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Toshniwal et al.

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(54) **TECHNIQUES FOR PARALLEL CASCADE FILTERING IN POINT CLOUDS**

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G01N 21/84 (2006.01)
G01S 7/4912 (2020.01)

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(52) **U.S. Cl.**

CPC ***G06T 5/70*** (2024.01); ***G01S 7/4912*** (2013.01); ***G01S 7/493*** (2013.01); ***G01S 17/32*** (2013.01);

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CPC G06V 10/462; G01S 7/4912; G01S 7/493; G01S 17/32; G01S 17/58; G01S 17/89
See application file for complete search history.

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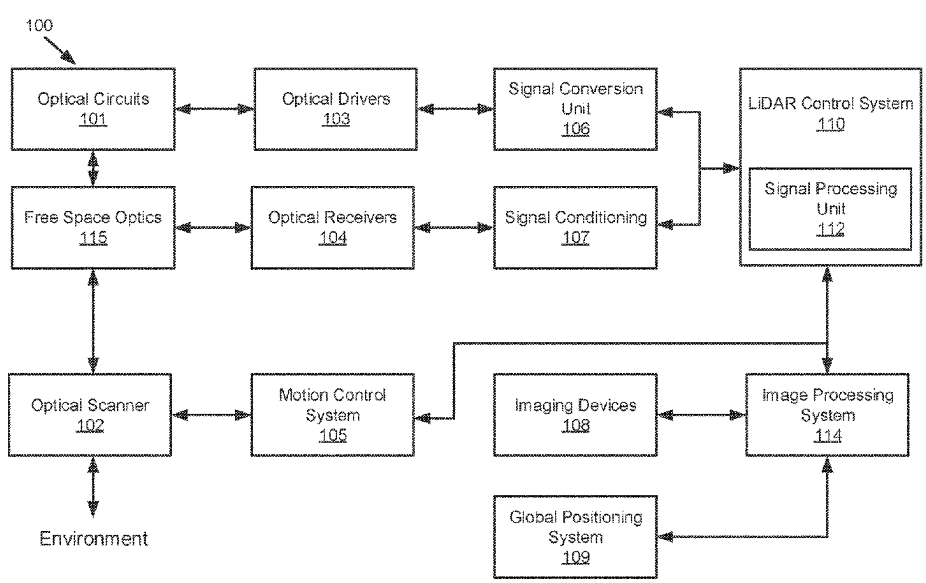
(57) **ABSTRACT**

A set of POIs of a point cloud are received at a first filter. Each POI of the set of POIs is filtered. At a second filter, based on a first metric, a first score of the POI is determined. At a third filter, based on a second metric, a second score of the POI is determined. At the first filter, based on the first score and the second score, whether to accept the POI, modify the POI, or reject the POI, is determined to extract range or velocity information.

21 Claims, 16 Drawing Sheets



Related U.S. Application Data

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(51) **Int. Cl.**

G01S 7/493	(2006.01)
G01S 17/32	(2020.01)
G01S 17/58	(2006.01)
G01S 17/89	(2020.01)
G06T 5/50	(2006.01)
G06T 5/70	(2024.01)
G06V 10/30	(2022.01)
G06V 10/44	(2022.01)
G06V 10/46	(2022.01)
G06V 20/64	(2022.01)

(52) **U.S. Cl.**

CPC ***G01S 17/58*** (2013.01); ***G01S 17/89*** (2013.01); ***G06T 5/50*** (2013.01); ***G06V 10/30*** (2022.01); ***G06V 10/443*** (2022.01); ***G06V 10/462*** (2022.01); ***G06V 20/64*** (2022.01)

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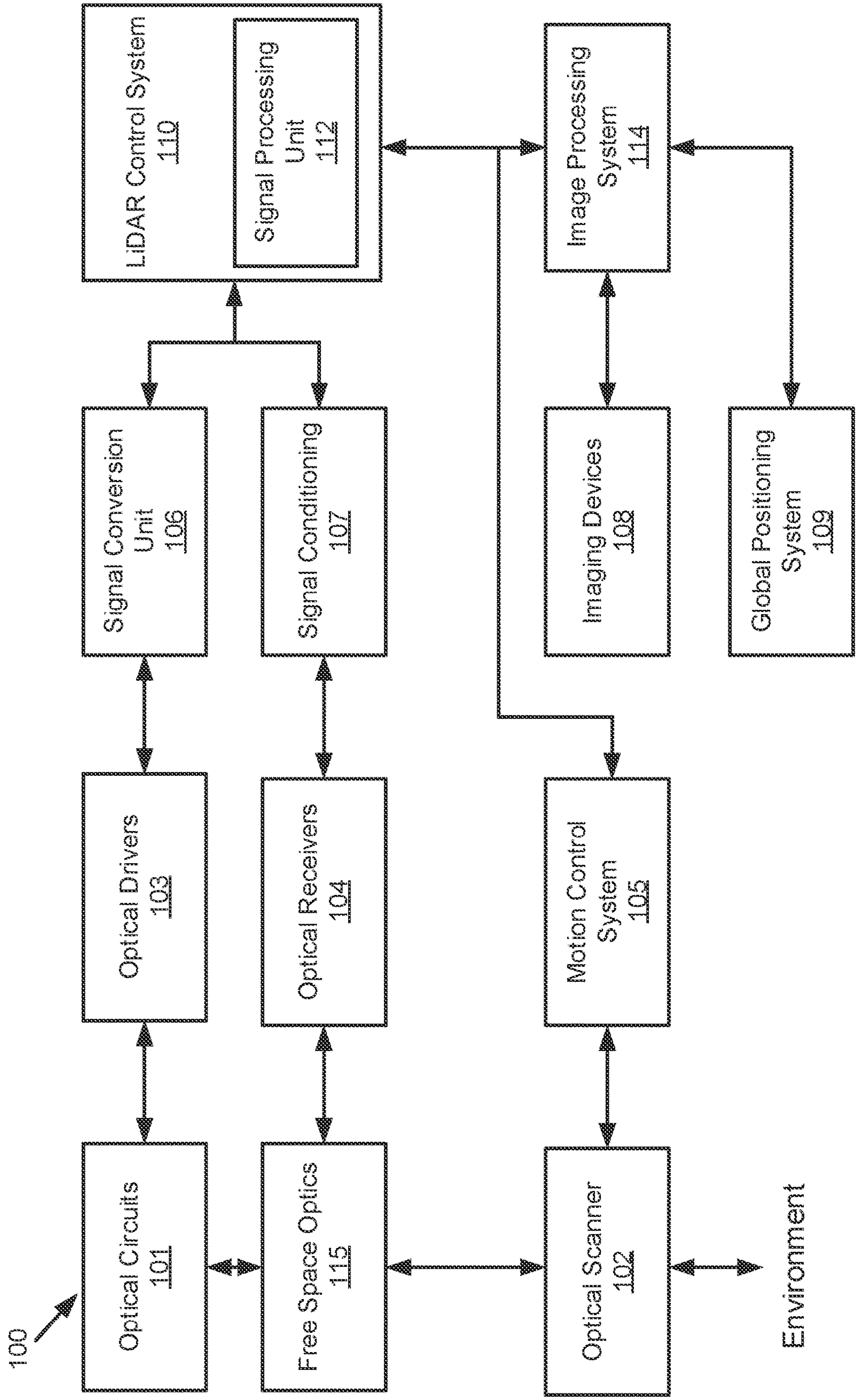
100
Optical Circuits 101
Free Space Optics 115
Optical Scanner 102
Environment
Optical Drivers 103
Optical Receivers 104
Motion Control System 105
Signal Conversion Unit 106
Signal Conditioning 107
Imaging Devices 108
Global Positioning System 109
LiDAR Control System 110
Signal Processing Unit 112
Image Processing System 114

FIG. 1A

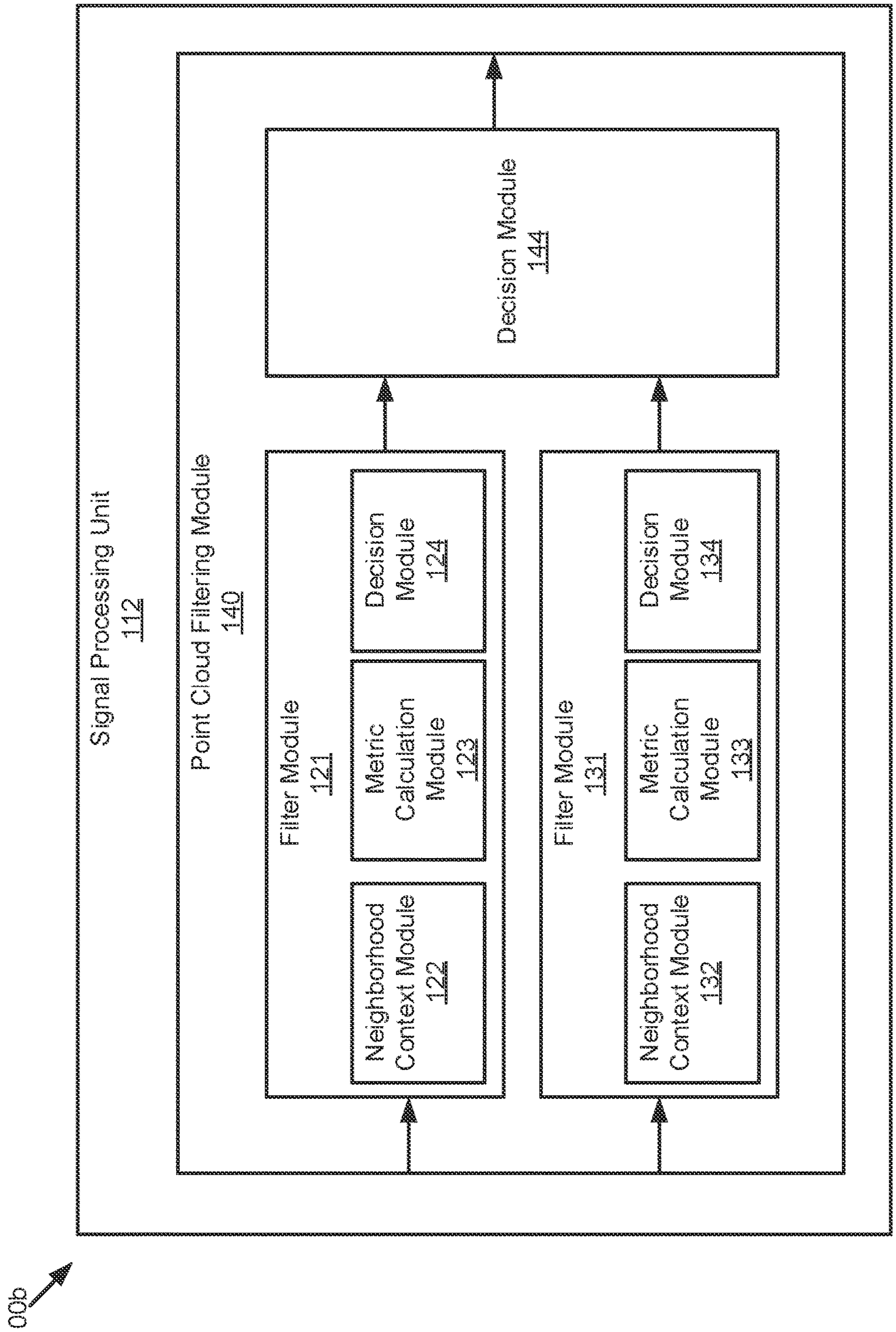
100b
Signal Processing Unit 112
Point Cloud Filtering Module 140
Filter Module 121
Neighborhood Context Module 122
Metric Calculation Module 123
Decision Module 124
Filter Module 131
Neighborhood Context Module 132
Metric Calculation Module 133
Decision Module 134
Decision Module 144

FIG. 1B

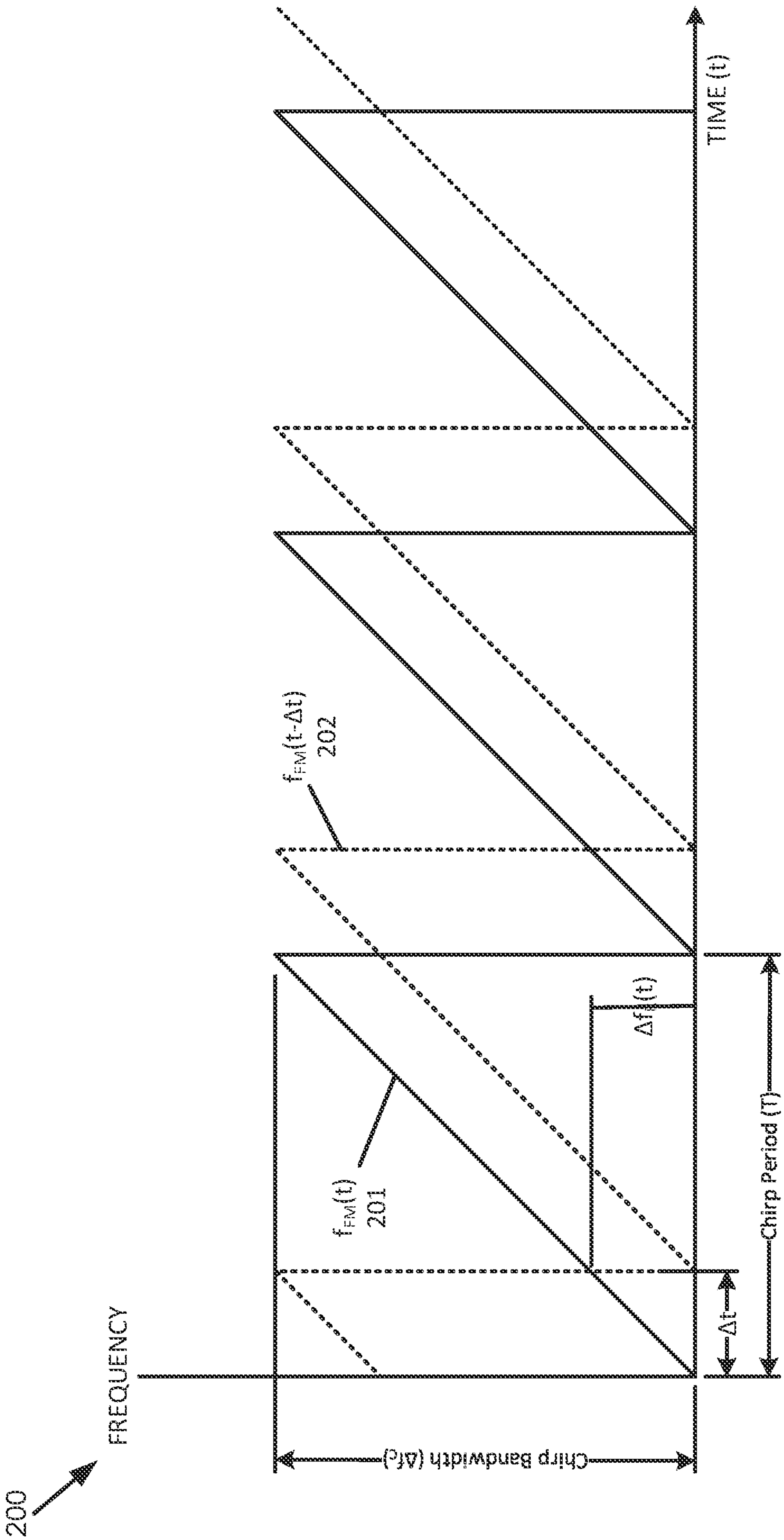
200
FREQUENCY
TIME (t)
$f_{FM}(t)$
201
$f_{FM}(t-\Delta t)$
202
$\Delta f_R(t)$
Δt
Chirp Period (T)
Chirp Bandwidth (Δf_C)

