US 20250265818A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2025/0265818 A1**

JIN et al. (43) **Pub. Date: Aug. 21, 2025**

(54) **SELF-CALIBRATED PYRAMID NETWORK FOR PILLAR-BASED DETECTOR**

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(21) Appl. No.: **18/669,245**

(22) Filed: **May 20, 2024**

Related U.S. Application Data

(60) Provisional application No. 63/554,765, filed on Feb. 16, 2024.

Publication Classification

(51) **Int. Cl.**

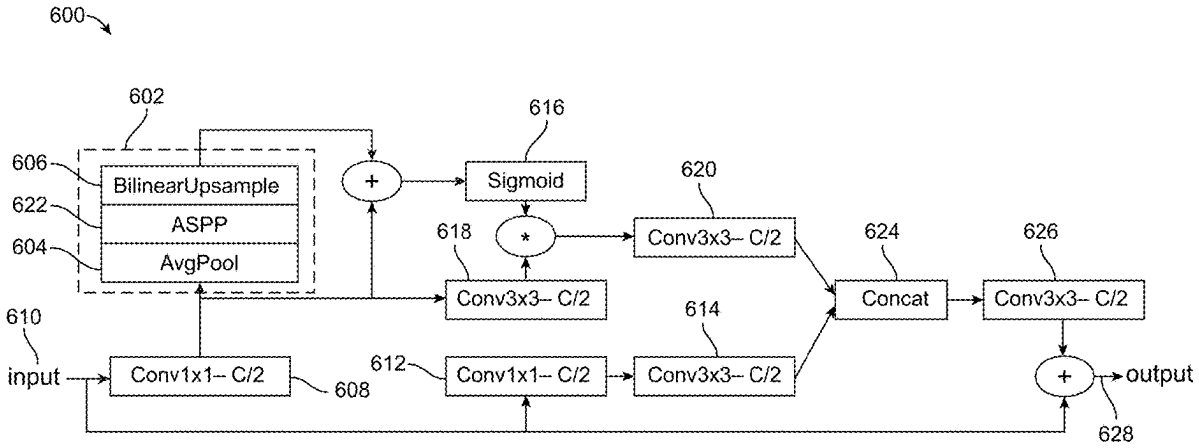
G06V 10/77	(2022.01)
G06V 10/82	(2022.01)
G06V 20/58	(2022.01)
G06V 20/64	(2022.01)

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

CPC ***G06V 10/7715*** (2022.01); ***G06V 10/82*** (2022.01); ***G06V 20/58*** (2022.01); ***G06V 20/64*** (2022.01)

(57) **ABSTRACT**

Techniques and systems are provided for object detection. For instance, a process can include receiving a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; downsampling the set of 3D features; pooling the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; upsampling the pooled set of 3D features to generate a upsampled pooled set of 3D features; predicting bounding boxes based on the upsampled pooled set of 3D features; and outputting the predicted bounding boxes.



