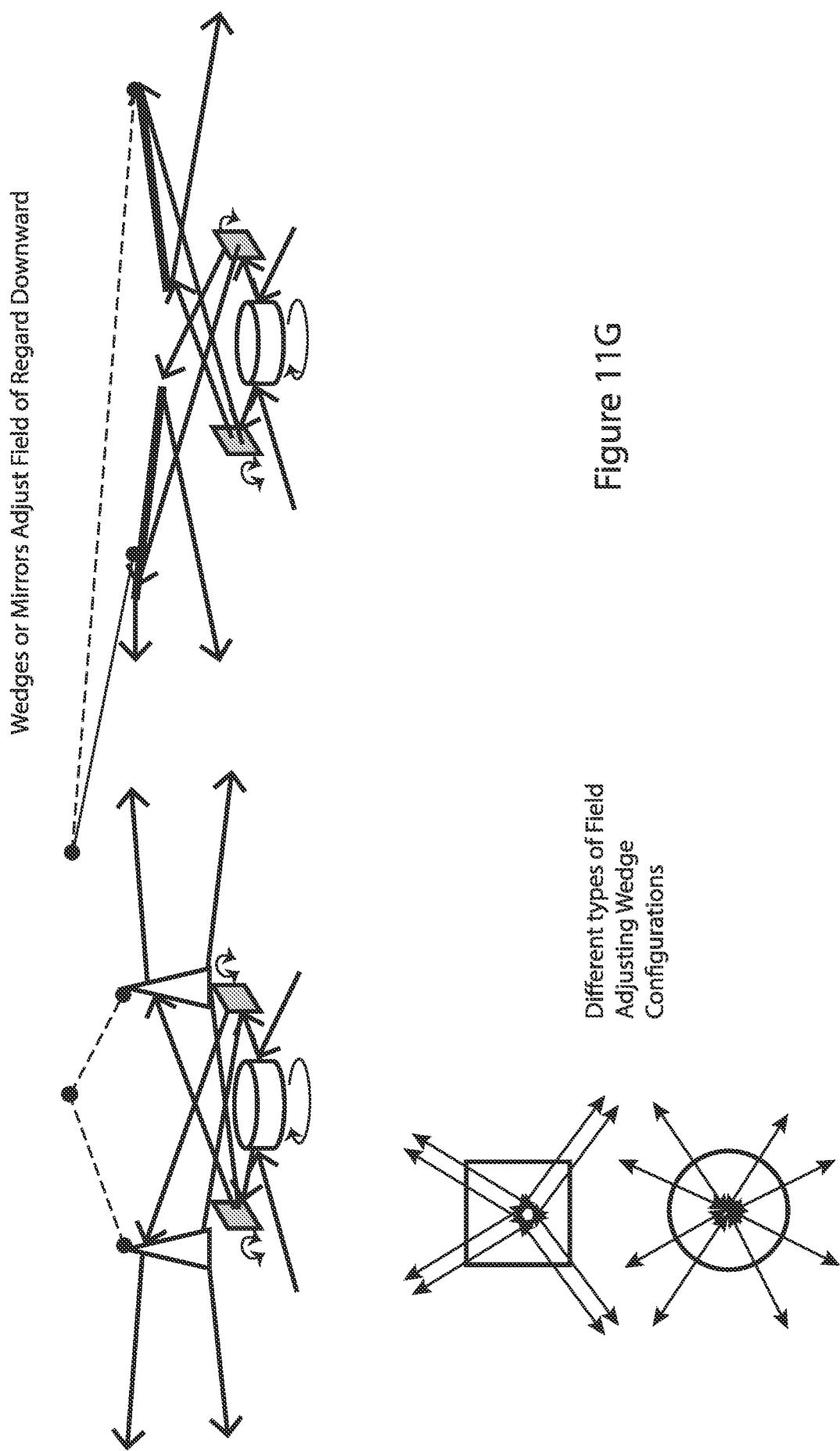
Non-Symmetric
Angle Variations

Figure 11F



Symmetric Angles



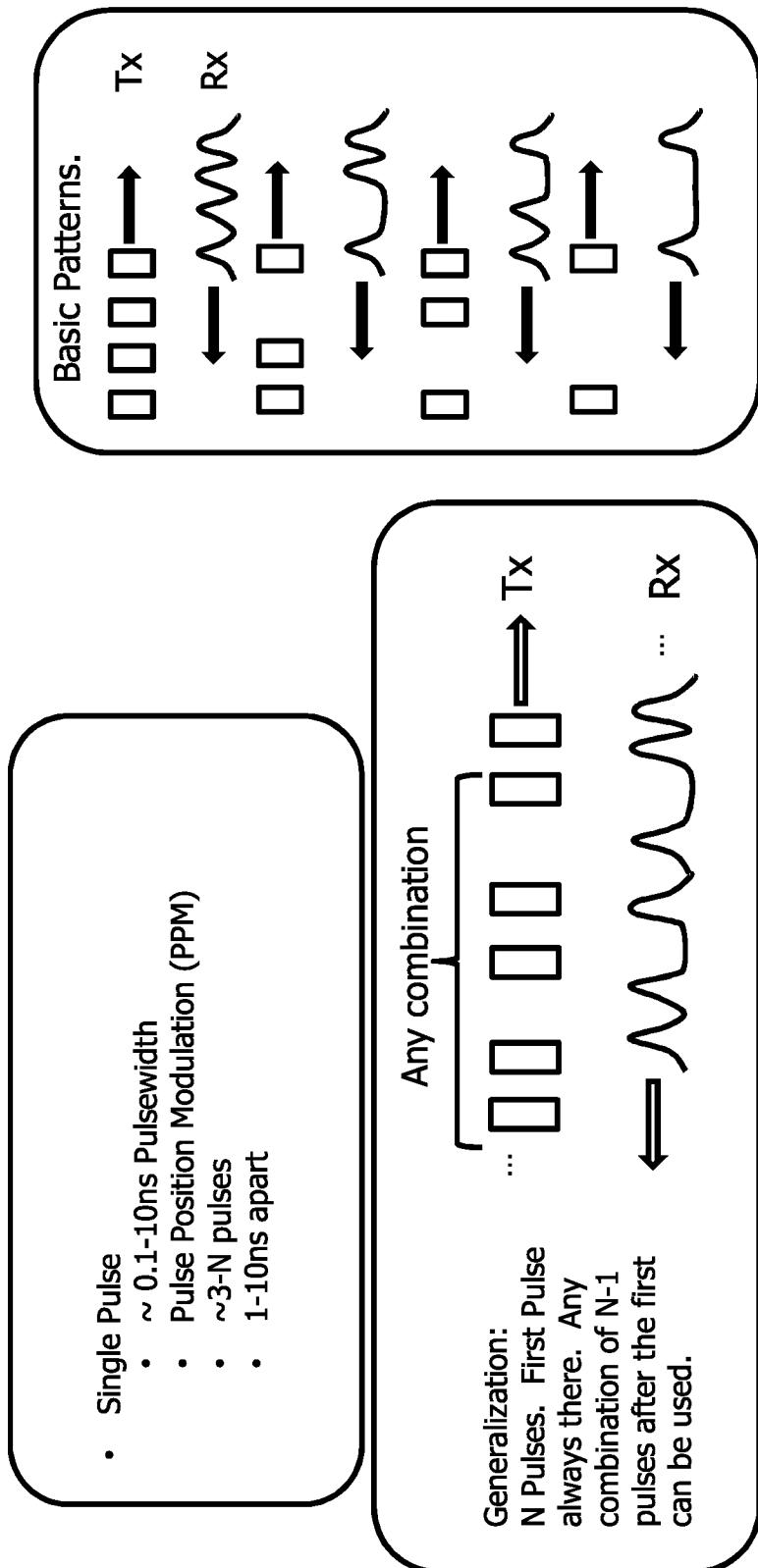
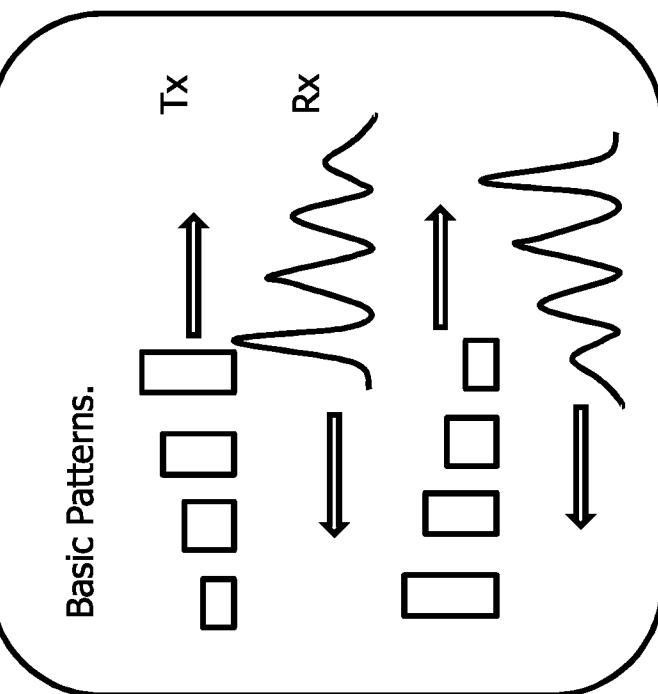


Figure 12A



- Short Asymmetric AM Burst
 - $\sim 0.1\text{-}10\text{ns}$ Pulsewidth
 - $\sim 2\text{-}10$ pulses
 - 1-10ns apart
 - Uses Amplitude Modulation (AM)
 - PPM may also be used in addition to this

Figure 12B