FIG. 2

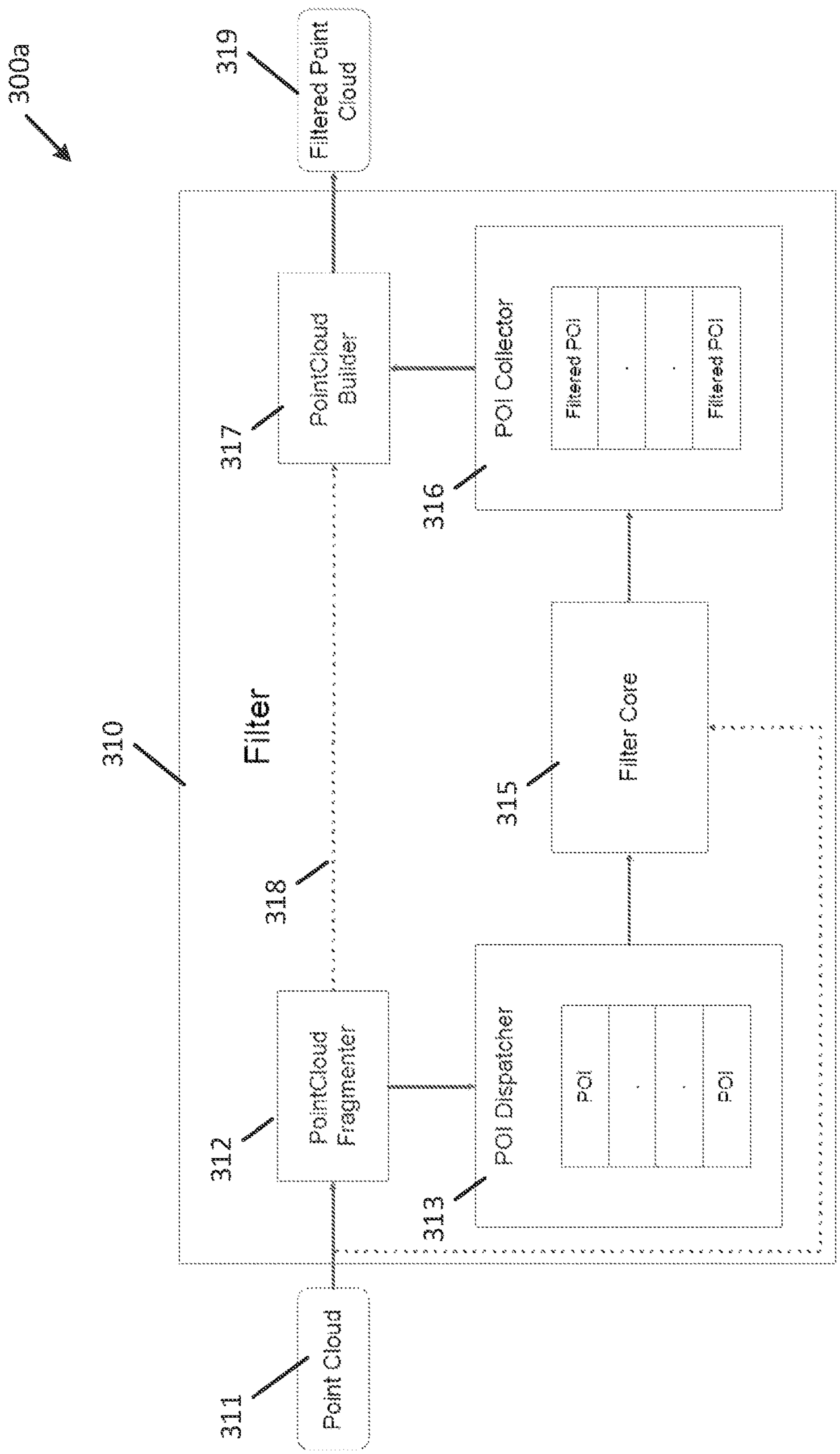
300a
319
Filtered Point Cloud
310
Filter
317
PointCloud Builder
316
POI Collector
Filtered POI
Filtered POI
315
Filter Core
318
312
PointCloud Fragmenter
313
POI Dispatcher
POI
POI
311
Point Cloud

FIG. 3A

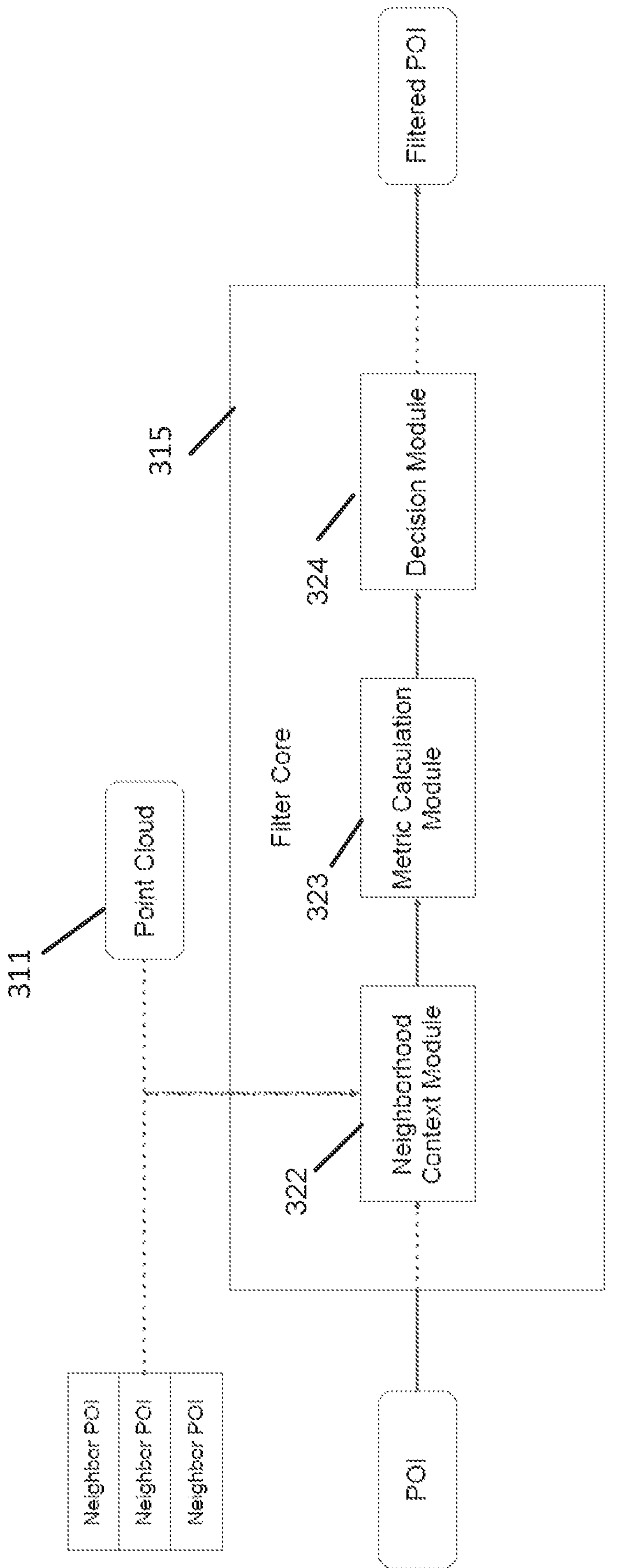
Filtered POI
315
Decision Module
324
Filter Core
Metric Calculation Module
323
Point Cloud
311
Neighborhood Context Module
322
Neighbor POI
Neighbor POI
Neighbor POI
POI

FIG. 3B

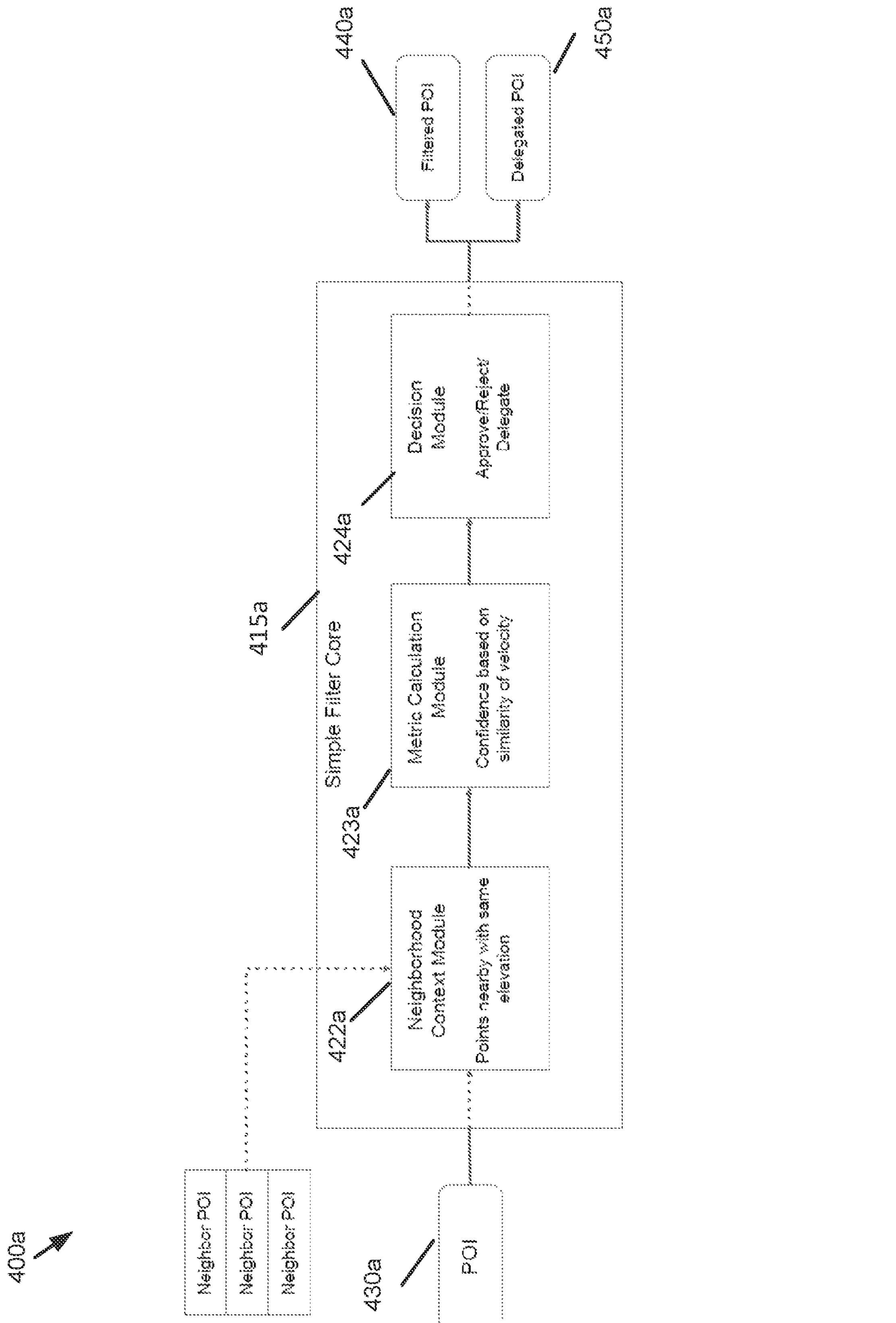
400a
Neighbor POI
Neighbor POI
Neighbor POI
430a
POI
415a
Simple Filter Core
422a
Neighborhood Context Module
Points nearby with same elevation
423a
Metric Calculation Module
Confidence based on similarity of velocity
424a
Decision Module
Approve/Reject/ Delegate
440a
Filtered POI
450a
Delegated POI

FIG. 4A

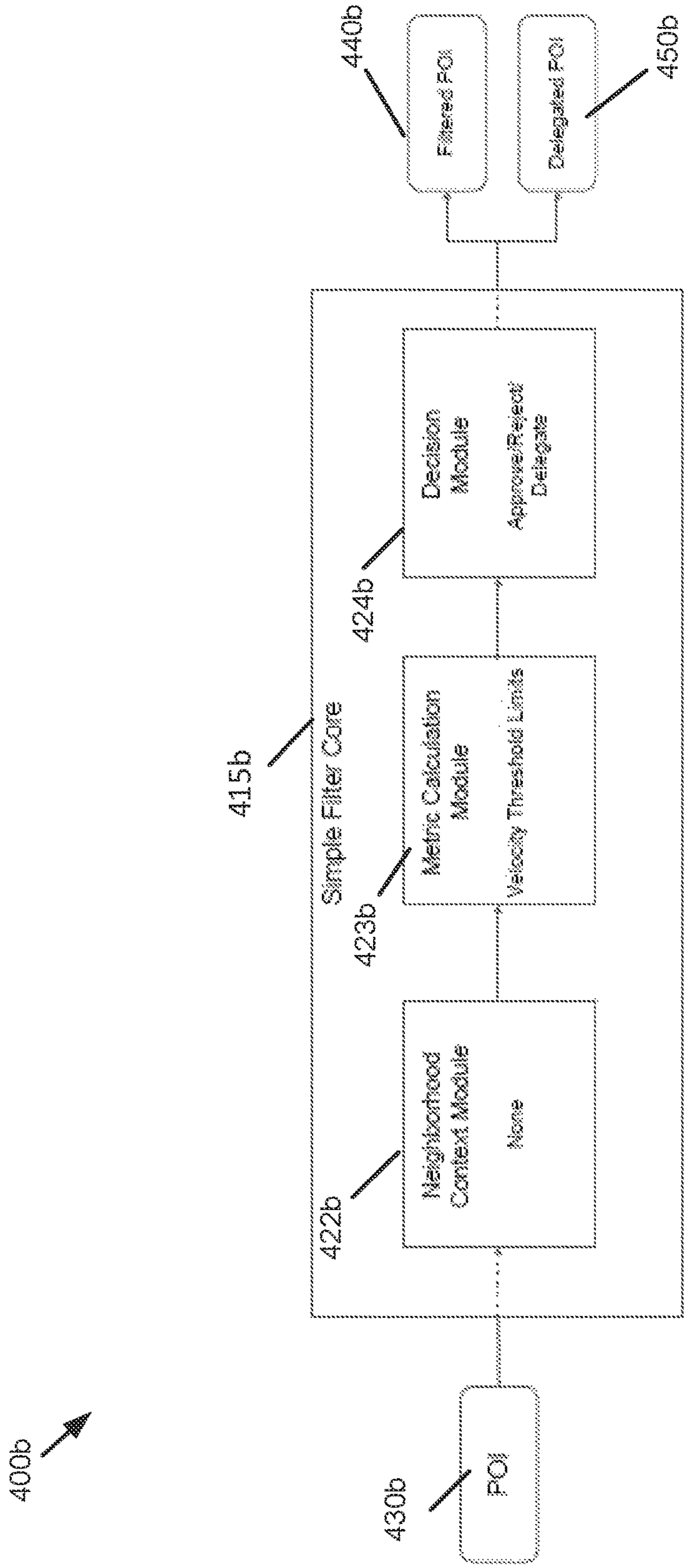
400b
430b
POI
415b
Simple Filter Core
422b
Neighborhood Context Module
None
423b
Metric Calculation Module
Velocity Threshold Limits
424b
Decision Module
Approve/Reject/Delegate
440b
Filtered POI
450b
Delegated POI

FIG. 4B

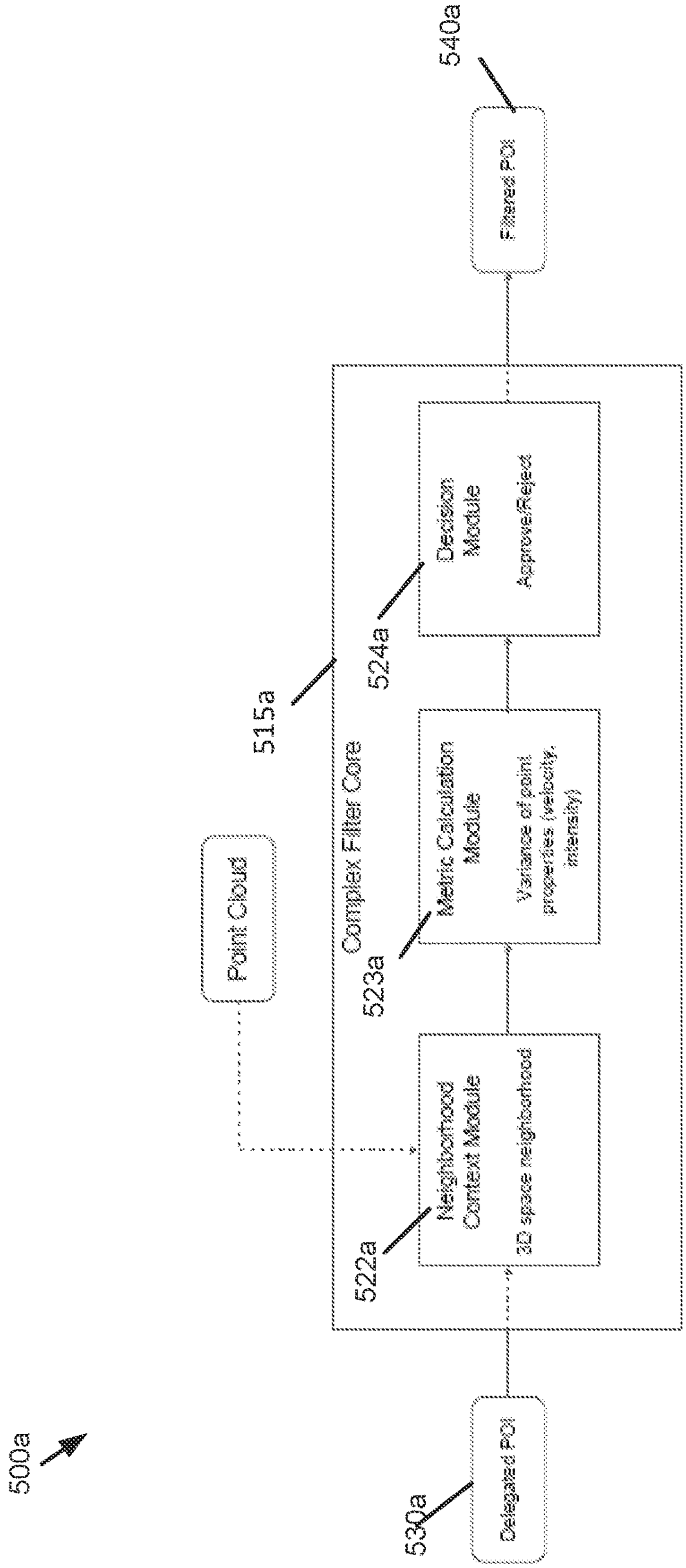
500a
530a
Delegated POI
Complex Filter Core
515a
522a
Neighborhood Context Module
3D space neighborhood
Point Cloud
523a
Metric Calculation Module
Variance of point properties (velocity, intensity)
524a
Decision Module
Approve/Reject
Filtered POI
540a

FIG. 5A

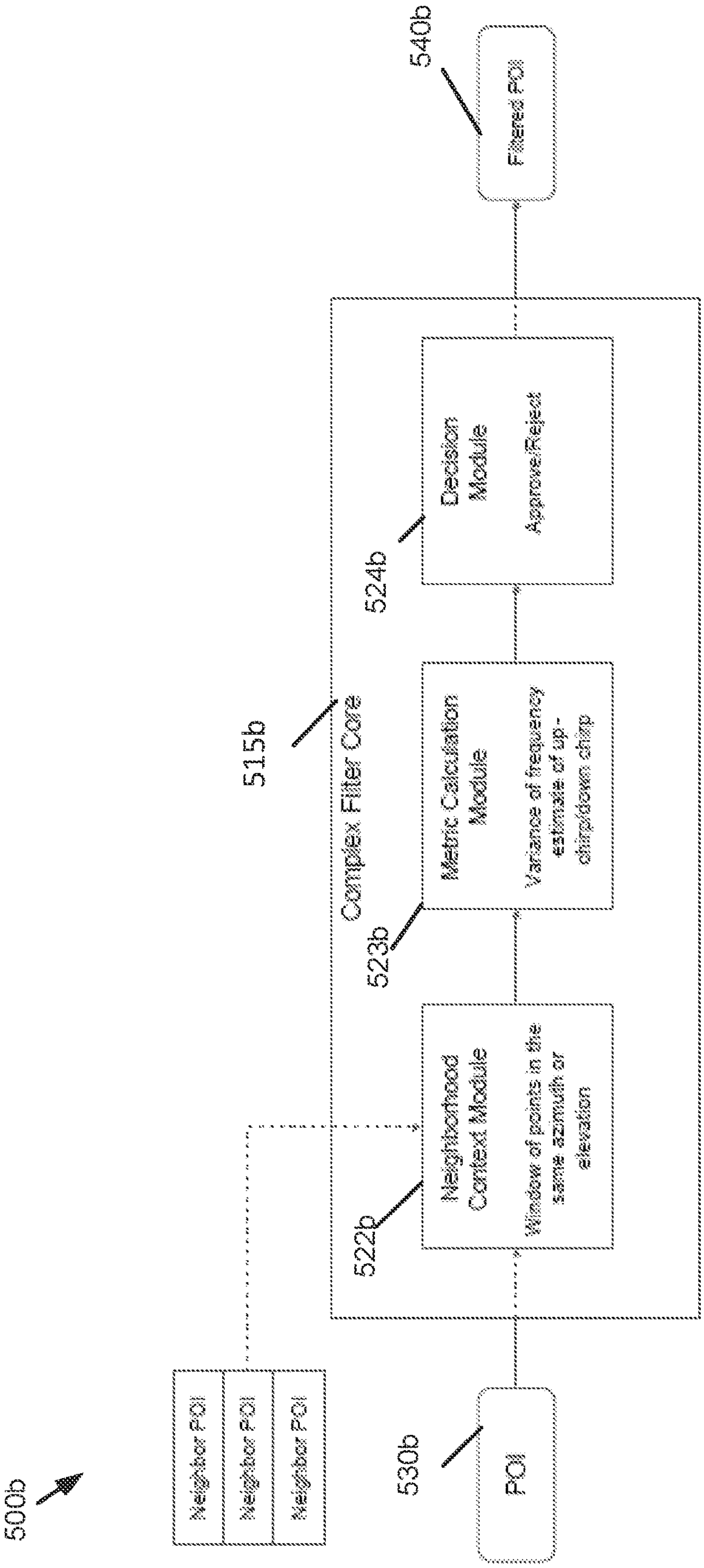
500b
Neighbor POI
Neighbor POI
Neighbor POI
530b
POI
515b
Complex Filter Core
522b
Neighborhood Context Module
Window of points in the same azimuth or elevation
523b
Metric Calculation Module
Variance of frequency estimate of up-chirp/down chirp
524b
Decision Module
Approve/Reject
540b
Filtered POI

FIG. 5B

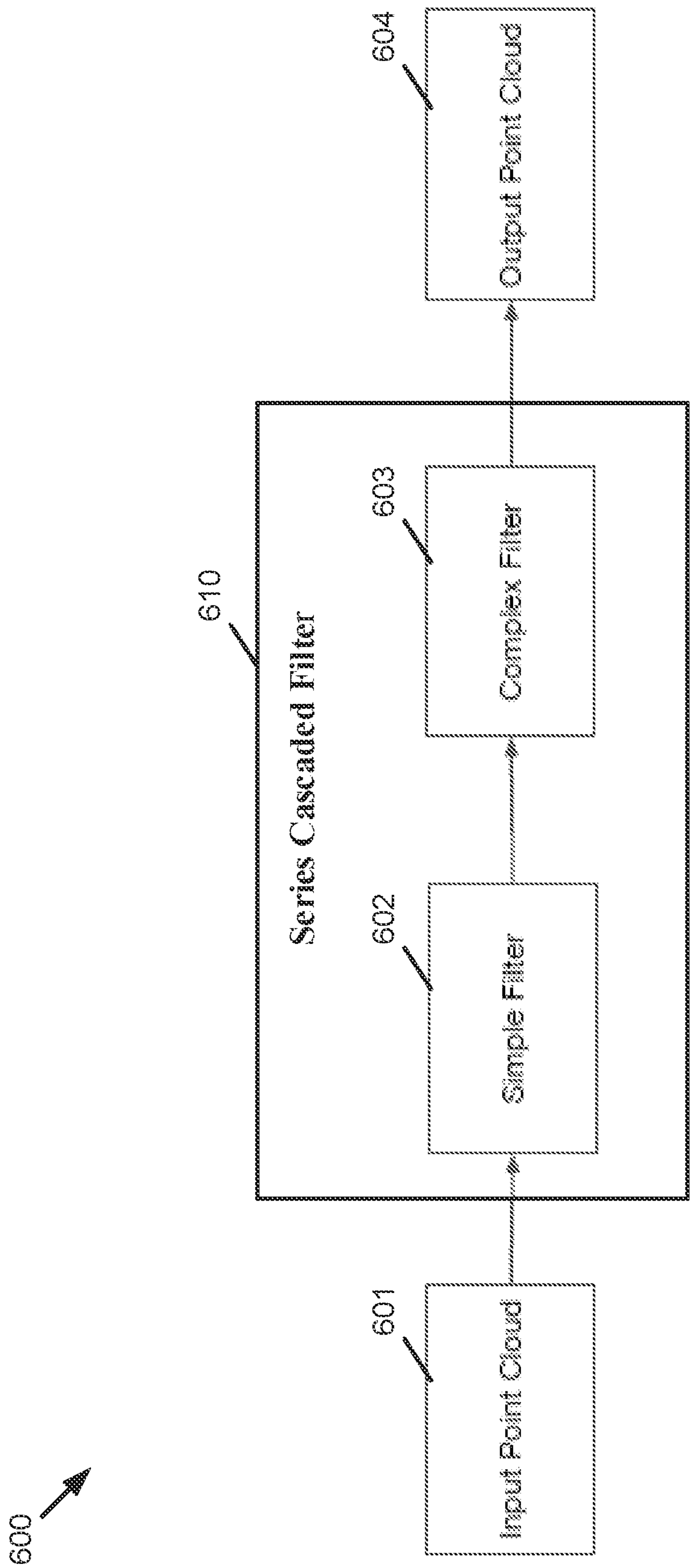
600
601
Input Point Cloud
610
Series Cascaded Filter
602
Simple Filter
603
Complex Filter
604
Output Point Cloud

FIG. 6

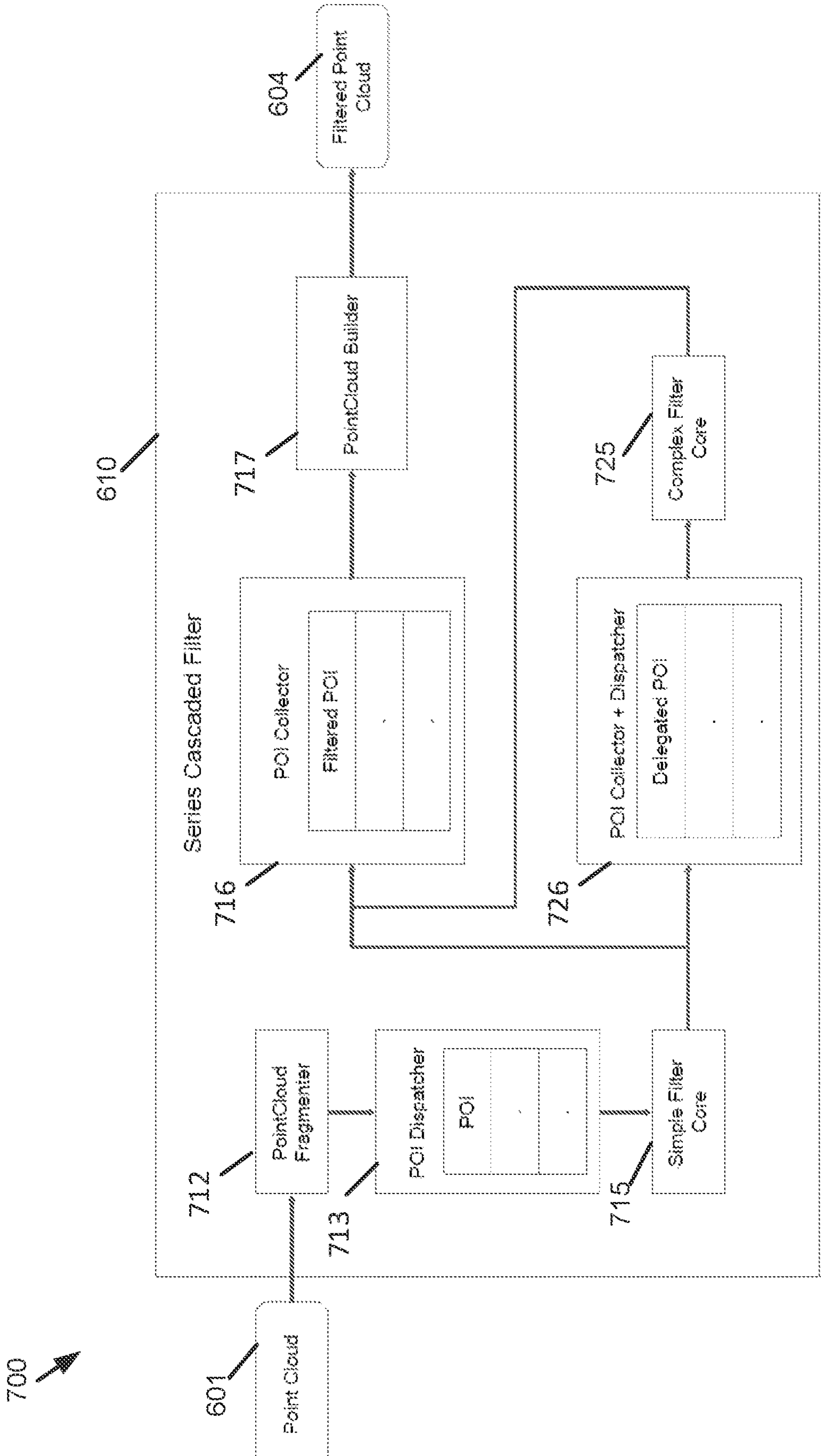
700
601
Point Cloud
610
Series Cascaded Filter
712
PointCloud Fragmenter
713
POI Dispatcher
POI
715
Simple Filter Core
716
POI Collector
Filtered POI
726
POI Collector + Dispatcher
Delegated POI
725
Complex Filter Core
717
PointCloud Builder
604
Filtered Point Cloud

FIG. 7

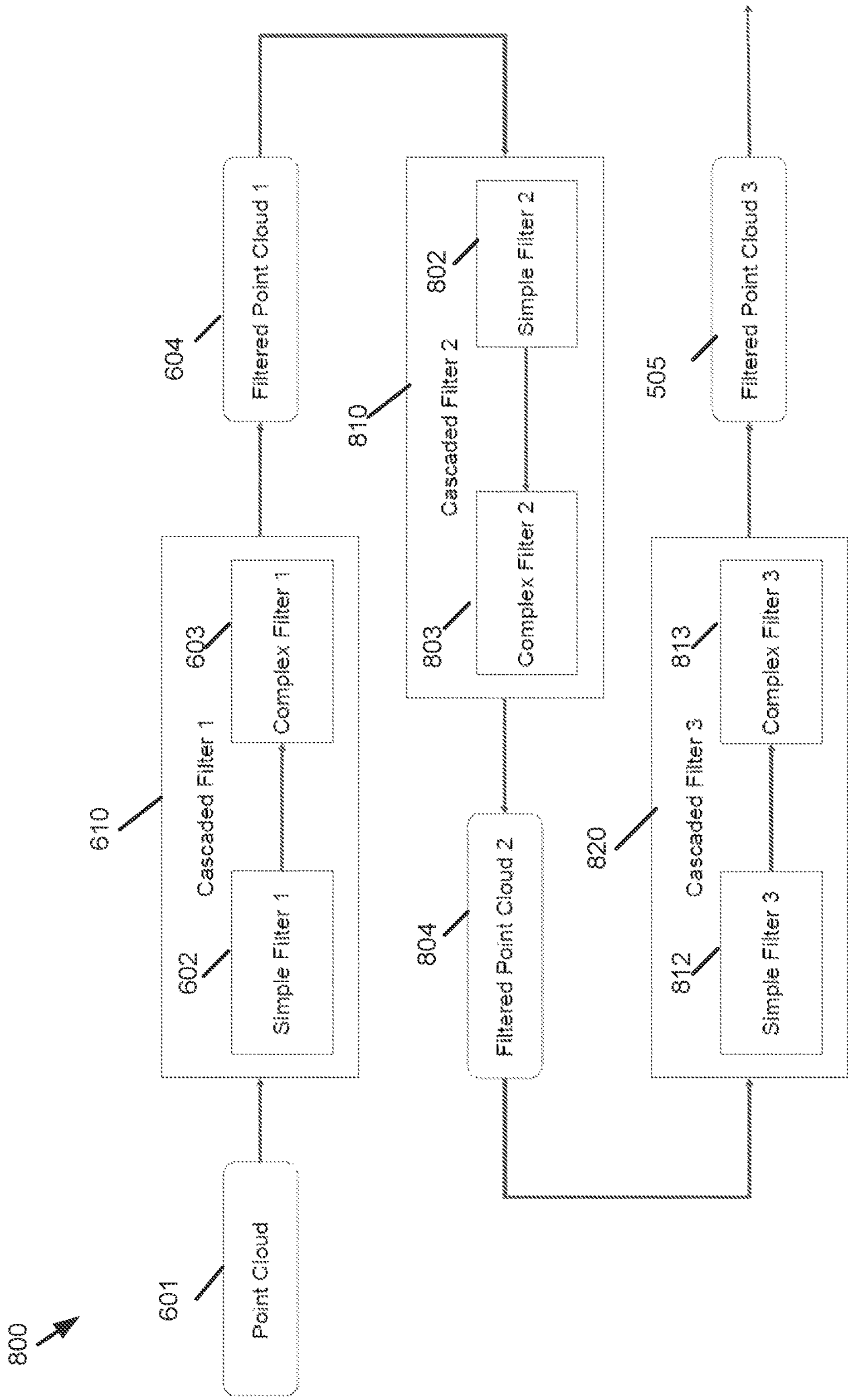
800
601
Point Cloud
610
Cascaded Filter 1
602
Simple Filter 1
603
Complex Filter 1
604
Filtered Point Cloud 1
810
Cascaded Filter 2
802
Simple Filter 2
803
Complex Filter 2
804
Filtered Point Cloud 2
820
Cascaded Filter 3
812
Simple Filter 3
813
Complex Filter 3
505
Filtered Point Cloud 3

FIG. 8

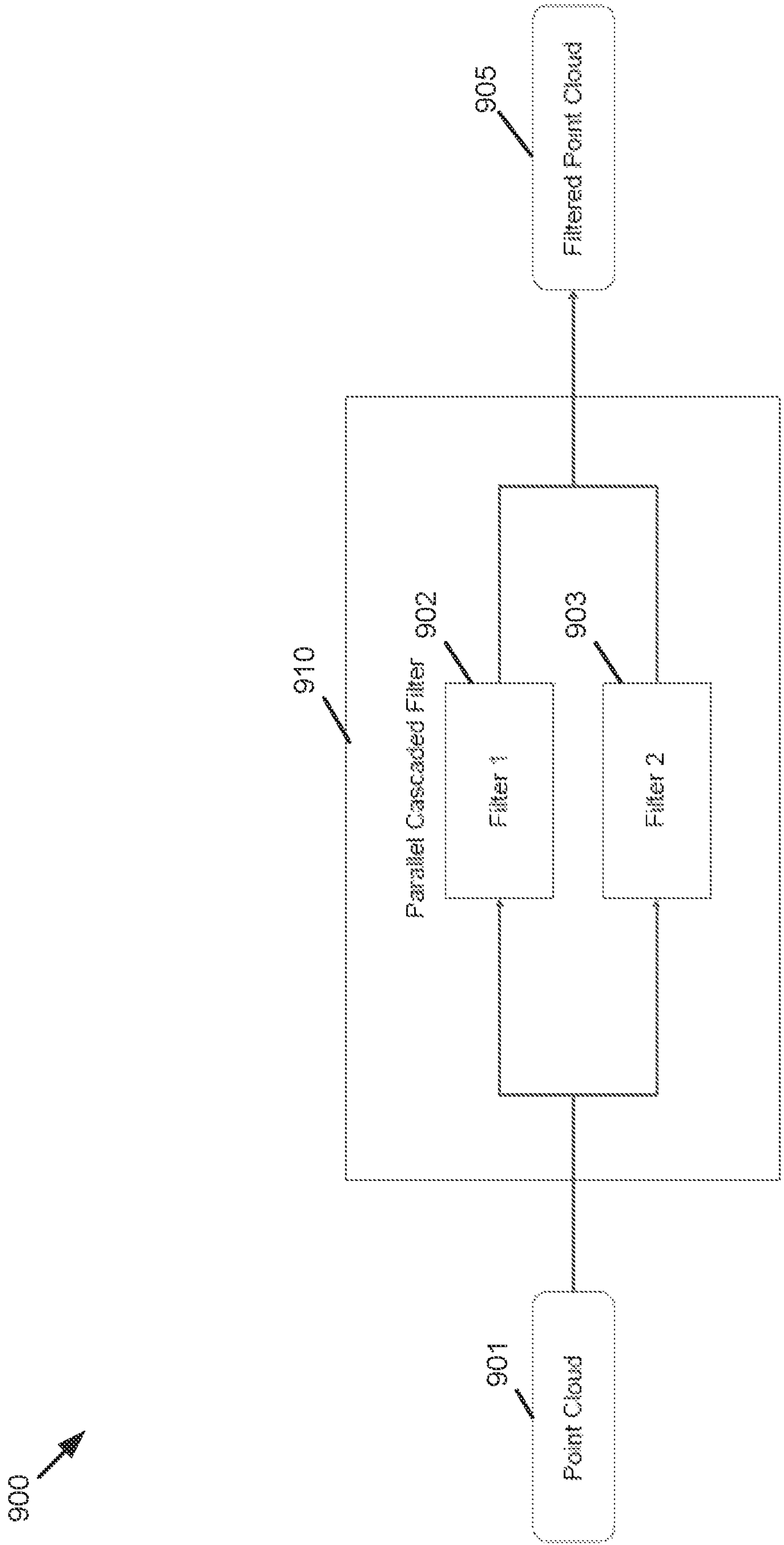
900
901
Point Cloud
910
Parallel Cascaded Filter
902
Filter 1
903
Filter 2
905
Filtered Point Cloud

FIG. 9

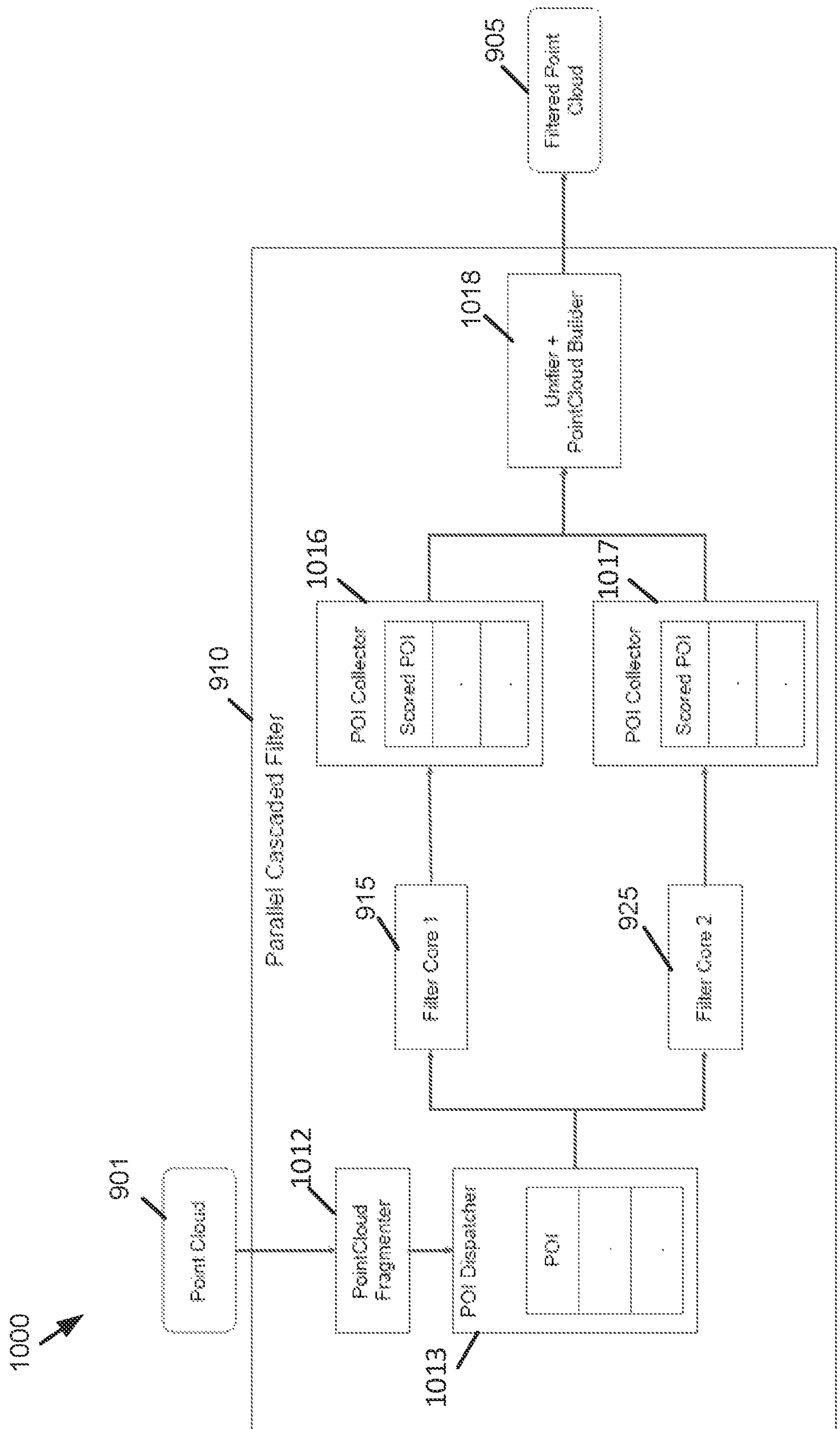
1000
Point Cloud
901
Parallel Cascaded Filter
910
PointCloud Fragmenter
1012
POI Dispatcher
1013
POI
Filter Core 1
915
Filter Core 2
925
POI Collector
Scored POI
1016
POI Collector
Scored POI
1017
Unifier + PointCloud Builder
1018
Filtered Point Cloud
905

FIG. 10

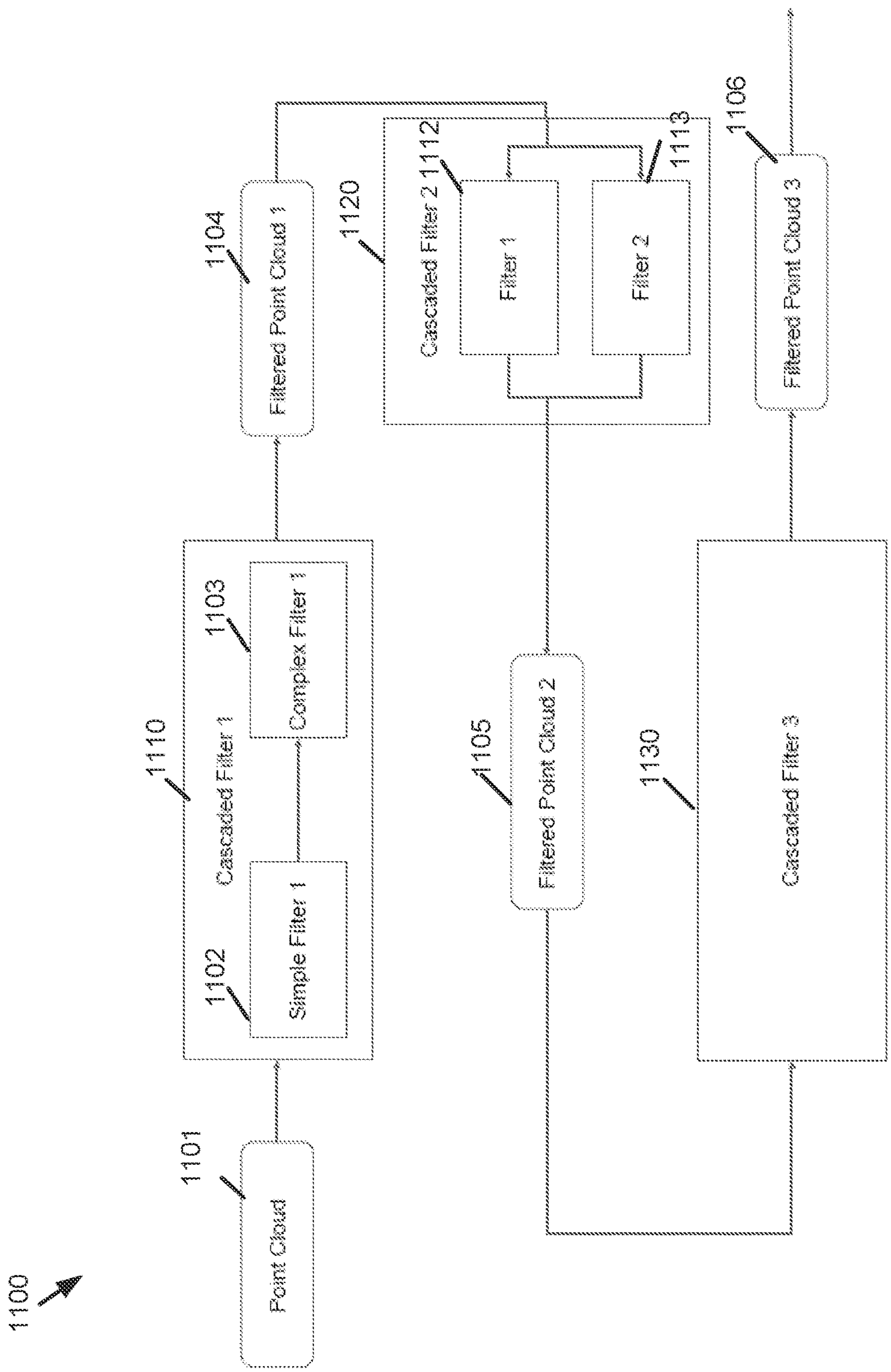
1100
Point Cloud
1101
Cascaded Filter 1
1110
Simple Filter 1
1102
Complex Filter 1
1103
Filtered Point Cloud 1
1104
Cascaded Filter 2
1120
Filter 1
1112
Filter 2
1113
Filtered Point Cloud 2
1105
Cascaded Filter 3
1130
Filtered Point Cloud 3
1106

FIG. 11

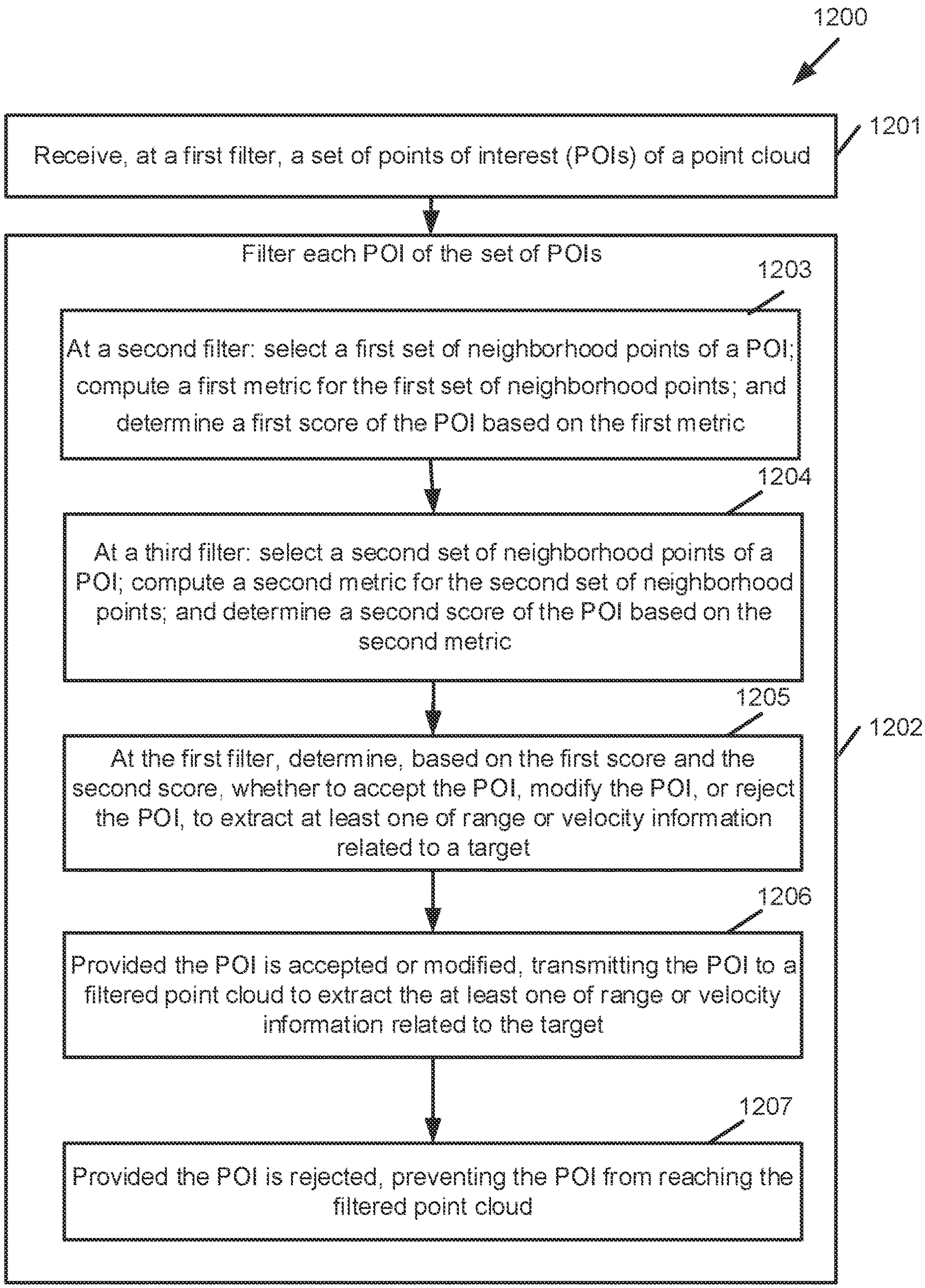
1200
1201
Receive, at a first filter, a set of points of interest (POIs) of a point cloud
1202
Filter each POI of the set of POIs
1203
At a second filter: select a first set of neighborhood points of a POI; compute a first metric for the first set of neighborhood points; and determine a first score of the POI based on the first metric
1204
At a third filter: select a second set of neighborhood points of a POI; compute a second metric for the second set of neighborhood points; and determine a second score of the POI based on the second metric
1205
At the first filter, determine, based on the first score and the second score, whether to accept the POI, modify the POI, or reject the POI, to extract at least one of range or velocity information related to a target
1206
Provided the POI is accepted or modified, transmitting the POI to a filtered point cloud to extract the at least one of range or velocity information related to the target
1207
Provided the POI is rejected, preventing the POI from reaching the filtered point cloud

FIG. 12

TECHNIQUES FOR PARALLEL CASCADE FILTERING IN POINT CLOUDS

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 17/398,440 filed on Aug. 10, 2021, which claims priority from and the benefit of U.S. Provisional Patent Application No. 63/092,228 filed on Oct. 15, 2020, the entire contents of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

The present disclosure relates generally to point set or point cloud filtering techniques and, more particularly, point set or point cloud filtering techniques for use in a light detection and ranging (LiDAR) system.

BACKGROUND

Frequency-Modulated Continuous-Wave (FMCW) LiDAR systems include several possible phase impairments such as laser phase noise, circuitry phase noise, flicker noise that the driving electronics inject on a laser, drift over temperature/weather, and chirp rate offsets. FMCW LiDAR point clouds may exhibit distinct noise patterns, which may arise from incorrect peak matching leading to falsely detected points that appear in the scene even when nothing is present. For example, when an FMCW LiDAR points to a fence or a bush, a number of ghost points may appear in the scene between the LiDAR and the fence. These ghost points or noisy points, which are also classified as False Alarm (FA) points, if left unfiltered, may introduce ghost objects and cause errors in the estimated target range/velocity.

SUMMARY

The present disclosure describes various examples of point cloud filters in LiDAR systems, e.g., parallel cascaded filters in LiDAR systems.

In some examples, disclosed herein is a method of filtering a point cloud. The characteristic features of FA points, which distinguish the FA points from true detections, may be exploited to identify the FA points and regions. When a point cloud is passed to a filtering algorithm, referred to herein as a filter, the filter works on either a single point or multiple points, referred to as points of interest (POI), at a given time. Some points and statistics from the neighborhood of the POI may be provided to the filter to provide a context. The context may be used to make a decision on the POI to check if the characteristics of the POI are consistent with the neighborhood points. The context may include contextual data around the POI to aid the filter to make a decision on the POI, by checking POI's consistency with the neighborhood points. Different metrics may be formulated to quantify these statistics/characteristics. Multiple filters may be designed to identify FA points with characteristics that are different from the point cloud. The identified FA points are then subsequently modified or removed from the point cloud. The resulting point cloud is a filtered out version of the original point cloud without the FA points. For example, the filter may iteratively get a POI from the point cloud, select points in the neighborhood of the POI to provide a context to the filter, and calculate a metric over the POI and its neighbors and then make a decision to keep, remove, or modify the POI (e.g., based on the calculated metric).

Embodiments of the present disclosure can include filters that incorporate the functionality of one or more filters. For example, a parallel cascaded filter may include multiple filters. The multiple filters may be used in parallel to score a POI. The multiple filters may be used on critical regions of the point cloud as the filters work independently to increase the confidence of the filter decision. Each of the multiple filters may determine a respective score of the POI. Multiple scores output from the multiple filters may be merged. The POI may be accepted, modified, or rejected on the basis of a set threshold in view of the multiple scores.

In some examples, a method of filtering points in a LiDAR system is disclosed herein. A set of POIs of a point cloud are received at a first filter, where each POI of the set of POIs comprises one or more points. Each POI of the set of POIs is filtered. At a second filter, a first set of neighborhood points of a POI is selected. A first metric for the first set of neighborhood points is computed. Based on the first metric, a first score of the POI is determined. At a third filter, a second set of neighborhood points of a POI is selected. A second metric for the second set of neighborhood points is computed. Based on the second metric, a second score of the POI is determined. At the first filter, based on the first score and the second score, whether to accept the POI, modify the POI, or reject the POI, is determined to extract at least one of range or velocity information related to a target. Provided the POI is accepted or modified, the POI is transmitted to a filtered point cloud to extract at least one of range or velocity information related to the target; provided the POI is rejected, the POI is prevented from reaching the filtered point cloud.

In some examples, a LiDAR system is disclosed herein. The LiDAR system comprises a processor and a memory to store instructions that, when executed by the processor, cause the system to receive, at a first filter, a set of POIs of a point cloud, where each POI of the set of POIs comprises one or more points. The system is further to filter each POI of the set of POIs. The system is to, at a second filter, select a first set of neighborhood points of a POI; compute a first metric for the first set of neighborhood points; and determine, based on the first metric, a first score of the POI. The system is to, at a third filter, select a second set of neighborhood points of a POI; compute a second metric for the second set of neighborhood points; and determine, based on the second metric, a second score of the POI. The system is to, at the first filter, based on the first score and the second score, determine whether to accept the POI, modify the POI, or reject the POI to extract at least one of range or velocity information related to the target. Provided the POI is accepted or modified, the system is to transmit the POI to a filtered point cloud to extract at least one of range or velocity information related to the target; provided the POI is rejected, the system is to prevent the POI from reaching the filtered point cloud.

In some examples, a LiDAR system is disclosed herein. The LiDAR system comprises an optical source to transmit a portion of a light signal towards a target, an optical receiver to receive a return beam from the target based on the light signal, a circuitry, and a memory to store instructions that, when executed by the processor, cause the system to receive, at a first filter, a set of POIs of a point cloud, where each POI of the set of POIs comprises one or more points. The system is further to filter each POI of the set of POIs. The system is to, at a second filter, select a first set of neighborhood points of a POI; compute a first metric for the first set of neighborhood points; and determine, based on the first metric, a first score of the POI. The system is to, at a third filter, select a second set of neighborhood points of a POI; compute a second metric for the second set of neighborhood points; and determine, based on the second metric, a second score of the POI. The system is to, at the first filter, based on the first score and the second score, determine whether to accept the POI, modify the POI, or reject the POI to extract at least one of range or velocity information related to the target. Provided the POI is accepted or modified, the system is to transmit the POI to a filtered point cloud; provided the POI is rejected, the system is to prevent the POI from reaching the filtered point cloud.

It should be appreciated that, although one or more embodiments in the present disclosure depict the use of point clouds, embodiments of the present invention are not limited as such and may include, but are not limited to, the use of point sets and the like.

These and other aspects of the present disclosure will be apparent from a reading of the following detailed description together with the accompanying figures, which are briefly described below. The present disclosure includes any combination of two, three, four or more features or elements set forth in this disclosure, regardless of whether such features or elements are expressly combined or otherwise recited in a specific example implementation described herein. This disclosure is intended to be read holistically such that any separable features or elements of the disclosure, in any of its aspects and examples, should be viewed as combinable unless the context of the disclosure clearly dictates otherwise.

It will therefore be appreciated that this Summary is provided merely for purposes of summarizing some examples so as to provide a basic understanding of some aspects of the disclosure without limiting or narrowing the scope or spirit of the disclosure in any way. Other examples, aspects, and advantages will become apparent from the following detailed description taken in conjunction with the accompanying figures which illustrate the principles of the described examples.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of various examples, reference is now made to the following detailed description taken in connection with the accompanying drawings in which like identifiers correspond to like elements:

FIG. **1**A is a block diagram illustrating an example LiDAR system according to embodiments of the present disclosure.

FIG. **1**B is a block diagram illustrating an example of a point cloud filtering module of a LiDAR system according to embodiments of the present disclosure.

FIG. **2** is a time-frequency diagram illustrating an example of FMCW LIDAR waveforms according to embodiments of the present disclosure.

FIG. **3**A is a block diagram illustrating an example of a point cloud filter according to embodiments of the present disclosure.

FIG. **3**B is a block diagram illustrating an example of a filter core of a point cloud filter according to embodiments of the present disclosure.

FIG. **4**A is a block diagram illustrating an example of a filter core according to embodiments of the present disclosure.

FIG. **4**B is a block diagram illustrating another example of a filter core according to embodiments of the present disclosure.

FIG. **5**A is a block diagram illustrating yet another example of a filter core, according to embodiments of the present disclosure.

FIG. **5**B is a block diagram illustrating still another example of a filter core, according to embodiments of the present disclosure.

FIG. **6** is a block diagram illustrating an example of a series cascaded point cloud filter according to embodiments of the present disclosure.

FIG. **7** is a block diagram illustrating detailed structure of a series cascaded point cloud filter according to embodiments of the present disclosure.

FIG. **8** is a block diagram illustrating an example of multiple series cascaded point cloud filters according to embodiments of the present disclosure.

FIG. **9** is a block diagram illustrating an example of a parallel cascaded point cloud filter according to embodiments of the present disclosure.

FIG. **10** is a block diagram illustrating detailed structure of a parallel cascaded point cloud filter according to embodiments of the present disclosure.

FIG. **11** is a block diagram illustrating an example of multiple cascaded point cloud filters according to embodiments of the present disclosure.

FIG. **12** is a block diagram illustrating an example of a process to filter a point cloud according to embodiments of the present disclosure.

DETAILED DESCRIPTION

Various embodiments and aspects of the disclosures will be described with reference to details discussed below, and the accompanying drawings will illustrate the various embodiments. The following description and drawings are illustrative of the disclosure and are not to be construed as limiting the disclosure. Numerous specific details are described to provide a thorough understanding of various embodiments of the present disclosure. However, in certain instances, well-known or conventional details are not described in order to provide a concise discussion of embodiments of the present disclosures.

The described LiDAR systems herein may be implemented in any sensing market, such as, but not limited to, transportation, manufacturing, metrology, medical, virtual reality, augmented reality, and security systems. According to some embodiments, the described LiDAR system may be implemented as part of a front-end of frequency modulated continuous-wave (FMCW) device that assists with spatial awareness for automated driver assist systems, or self-driving vehicles.

FIG. **1**A illustrates a LiDAR system **100** according to example implementations of the present disclosure. The LiDAR system **100** includes one or more of each of a number of components, but may include fewer or additional components than shown in FIG. **1**. According to some embodiments, one or more of the components described herein with respect to LiDAR system **100** can be implemented on a photonics chip. The optical circuits **101** may include a combination of active optical components and passive optical components. Active optical components may generate, amplify, and/or detect optical signals and the like. In some examples, the active optical component includes optical beams at different wavelengths, and includes one or more optical amplifiers, one or more optical detectors, or the like.

Free space optics **115** may include one or more optical waveguides to carry optical signals, and route and manipulate optical signals to appropriate input/output ports of the active optical circuit. The free space optics **115** may also include one or more optical components such as taps, wavelength division multiplexers (WDM), splitters/combiners, polarization beam splitters (PBS), collimators, couplers or the like. In some examples, the free space optics **115** may include components to transform the polarization state and direct received polarized light to optical detectors using a PBS, for example. The free space optics **115** may further include a diffractive element to deflect optical beams having different frequencies at different angles.

In some examples, the LiDAR system **100** includes an optical scanner **102** that includes one or more scanning mirrors that are rotatable along an axis (e.g., a slow-moving-axis) that is orthogonal or substantially orthogonal to the fast-moving-axis of the diffractive element to steer optical signals to scan a target environment according to a scanning pattern. For instance, the scanning mirrors may be rotatable by one or more galvanometers. Objects in the target environment may scatter an incident light into a return optical beam or a target return signal. The optical scanner **102** also collects the return optical beam or the target return signal, which may be returned to the passive optical circuit component of the optical circuits **101**. For example, the return optical beam may be directed to an optical detector by a polarization beam splitter. In addition to the mirrors and galvanometers, the optical scanner **102** may include components such as a quarter-wave plate, lens, anti-reflective coating window or the like.

To control and support the optical circuits **101** and optical scanner **102**, the LiDAR system **100** includes LiDAR control systems **110**. The LiDAR control systems **110** may include a processing device for the LiDAR system **100**. In some examples, the processing device may be one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, the processing device may be complex instruction set computing (CISC) microprocessor, reduced instruction set computer (RISC) microprocessor, very long instruction word (VLIW) microprocessor, or processor implementing other instruction sets, or processors implementing a combination of instruction sets. The processing device may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like.

In some examples, the LiDAR control systems **110** may include a signal processing unit **112** such as a digital signal processor (DSP). The LiDAR control systems **110** are configured to output digital control signals to control optical drivers **103**. In some examples, the digital control signals may be converted to analog signals through signal conversion unit **106**. For example, the signal conversion unit **106** may include a digital-to-analog converter. The optical drivers **103** may then provide drive signals to active optical components of optical circuits **101** to drive optical sources such as lasers and amplifiers. In some examples, several optical drivers **103** and signal conversion units **106** may be provided to drive multiple optical sources.

The LiDAR control systems **110** are also configured to output digital control signals for the optical scanner **102**. A motion control system **105** may control the galvanometers of the optical scanner **102** based on control signals received from the LIDAR control systems **110**. For example, a digital-to-analog converter may convert coordinate routing information from the LiDAR control systems **110** to signals interpretable by the galvanometers in the optical scanner **102**. In some examples, a motion control system **105** may also return information to the LiDAR control systems **110** about the position or operation of components of the optical scanner **102**. For example, an analog-to-digital converter may in turn convert information about the galvanometers' position to a signal interpretable by the LIDAR control systems **110**.

The LiDAR control systems **110** are further configured to analyze incoming digital signals. In this regard, the LiDAR system **100** includes optical receivers **104** to measure one or more beams received by optical circuits **101**. For example, a reference beam receiver may measure the amplitude of a reference beam from the active optical component, and an analog-to-digital converter converts signals from the reference receiver to signals interpretable by the LiDAR control systems **110**. Target receivers measure the optical signal that carries information about the range and velocity of a target in the form of a beat frequency, modulated optical signal. The reflected beam may be mixed with a second signal from a local oscillator. The optical receivers **104** may include a high-speed analog-to-digital converter to convert signals from the target receiver to signals interpretable by the LiDAR control systems **110**. In some examples, the signals from the optical receivers **104** may be subject to signal conditioning by signal conditioning unit **107** prior to receipt by the LiDAR control systems **110**. For example, the signals from the optical receivers **104** may be provided to an operational amplifier for amplification of the received signals and the amplified signals may be provided to the LIDAR control systems **110**.

In some applications, the LiDAR system **100** may additionally include one or more imaging devices **108** configured to capture images of the environment, a global positioning system **109** configured to provide a geographic location of the system, or other sensor inputs. The LiDAR system **100** may also include an image processing system **114**. The image processing system **114** can be configured to receive the images and geographic location, and send the images and location or information related thereto to the LiDAR control systems **110** or other systems connected to the LIDAR system **100**.

In operation according to some examples, the LiDAR system **100** is configured to use nondegenerate optical sources to simultaneously measure range and velocity across two dimensions. This capability allows for real-time, long range measurements of range, velocity, azimuth, and elevation of the surrounding environment.

In some examples, the scanning process begins with the optical drivers **103** and LiDAR control systems **110**. The LiDAR control systems **110** instruct the optical drivers **103** to independently modulate one or more optical beams, and these modulated signals propagate through the passive optical circuit to the collimator. The collimator directs the light at the optical scanning system that scans the environment over a preprogrammed pattern defined by the motion control system **105**. The optical circuits **101** may also include a polarization wave plate (PWP) to transform the polarization of the light as it leaves the optical circuits **101**. In some examples, the polarization wave plate may be a quarter-wave plate or a half-wave plate. A portion of the polarized light may also be reflected back to the optical circuits **101**. For example, lensing or collimating systems used in LIDAR system **100** may have natural reflective properties or a reflective coating to reflect a portion of the light back to the optical circuits **101**.

Optical signals reflected back from the environment pass through the optical circuits **101** to the receivers. Because the polarization of the light has been transformed, it may be reflected by a polarization beam splitter along with the portion of polarized light that was reflected back to the optical circuits **101**. Accordingly, rather than returning to the same fiber or waveguide as an optical source, the reflected light is reflected to separate optical receivers. These signals interfere with one another and generate a combined signal. Each beam signal that returns from the target produces a time-shifted waveform. The temporal phase difference between the two waveforms generates a beat frequency measured on the optical receivers (photodetectors). The combined signal can then be reflected to the optical receivers **104**.

The analog signals from the optical receivers **104** are converted to digital signals using ADCs. The digital signals are then sent to the LiDAR control systems **110**. A signal processing unit **112** may then receive the digital signals and interpret them. In some embodiments, the signal processing unit **112** also receives position data from the motion control system **105** and galvanometers (not shown) as well as image data from the image processing system **114**. The signal processing unit **112** can then generate a 3D point cloud with information about range and velocity of points in the environment as the optical scanner **102** scans additional points. The signal processing unit **112** can also overlay a 3D point cloud data with the image data to determine velocity and distance of objects in the surrounding area. The system also processes the satellite-based navigation location data to provide a precise global location.

FIG. **1**B is a block diagram **100***b* illustrating an example of a point cloud filtering module **140** in a LiDAR system according to embodiments of the present disclosure. The signal processing unit **112** may include the point cloud filtering module **140**. It should be noted that, although the point cloud filtering module is depicted as residing within the signal processing unit **112**, embodiments of the present disclosure are not limited as such. For instance, in one embodiment, the point cloud filtering module **140** can reside in computer memory (e.g., RAM, ROM, flash memory, and the like) within system **100** (e.g., LiDAR control system **110**). According to some embodiments, point cloud filtering module **140** can be a filter that includes one or more filters.

With reference to FIG. **1**B, the point cloud filtering module **140** includes the functionality to select neighborhood data points from a set of points, compute metrics, and make determinations concerning the acceptance, modification, removal and/or transmission of points to a point set or point cloud using one or more filters.

For instance, the point cloud filtering module **140** can include a filter module **121**, a filter module **131** and a decision module **144**. In some scenarios, the point cloud filtering module **140** may receive (e.g., acquire, obtain, generate or the like) a set of POIs from a point cloud, where each POI of the set of POIs includes one or more points. The filter module **140** includes the functionality to filter a POI of a given set of POIs provided by a particular point cloud.

As depicted in FIG. **1**B, the filter module **121** may include a neighborhood context module **122**, a metric calculation module **123** and a decision module **124**. The neighborhood context module **122** includes the functionality to select a set of neighborhood points of a POI. The metric calculation module **123** includes the functionality to compute one or more metrics for a given set of neighborhood points. The decision module **124** includes the functionality to determine, based on a particular metric, a score of the POI.

According to some embodiments, the filter module **131** includes a neighborhood context module **132**, a metric unit **133** and a determination unit **134** that are separate from the modules depicted in filter module **121**. For instance, the neighborhood context module **132** includes the functionality to select a different set of neighborhood points for a particular POI. The metric calculation module **133** includes the functionality to compute a different metric for the different set of neighborhood points. The decision module **134** includes the functionality to determine, based on the different metric, a score of the POI.

The decision module **144** may receive both scores from the decision module **124** and the decision module **134**. The decision module **144** includes the functionality to determine, based on the score from the decision module **124** and the score from the decision module **134**, whether to accept the POI, modify the POI, or reject the POI, to extract at least one of range or velocity information related to a target. As will be described in greater detail, filter modules **121**, **131** and decision module **144** can be included in a parallel cascaded filter. In some scenarios, the point cloud filtering module **140** may include one or more parallel cascaded filters.

FIG. **2** is a time-frequency diagram **200** of an FMCW scanning signal **101***b* that can be used by a LiDAR system, such as system **100**, to scan a target environment according to some embodiments. In one example, the scanning waveform **201**, labeled as $f_{FM}(t)$, is a sawtooth waveform (sawtooth "chirp") with a chirp bandwidth Δfc and a chirp period Tc. The slope of the sawtooth is given as k=(Δfc/Tc). FIG. **2** also depicts target return signal **202** according to some embodiments. Target return signal **202**, labeled as $f_{FM}(t-\Delta t)$, is a time-delayed version of the scanning signal **201**, where Δt is the round trip time to and from a target illuminated by scanning signal **201**. The round trip time is given as Δt=2R/v, where R is the target range and v is the velocity of the optical beam, which is the speed of light c. The target range, R, can therefore be calculated as R=c(Δt/2). When the return signal **202** is optically mixed with the scanning signal, a range dependent difference frequency ("beat frequency") $\Delta f_R(t)$ is generated. The beat frequency $\Delta f_R(t)$ is linearly related to the time delay Δt by the slope of the sawtooth k. That is, $\Delta f_R(t)=k\Delta t$. Since the target range R is proportional to Δt, the target range R can be calculated as $R=(c/2)(\Delta f_R(t)/k)$. That is, the range R is linearly related to the beat frequency $\Delta f_R(t)$. The beat frequency $\Delta f_R(t)$ can be generated, for example, as an analog signal in optical receivers **104** of system **100**. The beat frequency can then be digitized by an analog-to-digital converter (ADC), for example, in a signal conditioning unit such as signal conditioning unit **107** in LIDAR system **100**. The digitized beat frequency signal can then be digitally processed, for example, in a signal processing unit, such as signal processing unit **112** in system **100**. It should be noted that the target return signal **202** will, in general, also include a frequency offset (Doppler shift) if the target has a velocity relative to the LIDAR system **100**. The Doppler shift can be determined separately, and used to correct the frequency of the return signal, so the Doppler shift is not shown in FIG. **2** for simplicity and ease of explanation. It should also be noted that the sampling frequency of the ADC will determine the highest beat frequency that can be processed by the system without aliasing. In general, the highest frequency that can be processed is one-half of the sampling frequency (i.e., the "Nyquist limit"). In one example, and without limitation, if the sampling frequency of the ADC is 1 gigahertz, then the highest beat frequency that can be processed without aliasing (Δf_{Rmax}) is 500 megahertz. This limit in turn determines the maximum range of the system as $R_{max}=(c/2)(\Delta f_{Rmax}/k)$ which can be adjusted by changing the chirp slope k. In one example, while the data samples from the ADC may be continuous, the subsequent digital processing described below may be partitioned into "time segments" that can be associated with some periodicity in the LIDAR system **100**. In one example, and without limitation, a time segment might correspond to a predetermined number of chirp periods T, or a number of full rotations in azimuth by the optical scanner.

FIG. **3**A is a block diagram that depicts system **300***a* which includes the use of a point cloud filter (e.g., point cloud filter **310**) according to embodiments of the present disclosure. In some scenarios, a point cloud (e.g., **311**) is a set of data points (or points) in the scene collected using one or more components of a light scanning system (e.g., LiDAR system **100**). It should be noted that the terms "data point" and "point" are interchangeably used in the present disclosure.

Each point has a set of coordinates, e.g., (X, Y, Z) and/or (Range, Azimuth, Elevation), which can be used by LiDAR system **100** to determine a point's location in the scene relative to the position of one or more sensors used by LiDAR system **100**. Additional attributes such as velocity, intensity, reflectivity, time recorded, metadata and the like may also be calculated for a particular point. True detection (TD) points are points in the scene that represent an object or segment of the scene such as ground, foliage, etc. False alarm (FA) points are untrue detection points, e.g., ghost points or noisy points, in the scene. FA points cannot be associated with any object or segment of the scene.

In some scenarios, point clouds (e.g., FMCW LiDAR point clouds) exhibit distinct noise patterns which primarily arise from incorrect peak matching leading to FA points that appear in the scene even when nothing is present. For example, when an FMCW LiDAR system scans points corresponding to a fence or a bush, a number of FA points, e.g., ghost points, may appear in the scene between the LiDAR system and the fence. The FA points have characteristic features which distinguish them from True Detection (TD) points. As described in greater detail herein, embodiments of the present disclosure can exploit these distinguishing features to identify these points and regions, and then subsequently modify or remove them from the point cloud while leaving the TD points untouched. The resulting point cloud (e.g., filtered point cloud **319**) is a filtered out version of the original point cloud (e.g., point cloud **311**) without the FA points.

As described herein, the point cloud filtering performed by the embodiments can remove points from a point cloud which do not satisfy a predetermined threshold for a metric. For example, a filter may refer to a filtering technique or algorithm which processes a point cloud and outputs a filtered point cloud. In some embodiments, a filter may include a process in which a point cloud is processed, e.g., points not satisfying a predetermined threshold for a metric are removed, and a filtered point cloud is outputted. The filtered point cloud produced by embodiments described herein may have some points modified and some points removed.

The filter processes, described herein according to embodiments, can process a predetermined number of points, e.g., a single point or multiple points, at a time. A predetermined number of points that the filter is configured to work on at a given time include POIs. Each POI may include one or more points. The POIs may be identified by embodiments based on a predetermined threshold, such as a velocity threshold or other types of trivial identifiers. The filters described herein can be configured to work on a POI at a time, where the POI may include a single point or multiple points.

As will be explained in greater detail, upon receipt of one or more points from a point cloud, the filters described herein can work on either a POI, a single point or multiple points, at a given time. These filters can be configured to use points and statistics from the neighborhood of the POI may be provided to the filter to provide a context. The filters can be configured to use contextual information to make decisions made for a POI and to check if the characteristics of the POI are consistent with the neighborhood points. The contextual information may include contextual data around the POI to aid the filter to make a decision on the POI, by checking POI's consistency with the neighborhood points. The embodiments described herein can be configured to use different metrics to quantify these statistics/characteristics. Multiple filters may be used to identify FA points with characteristics that are different from the point cloud. The identified FA points are then subsequently modified or removed by the described embodiments from the point cloud. The resulting point cloud is a filtered out version of the original point cloud without the FA points.

For instance, as depicted in the FIG. **3**A embodiment, the point cloud **311** may be received, for example, by the filter **310**. In one scenario, the filter **310** may include a point cloud fragmenter **312**, a POI dispatcher **313**, a filter core **315**, a POI collector **316**, and/or a point cloud builder **317**. The point cloud **311** may be fed into the point cloud fragmenter **312**, which identifies regions of the point cloud **311** that the filter **310** will be working on and creates one or more POIs that can be sent to the POI dispatcher **313**. Portions of the point cloud **311** that the filter **310** does not work on are communicated or transmitted to the point cloud builder **317**. The point cloud fragmenter **312** identifies the regions of the point cloud **311** that may have FA points, which in turn identifies a set of POIs for the filter to work on. The point cloud fragmenter **312** identifies the set of POIs in the regions that the filter **310** will be working on based on a predetermined threshold, for example, a velocity threshold. For example, if the filter **310** works on all points with a velocity >10 m/s, then the point cloud fragmenter **312** is configured to ignore any points with a velocity <10 m/s. The ignored points are then transmitted (e.g., communicated) to the point cloud builder **317** through the link **318** in between the point cloud fragmenter **312** and the point cloud builder **317**. The points that the filter **310** has not worked on may be considered as approved by the filter **310** and are therefore present in the output point cloud **319**.

In one scenario, a size of the POI may be chosen, for example, a quantity of points in the POI. Then the regions of the point cloud **311** that the filter **310** would be working on may be identified. The size of the POI and the region information may help the point cloud fragmenter **312** to fragment the point cloud **311** into the set of POIs that the filter core **315** can work on.

The POI dispatcher **313** receives the POIs from the point cloud fragmenter **312** and sends the POIs to the filter core **315**, one POI at a time, for processing. In some scenarios, this dispatch mechanism may be parallelized on multiple threads/graphics processing unit (GPU) cores or field-programmable gate array (FPGA) for faster processing. The dispatch strategy chosen by embodiments can depend on how the filter Core **315** operates on the POI. In scenarios, multiple filter cores may be initialized to process multiple threads or GPU cores. In these scenarios, the POI dispatcher **313** can be configured to handle this coordination.

The filter core **315** houses one or more modules of the filter **310** which can each be configured to process the POIs, which will be discussed below. The filter core **315** may be configured to select a combination of neighborhood context strategy, metric and decision that the filter will be making. The combination may depend on the noise pattern that the filter is configured to target.

In some embodiments, the filter **310** may be configured to make decisions on the POIs including approving, modifying, rejecting, delegating (transmitting to another filter), or scoring the POI. Once a POI is processed, the filter may determine a "filtered POI" which includes a decision made for the POI (e.g., including, but not limited to, approved, modified, rejected, delegated, or scored).

The POI collector **316** can be configured to collect the filtered POIs received from the filter core **315** and send the filtered POIs to the point cloud builder **317**, for example, once all the POIs are processed.

The point cloud builder **317** can be configured to construct the point cloud **319** from all the approved points in the POIs and the bypassed POIs received from the point cloud fragmenter **312**. The filtered point cloud **319** is output from the filter **310**. In some scenarios, the filtered point cloud **319** may have less number of points than the input point cloud **311**, as the points rejected by the filter **310** may be removed from the input point cloud **311**. The point cloud builder **317** can be configured to operate in tandem with the point cloud fragmenter **312**. The point cloud builder **317** is configured to receive information related to points which are not being processed by the filter core **315**.

The filter **310** may also be configured to selectively operate on a smaller point group instead of waiting for the entire point cloud frame to be built to reduce overall system latency.

FIG. **3**B is a block diagram illustrating an example of the filter core **315** of the point cloud filter **310** according to embodiments of the present disclosure. A filter core may be configured to target noise with specific characteristics. Multiple filter cores may be designed to tackle different potential noise patterns in the scene. The function of the filter, as described herein, may be encompassed by the filter core. It should be appreciated that the terms "filter" and "filter core" may be used interchangeably herein. In some embodiments, the filter core **315** may include a neighborhood context module **322**, a metric calculation module **323** and a decision module **324**. The neighborhood context module **322** is configured to select a set of neighborhood points of a POI. The metric calculation module **323** is configured to compute a metric for the set of neighborhood points. The decision module **124** is configured to determine, based on the metric, whether to accept the POI, modify the POI, reject the POI, transmit the POI to another filter, or score the POI.

In some implementations, the filter core **315** may be configured to process only one POI at a time. The neighborhood context module **322** can also be configured to receive one or more neighbor POIs, statistics of the neighbor POIs, and/or the entire point cloud **311**. This contextual information may be used to make a decision on the POI by checking if the characteristics are consistent with the neighborhood points. In some instances, a metric may be used by the embodiments described herein for the type of noise that the filter is processing. After processing the POI, the decision module **124** may be configured to perform one or more actions including, but not limited to, accepting, modifying, discarding, transmitting (delegating) the POI, or scoring the POI.

FIG. **4**A is a block diagram of a system **400**_a_ that includes a filter core as used in accordance with embodiments of the present disclosure. In one embodiment, the filter core includes a simple filter core **415**_a_. It should be noted that the term "filter" and "filter core" may be used interchangeably in this disclosure. According to some embodiments, a filter can operate on a set of POIs in a point cloud that may be based on, for example, a combination of different selection of neighborhood data points, different metrics, and/or decisions. The filter may be a simple filter or a complex filter, as described herein. It should be appreciated that the examples described herein are only for illustration purposes. There may be many other embodiments of a simple filter core based on this disclosure.

Referring to FIG. **4**A, in some scenarios, a simple filter core, e.g., the simple filter core **415**_a_, includes fewer computational resources to perform the filtering operations described herein relative to a complex filter core, e.g., a complex filter core **515**_a_ (which will be described in FIG. **5**A). For instance, the computational resources resident on the simpler filter core, e.g., the simpler filter core **415**_a_, enable the simpler filter core to perform filtering operations that require shorter compute time, access fewer resources, and/or consume less power relative to the computational resources required by the complex filer core, e.g., the complex filer core **515**_a_. For instance, predetermined thresholds can be used to determine the amount of processing to be performed at the simple filter or the simple filter core (e.g., including, but not limited to, compute time thresholds, power thresholds, and the like). Additional examples that demonstrate the hardware/software profile of simple filters are described herein.

As depicted in FIG. **4**A, the simple filter core **415**_a_ may include a neighborhood context module **422**_a_, a metric calculation module **423**_a_, and a decision module **424**_a_. The neighborhood context module **422**_a_ may be configured to select a window of points nearby for a POI **430**_a_, for example, a window of data points around the POI having either the same azimuth/elevation.

The metric calculation module **423**_a_ may be configured to compute a confidence metric based on a similarity of point properties, e.g., velocity, across the POI and the selected neighborhood data points. The simple filter core **415**_a_ may be configured to check if the POI has properties that are not drastically different from the neighborhood points. For example, if the minimum, maximum, or range of velocity of the POI is within a respective predetermined threshold to the minimum, maximum, or range of the neighborhood points, then the confidence metric of the POI may be determined to be high.

The decision module **424**_a_ may be configured to determine, based on the confidence metric, whether to accept the POI, modify the POI, reject the POI, score the POI, or delegate/transmit the POI to the complex filter core, e.g., **515**_a_. The POI may be approved if the confidence metric of the POI is determined to be high. For example, when the confidence metric is within a first predetermined threshold, the POI **430**_a_ is accepted and becomes a filtered POI **440**_a_. When the confidence metric is within the first predetermined threshold, but there are detected inconsistencies with the neighborhood context within a particular predetermined threshold, modifications may be made to the POI. For example, point properties such as range and/or velocity may be modified. When the confidence metric of the POI is not consistent with the neighborhood points, e.g., not consistent with a second predetermined or specified threshold, the POI is classified as an FA. The POI is to be discarded or removed or filtered out.

When a decision cannot be made, but the POI was found suspicious, then the POI may be marked as a delegated POI **450***a* and transmitted (e.g., delegated) to a complex filter core, e.g., the complex filter core **515***a*. The POI may be passed to the complex filter core, e.g., the complex filter core **515***a*. The complex filter core, e.g., the complex filter core **515***a* may be configured to make a decision to accept, modify, or reject the POI. Delegating determinations in this manner can reduce the load on the subsequent complex filter core, e.g., the complex filter core **515***a*, as the subsequent complex filter core, e.g., the complex filter core **515***a*, does not operate on the entire point cloud but only on a subset of points (i.e., the undetermined or transmitted POIs).

With a probability that the POI is not an FA, the decision module **424***a* may score the POI. When the confidence metric is within a predetermined threshold, there is the probability that the POI is not an FA. Then, the POI may be assigned a score by the decision module **424***a*. A different filter or algorithm may be used to assign or determine a different score for the POI. Multiple filters or algorithms may be used to assign or determine multiple scores for the POI. An additional filter or an additional decision module may look at the multiple scores and remove the POI if the POI has at least one score of the multiple scores that is lower than the predetermined threshold.

FIG. **4**B is a block diagram of a system **400***b* that includes a simple filter core **415***b* as used in accordance with embodiments of the present disclosure. FIG. **4**B provides an additional example that demonstrates the types of functions the simple filter can perform based on its respective hardware/software profiles described herein. For instance, simple filter can be configured to perform the operations described herein constrained by compute time, power consumption, etc.

With reference to FIG. **4**B, the simple filter core **415***b* may include a neighborhood context module **422***b*, a metric calculation module **423***b*, and a decision module **424***b*. The neighborhood context module **422***b* may be configured to bypass selecting a neighborhood for a POI **430***b*. The metric calculation module **423***b* may be configured to check if the POI has a very low velocity (lower than a first predetermined threshold, e.g., 1 m/s) or the POI points has a very high velocity (higher than a second predetermined threshold, e.g., 100 m/s). The decision module **424***b* may approve the POI if the POI has a very low velocity, the POI may become a filtered POI **440***b*. The decision module **424***b* may be configured to reject the POI if the POI points have a very high velocity. The decision module **424***b* may be configured to delegate (transmit) any POI, e.g., with a velocity in between the first predetermined threshold and the second predetermined threshold, then the POI may become a delegated POI **450***b*. Because most of the scene is usually static, any noisy dynamic points may be addressed by the complex filter core, e.g., **515***b*. With a probability that the POI is not an FA, the decision module **424***b* may score the POI. When the confidence metric is within a predetermined threshold, there is the probability that the POI is not an FA. Then, the POI may be assigned a score by the decision module **424***b*.

FIG. **5**A is a block diagram of a system **500***a* that includes a complex filter core **515***a* as used in accordance with embodiments of the present disclosure. In some scenarios, the complex filter core **515***a* includes more computational resources to perform complex filtering operations described herein. The complex filter core **515***a* can be configured to perform one or more complex operations in a manner that requires access to more computational resources, more compute time, and/or more power relative to a simple filter described herein. For instance, predetermined thresholds can be used to determine the amount of processing to be performed at the complex filter, e.g., the complex filter core **515***a*, (e.g., including, but not limited to, compute time thresholds, power thresholds, and the like). In some scenarios, certain FA data points or POI points may require a broader neighborhood context and/or greater computational resources for detection by the complex filter. Additional examples that demonstrate the hardware/software profile of complex filters are described herein.

For instance, with reference now to FIG. **5**A, in one embodiment, the complex filter core **515***a* may include a neighborhood context module **522***a*, a metric calculation module **523***a*, and a decision module **524***a*. The neighborhood context module **522***a* may be configured to select a 3D space neighborhood for a delegated POI **530***a* (e.g., **450***a*). To get the neighborhood data points in the neighborhood, a search tree (KD Tree, OctTree, or variants) may be constructed on all the POIs.

The metric calculation module **523***a* may be configured to compute a variance of point properties including velocity, intensity, or range, etc. A variance of the POI properties may be computed or calculated over the 3-D space neighborhood. The POI properties may include the velocity, intensity, range, or even higher order moments such as skewness and kurtosis, etc., of the data point/POI. The variance of the POI properties (e.g., the velocity or intensity) may be calculated over the neighborhood (e.g., neighborhood data points).

The decision module **524***a* may be configured to determine, based on the confidence metric, whether to accept the POI, modify the POI, reject the POI, or delegate/transmit the POI to another filter core. The variance of the data point/POI properties (e.g., the velocity or intensity) may be compared against a predetermined threshold. When the POI properties (e.g., the velocity or intensity) are lower than the predetermined threshold, the data point/POI may be accepted or approved to become a filtered POI **540***a*. The filtered POI **540***a* may be added to a filtered output point cloud. When the POI properties (e.g., the velocity or intensity) are not lower than the predetermined threshold, the data point/POI may be rejected. When a decision cannot be made, then the POI may be transmitted to the subsequent filter core. With a probability that the POI is not an FA, the decision module **524***a* may score the POI. When the confidence metric is within a predetermined threshold, there is the probability that the POI is not an FA. Then, the POI may be assigned a score by the decision module **524***a*.

Referring to FIG. **5**B, the complex filter core **515***b* may include a neighborhood context module **522***b*, a metric calculation module **523***b*, and a decision module **524***b*. The neighborhood context module **522***b* may select a window of data points in the same azimuth or elevation around a POI **530***b*. The neighborhood context module **522***b* may select a window of points adjacent in the scan pattern. In some embodiments, a plurality of neighborhood data points including a 2-D or 3-D space neighborhood may be selected in order to consider additional ranges of data points.

The up-chirp and down-chirp frequencies from the window of points adjacent in the scan pattern may be stored. The metric calculation module **523***b* may compute the metric, which may be the variance of the up-chirp or the down-chirp frequencies from the window of points. For example, the variance of the up-chirp frequencies, or the variance of the down-chirp frequencies, or the difference between the variance of the up-chirp frequencies and the variance of the down-chirp frequencies may be compared against respective predetermined thresholds.

If the variance of the up-chirp frequencies, or the variance of the down-chirp frequencies, or the difference between the variance of the up-chirp frequencies and the variance of the down-chirp frequencies is not lower than the respective predetermined threshold, the decision module **524***b* may determine to reject the POI. Otherwise, the data POI may be approved to become a filtered POI **540***b* or delegated/transmitted to another filter (not shown).

With a probability that the POI is not an FA, the decision module **524***b* may score the POI. When the confidence metric is within a predetermined threshold, there is the probability that the POI is not an FA. Then, the POI may be assigned a score by the decision module **524***b*.

FIG. **6** is a block diagram of a system **600** that includes a series cascaded point cloud filter **610** according to embodiments of the present disclosure. According to some embodiments, the series cascaded point cloud filter **610** may include at least one simple filter **602** (e.g., **415***a*, **415***b*) and at least one complex filter **603** (e.g., **515***a*, **515***b*). An input point cloud **601** may be filtered by the simple filter **602** and the complex filter **603**. An output point cloud **604** may be the filtered point cloud. In some scenarios, simple filter **602** includes fewer computational resources to perform the filtering operations described herein relative to the complex filter **603**. In such cases, the computational resources required by the simpler filter **602** enable it to perform filtering operations that require shorter compute time relative to the computational resources resident on the complex filter **603**.

As discussed above, the simple filter **602** can be configured to perform computationally inexpensive operations to determine neighborhood data points or compute the metric in a manner that requires fewer computational resources, less compute time, and/or less power relative to the complex filter **603**.

As an example, the series cascaded point cloud filter may include the simple filter core **415***a* as described in connection with FIG. **4**A and the complex filter core **515***a* as described in connection with FIG. **5**A. As another example, the series cascaded point cloud filter may include the simple filter core **415***b* as described in connection with FIG. **4**B and the complex filter core **515***b* as described in connection with FIG. **5**B. It should be appreciated that the examples described herein are only for illustration purposes. There may be many other embodiments of the series cascaded filter based on this disclosure.

Filter performance may be measured by one or more of the following: latency, computational load, FA rejected, or TD approved. An ideal filter should take less time to process the point cloud, thereby adding a lower latency. Computational load refers to an amount of computational resources required because of the introduction of the filter. An ideal filter takes less amount of computational resources to process the point cloud. FA rejected refers to a quantity of FA points or a number of FA points removed by the Filter. An ideal filter removes all the FA points in the POIs which the filter processes. FA rejected may be determined by:

$$m_{FA}=\text{removed}_{FA}/\text{total}_{FA}$$

TD approved refers to a quantity of TD points or a number of TD points approved by the filter. An ideal filter approves all the TD points in the POIs which the filter processes. TD approved may be determined by:

$$m_{TD}=\text{approved}_{TD}/\text{total}_{TD}$$

A combination of different filters may be employed to achieve an optimal performance. For example, a combination of one or more simple filters and one or more complex filters may be used to balance the accuracy, the operational cost and the latency.

Referring to FIG. **6**, embodiments of the present disclosure can be configured to use cascaded filters when processing point clouds in a manner that reduces latency. The series cascaded filter **610** may be configured using one or more functions provided by both a simple filter core and a complex filter core. For example, simple filters may operate on as many POIs as possible, while suspect POIs may be transmitted or delegated to complex filters to operate on. The series cascaded filter **610** has the advantages of being almost as fast as a simple filter while having high FA rejected m_{FA} and high TD approved mm. By using the combination of the simple filter core and the complex filter core, the series cascaded filter may have a high FA rejection percentage and a high TD approval percentage while saving the computing time and the amount of computational resources to process the point cloud, thereby improving the performance with a lower latency.

The input point cloud **601** may be received by the series cascaded filter **610**. At the simple filter **602**, each POI of the input point cloud **601** is filtered. The simple filter may accept or discard as many POIs as possible, and transmit or delegate the suspect POIs to the complex filter **603**. At the complex filter **603**, the suspect POIs may be accepted or discarded. The filtered point cloud **604** may be output based on the simple filter **602** and the complex filter **603**.

FIG. **7** is a block diagram **700** illustrating detailed structure of the series cascaded point cloud filter **610** according to some embodiments. For example, the series cascaded point cloud filter **610** may include a point cloud fragmenter **712**, a POI dispatcher **713**, a simple filter core **715** (e.g., the filter core for the simple filter **602**), a complex filter core **725** (e.g., the filter core for the complex filter **603**), a POI collector **716**, a POI collector and dispatcher **726**, and/or a point cloud builder **717**. The point cloud **601** may be obtained (e.g., received, acquired) by the point cloud fragmenter **712**, which identifies regions of the point cloud **601** that the filter **610** will be working on and creates POIs that can be sent to the POI dispatcher **713**. Portions of the point cloud **601** that the filter **610** won't be working on may be transmitted to the point cloud builder **717** (link not shown). The POI dispatcher **713** receives the POIs from the point cloud fragmenter **712** and sends the POIs to the simple filter core **715** one POI at a time for processing.

According to some embodiments, the POI collector and dispatcher **726** may be placed in between the simple filter core **715** and the complex filter core **725** to aid in the transfer of the POIs to the complex filter core **725** for further processing to render a determination. Once the complex filter core **725** operates on the POI, the POI is sent to the POI collector **716**, which collects the POIs processed from the simple filter core **715** and the complex filter core **725**. These pooled POIs are then sent to the point cloud builder **717**.

FIG. **8** is a block diagram of a system **800** that includes multiple series cascaded point cloud filters (e.g., **610**, **810**, **820**) according to embodiments of the present disclosure. Using multiple series cascaded point cloud filters in the manner described herein enable embodiments of the present disclosure to achieve an optimal performance to balance accuracy, operational costs and latency.

Referring to FIG. **8**, the series cascaded point cloud filter **610** may be followed by a series cascaded point cloud filter **810**. The output point cloud **604** of the series cascaded point cloud filter **610** may be the filtered point cloud **1**, which may be an input point cloud for the series cascaded point cloud filter **810**. The series cascaded point cloud filter **810** may include a simple filter **802** and a complex filter **803**. The simple filter **802** has similar functions like the simple filter **602**. The complex filter **803** has similar functions like the complex filter **603**. Thus, the series cascaded point cloud filter **810** may include one or more functions of the simple filter **602** and the complex filter **603**.

Similarly, the series cascaded point cloud filter **810** may be followed by a series cascaded point cloud filter **820**, which may include an additional simple filter (e.g., simple filter **812**) and an additional complex filter **813** (e.g., complex filter **813**). The output point cloud **804** of the series cascaded point cloud filter **810** may be the filtered point cloud **2**, which may be an input point cloud for the series cascaded point cloud filter **820**. In this fashion, embodiments of the present disclosure can use multiple series cascaded point cloud filters to perform filtering techniques.

FIG. **9** is a block diagram of a system **900** that includes a parallel cascaded point cloud filter **910** according to embodiments of the present disclosure. According to some embodiments, the parallel cascaded point cloud filter **910** may include at least two filters **902** and **903**. The at least two filters **902** and **903** may be at least two different filters. For example, the at least two filters **902** and **903** may include at least two of the filters **415***a*, **415***b*, **515***a*, or **515***b*. The at least two filters **902** and **903** may have different neighborhood selection and different metrics. The at least two filters **902** and **903** may be simple filters, complex filters, or a combination of simple and complex filters. Part of the at least two filters may be simple filter(s), and part of the at least two filters may be complex filter(s).

An input point cloud **901** may be filtered by the filter **902** and the filter **903** independently in parallel. For example, a POI may be received at the filter **902** and at the filter **903** independently in parallel. The filters **902** and **903** may be used in parallel to score POIs. The parallel cascaded point cloud filter **910** including at least two filters **902** and **903** may be used on critical regions of the point cloud **901** as the two filters **902** and **903** work independently, thereby increasing the confidence of the filter decision.

The filter **902** may include a neighborhood context module to select a set of neighborhood points of the POI, a metric calculation module to compute a metric for the set of neighborhood points, and a decision module to determine a score of the POI based on the metric. The filter **903** may include a different neighborhood context module to select a different set of neighborhood points of the POI, a different metric calculation module to compute a different metric, and a different decision module to determine a score of the POI.

When the filters **902** and **903** are used in parallel, the decision module of the filter **902** may determine one score for the POI according to a predetermined rule, and the decision module of the filter **903** may determine another score for the POI according to the predetermined rule. In this case, the decision modules of the filters may only score the POI. The decision modules of the filter **902** and **903** may determine a respective score of the POI independently in parallel according to the predetermined rule. The filters **902** and **903** may output the scores of the POI independently in parallel.

The output scores of the POI from both the filter **902** and the filter **903** may be merged. The POI may be accepted, modified, or rejected based on the output scores of the POI from both filters **902** and **903** according to a set of predetermined thresholds. As an example, when at least one of the scores from both filters **902** and **903** is below a first predetermined threshold, the POI may be rejected. As another example, when both scores are above the first predetermined threshold but one score of the two scores is below a second predetermined threshold, the POI may be modified. As yet another example, when both scores are above the second predetermined threshold, the POI may be accepted.

The parallel cascaded point cloud filter **910** may transmit the accepted or modified POI to an output point cloud **905**, which may be the filtered point cloud. The rejected POI may be deleted or removed.

FIG. **10** is a block diagram **1000** illustrating detailed structure of the parallel cascaded point cloud filter **910** according to some embodiments. For example, the parallel cascaded point cloud filter **910** may include a point cloud fragmenter **1012**, a POI dispatcher **1013**, a filter core **915** (e.g., the filter core for the filter **902**), a filter core **925** (e.g., the filter core for the complex filter **903**), a POI collector **1016**, a POI collector **1017**, and/or a unifier with point cloud builder **1018**. The point cloud **901** may be obtained (e.g., received, acquired) by the point cloud fragmenter **1012**, which identifies regions of the point cloud **901** that the filter **910** will be working on and creates POIs that can be sent to the POI dispatcher **1013**. Portions of the point cloud **901** that the filter **910** won't be working on may be transmitted to the point cloud builder **1018** (link not shown). The POI dispatcher **1013** receives the POIs from the point cloud fragmenter **1012** and sends the POIs to the filter core **915** and the filter core **925** in parallel, one POI at a time for processing.

According to some embodiments, the filter core **915** and the filter **925** operate on the POI independently in parallel. The filter core **915** may determine a score for the POI. The filter core **915** may determine another score for the POI. After the POI is processed by the filter core **915**, the scored POI, which is the POI with the score from the filter core **915**, is sent to the POI collector **1016**. After the POI is processed by the filter core **925**, the scored POI, which is the POI with another score from the filter core **925**, is sent to the POI collector **1017**. These scored POIs are then sent to the unifier with point cloud builder **1018**.

The unifier with point cloud builder **1018** may be tasked with merging the scored POIs output from both the filter cores **915**, **925**. The unifier with point cloud builder **1018** may determine to accept, modify or reject the scored POIs on the basis of a set thresholds. The POI may be accepted, modified, or rejected based on the output scores of the POI from both filter cores **915** and **925** according to a set of predetermined thresholds. As an example, when both scores from both filter cores **915** and **925** exceed the predetermined thresholds, the POI may be rejected. As another example, when at least one of the scores is below the predetermined thresholds, the POI may be modified/accepted/removed. As yet another example, when both scores are below the predetermined thresholds, the POI may be accepted. The parallel cascaded point cloud filter **910** may transmit the accepted or modified POI to a filtered point cloud **905**. The rejected POI may be deleted or removed.

FIG. **11** is a block diagram of a system **1100** that includes multiple cascaded point cloud filters (e.g., **1110**, **1120**, **1130**) according to embodiments of the present disclosure. Using multiple cascaded point cloud filters in the manner described herein enable embodiments of the present disclosure to achieve an optimal performance to improve confidence and balance accuracy, operational costs and latency.

Referring to FIG. **11**, an input point cloud **1101** may be received by a series cascaded point cloud filter **1110**, which may be followed by a parallel cascaded point cloud filter **11200**. The output point cloud **1104** of the series cascaded point cloud filter **1110** may be the filtered point cloud **1**, which may be an input point cloud for the parallel cascaded point cloud filter **1120**. The series cascaded point cloud filter **1110** may include a simple filter **1102** and a complex filter **1103**. The simple filter **1102** has similar functions like the simple filter **602**. The complex filter **1103** has similar functions like the complex filter **603**. Thus, the series cascaded point cloud filter **1110** may include one or more functions of the simple filter **1102** and the complex filter **1103**.

The parallel cascaded point cloud filter **1120** may include a filter **1112** and a filter **1113** in parallel. The filters **1112**, **1113** have similar functions like the filters **902**, **903**. The output point cloud **1105** of the parallel cascaded point cloud filter **1120** may be the filtered point cloud **2**, which may be an input point cloud for another cascaded point cloud filter **1130**. The cascaded point cloud filter **1130** may be a series cascaded point cloud filter, or a parallel cascaded point cloud filter. In this fashion, embodiments of the present disclosure can use multiple series cascaded point cloud filters to perform filtering techniques to achieve an optimal performance to improve confidence and balance accuracy, operational costs and latency.

FIG. **12** is a flow diagram illustrating an example of a process to filter a point cloud according to embodiments of the present disclosure. For example, the process may be performed by a signal processing unit **112** of a LiDAR system, as illustrated in FIG. **1**A-FIG. **1**B. In this process, the FA points may be removed, thereby, the accuracy in the estimated target range/velocity may be improved.

At block **1201**, at a first filter, a set of POIs of a point cloud are received, where each POI of the set of POIs includes one or more points. In one embodiment, the first filter may be a parallel cascaded point cloud filter which includes a second filter and a third filter.

At block **1202**, each POI of the set of POIs is filtered, where filtering each POI comprises filtering at the second filter, filtering at the third filter, and filtering at the first filter.

At block **1203**, at the second filter, a first set of neighborhood points of a POI is selected; a first metric for the first set of neighborhood points is computed; and a first score of the POI is determined based on the first metric.

At block **1204**, at the third filter, a second set of neighborhood points of the POI is selected; a second metric for the second set of neighborhood points is computed; and a second score of the POI is determined based on the second metric.

At block **1205**, at the first filter, e.g., at a decision module of the first filter, based on the first score and the second score, whether to accept the POI, modify the POI, or reject the POI is determined, to extract at least one of range or velocity information related to a target.

At block **1206**, provided the POI is accepted or modified, the POI is transmitted to a filtered point cloud, which may be an output point cloud.

At block **1207**, provided the POI is rejected, the POI is prevented from reaching the filtered point cloud.

In one embodiment, each POI of the set of POIs is filtered at the second filter and at the third filter independently in parallel.

In one embodiment, the POI is received at the second filter and at the third filter independently in parallel.

In one embodiment, the POI is rejected in response to determining that at least one of the first score or the second score is below a predetermined threshold.

In one embodiment, the POI is accepted or modified in response to determining that both the first score and the second score are not below a predetermined threshold.

In one embodiment, the second set of neighborhood points are different than the first set of neighborhood points.

In one embodiment, the second metric for the second set of neighborhood points is different than the first metric for the first set of neighborhood points.

The preceding description sets forth numerous specific details such as examples of specific systems, components, methods, and so forth, in order to provide a thorough understanding of several examples in the present disclosure. It will be apparent to one skilled in the art, however, that at least some examples of the present disclosure may be practiced without these specific details. In other instances, well-known components or methods are not described in detail or are presented in block diagram form in order to avoid unnecessarily obscuring the present disclosure. Thus, the specific details set forth are merely exemplary. Particular examples may vary from these exemplary details and still be contemplated to be within the scope of the present disclosure.

Any reference throughout this specification to "one example" or "an example" means that a particular feature, structure, or characteristic described in connection with the examples are included in at least one example. Therefore, the appearances of the phrase "in one example" or "in an example" in various places throughout this specification are not necessarily all referring to the same example.

Although the operations of the methods herein are shown and described in a particular order, the order of the operations of each method may be altered so that certain operations may be performed in an inverse order or so that certain operations may be performed, at least in part, concurrently with other operations. Instructions or sub-operations of distinct operations may be performed in an intermittent or alternating manner.

The above description of illustrated implementations of the invention, including what is described in the Abstract, is not intended to be exhaustive or to limit the invention to the precise forms disclosed. While specific implementations of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. The words "example" or "exemplary" are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "example" or "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Rather, use of the words "example" or "exemplary" is intended to present concepts in a concrete fashion. As used in this application, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or". That is, unless specified otherwise, or clear from context, "X includes A or B" is intended to mean any of the natural inclusive permutations. That is, if X includes A; X includes B; or X includes both A and B, then "X includes A or B" is satisfied under any of the foregoing instances. In addition, the articles "a" and "an" as used in this application and the appended claims should generally be construed to mean "one or more" unless specified otherwise or clear from context to be directed to a singular form. Furthermore, the terms "first," "second," "third," "fourth," etc. as used herein are meant as labels to distinguish among different elements and may not necessarily have an ordinal meaning according to their numerical designation.

What is claimed is:

1. A method of filtering points in a light detection and ranging (LiDAR) system, comprising:
receiving, at a first filter, a set of points of interest (POIs) of a point cloud; and
filtering each POI of the set of POIs, the filtering comprising:
at a second filter:
determining a first score of a POI based on a first metric;
at a third filter:
determining a second score of the POI based on a second metric; and
at the first filter:
determining, based on the first score and the second score, whether to accept, modify, or reject the POI, to extract at least one of range or velocity information related to a target.

2. The method of claim **1**, wherein the filtering each POI of the set of POIs comprises filtering at the second filter and at the third filter independently in parallel.

3. The method of claim **1**, wherein the POI is received at the second filter and at the third filter independently in parallel.

4. The method of claim **1**, wherein the determining, based on the first score and the second score, whether to accept, modify, or reject the POI, comprises determining to reject the POI in response to determining that at least one of the first score or the second score is below a predetermined threshold.

5. The method of claim **1**, wherein the determining, based on the first score and the second score, whether to accept, modify, or reject the POI, comprises determining to accept or modify the POI in response to determining that both the first score and the second score are not below a predetermined threshold.

6. The method of claim **1**, wherein the filtering further comprises:
at the second filter:
selecting a first set of neighborhood points of the POI; and
at the third filter:
selecting a second set of neighborhood points of the POI, wherein the second set of neighborhood points is different than the first set of neighborhood points.

7. The method of claim **1**, wherein the filtering further comprises:
at the second filter:
computing the first metric for a first set of neighborhood points; and
at the third filter:
computing the second metric for a second set of neighborhood points, wherein the second metric for the second set of neighborhood points is different than the first metric for the first set of neighborhood points.

8. A light detection and ranging (LiDAR) system, comprising:
a processor; and
a memory to store instructions that, when executed by the processor, cause the LiDAR system to:
receive, at a first filter, a set of points of interest (POIs) of a point cloud; and
filter each POI of the set of POIs, wherein to filter each POI of the set of POIs, the instructions, when executed by the LiDAR system, cause the LiDAR system to:
at a second filter:
determine a first score of a POI based on a first metric;
at a third filter:
determine a second score of the POI based on a second metric; and
at the first filter:
determine, based on the first score and the second score, whether to accept, modify, or reject the POI, to extract at least one of range or velocity information related to a target.

9. The LiDAR system of claim **8**, wherein the LiDAR system is to filter at the second filter and at the third filter independently in parallel.

10. The LiDAR system of claim **8**, wherein the POI is received at the second filter and at the third filter independently in parallel.

11. The LiDAR system of claim **8**, wherein the LiDAR system is to reject the POI in response to determining that at least one of the first score or the second score is below a predetermined threshold.

12. The LiDAR system of claim **8**, wherein the LiDAR system is to accept or modify the POI in response to determining that both the first score and the second score are not below a predetermined threshold.

13. The LiDAR system of claim **8**, wherein the LiDAR system is further to:
at the second filter:
select a first set of neighborhood points of the POI; and
at the third filter:
select a second set of neighborhood points of the POI, wherein the second set of neighborhood points is different than the first set of neighborhood points.

14. The LiDAR system of claim **8**, wherein the LiDAR system is further to:
at the second filter:
compute the first metric for a first set of neighborhood points; and
at the third filter:
compute the second metric for a second set of neighborhood points, wherein the second metric for the second set of neighborhood points is different than the first metric for the first set of neighborhood points.

15. A light detection and ranging (LiDAR) system, comprising:
an optical source to transmit a portion of a light signal towards a target;
an optical receiver to receive a return beam from the target based on the light signal;
a circuitry; and
a memory to store instructions that, when executed by the circuitry, cause the LiDAR system to:
receive, at a first filter, a set of points of interest (POIs) of a point cloud; and
filter each POI of the set of POIs, wherein to filter each POI of the set of POIs, the instructions, when executed by the circuitry, cause the LiDAR system to:
at a second filter:
determine a first score of a POI based on a first metric;
at a third filter:
determine a second score of the POI based on a second metric; and

at the first filter:

determine, based on the first score and the second score, whether to accept, modify, or reject the POI, to extract at least one of range or velocity information related to the target.

16. The LiDAR system of claim **15**, wherein the LiDAR system is to filter at the second filter and at the third filter independently in parallel.

17. The LiDAR system of claim **15**, wherein the POI is received at the second filter and at the third filter independently in parallel.

18. The LiDAR system of claim **15**, wherein the LiDAR system is to reject the POI in response to determining that at least one of the first score or the second score is below a predetermined threshold.

19. The LiDAR system of claim **15**, wherein the LiDAR system is to accept or modify the POI in response to determining that both the first score and the second score are not below a predetermined threshold.

20. The LiDAR system of claim **15**, wherein the LiDAR system is to:

at the second filter:

select a first set of neighborhood points of the POI; and

at the third filter:

select a second set of neighborhood points of the POI, wherein the second set of neighborhood points is different than the first set of neighborhood points.

21. The LiDAR system of claim **15**, wherein the LiDAR system is further to:

at the second filter:

compute the first metric for a first set of neighborhood points; and

at the third filter:

compute the second metric for a second set of neighborhood points, wherein the second metric for the second set of neighborhood points is different than the first metric for the first set of neighborhood points.

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