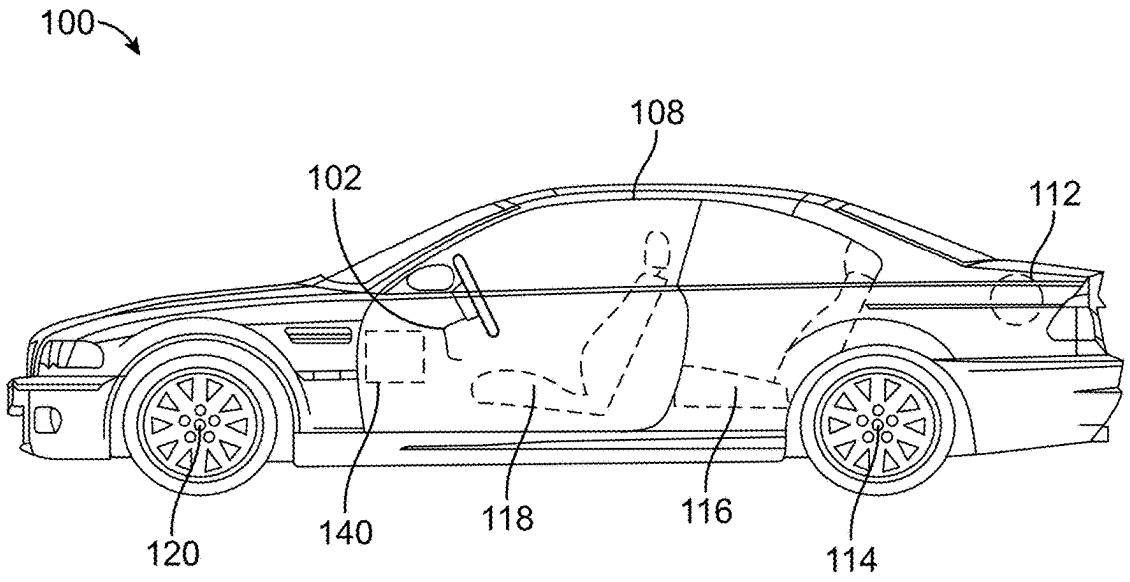

100
108
102
112
120
140
118
116
114

FIG. 1A

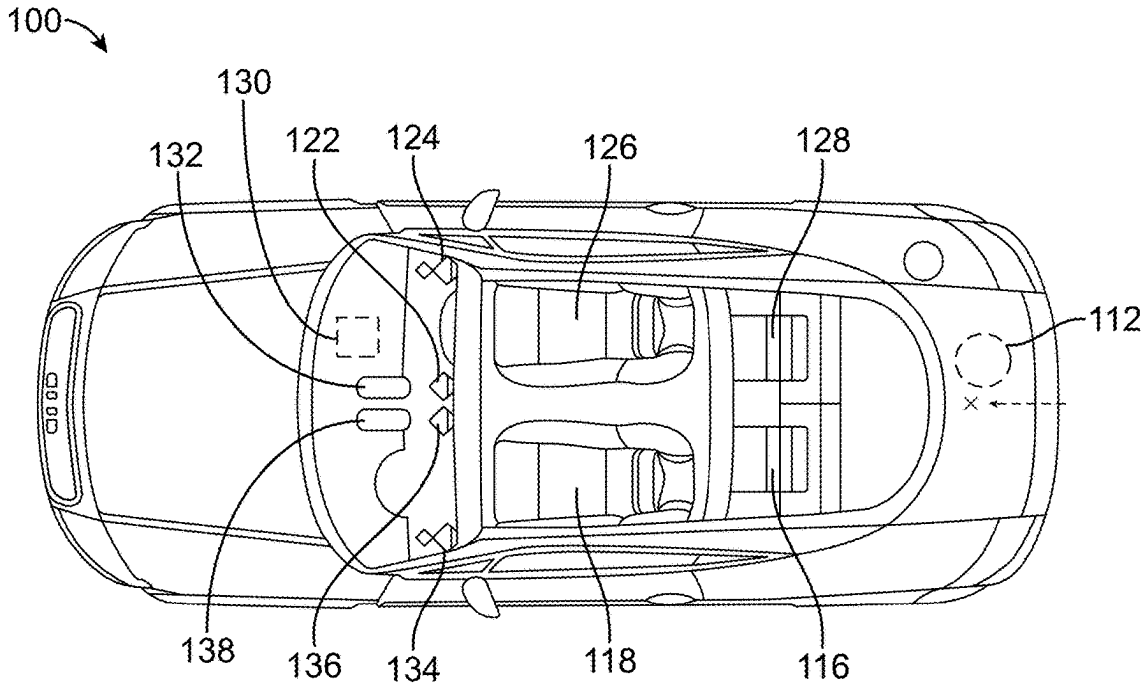

100
130
132
122
124
126
128
112
138
136
134
118
116

FIG. 1B

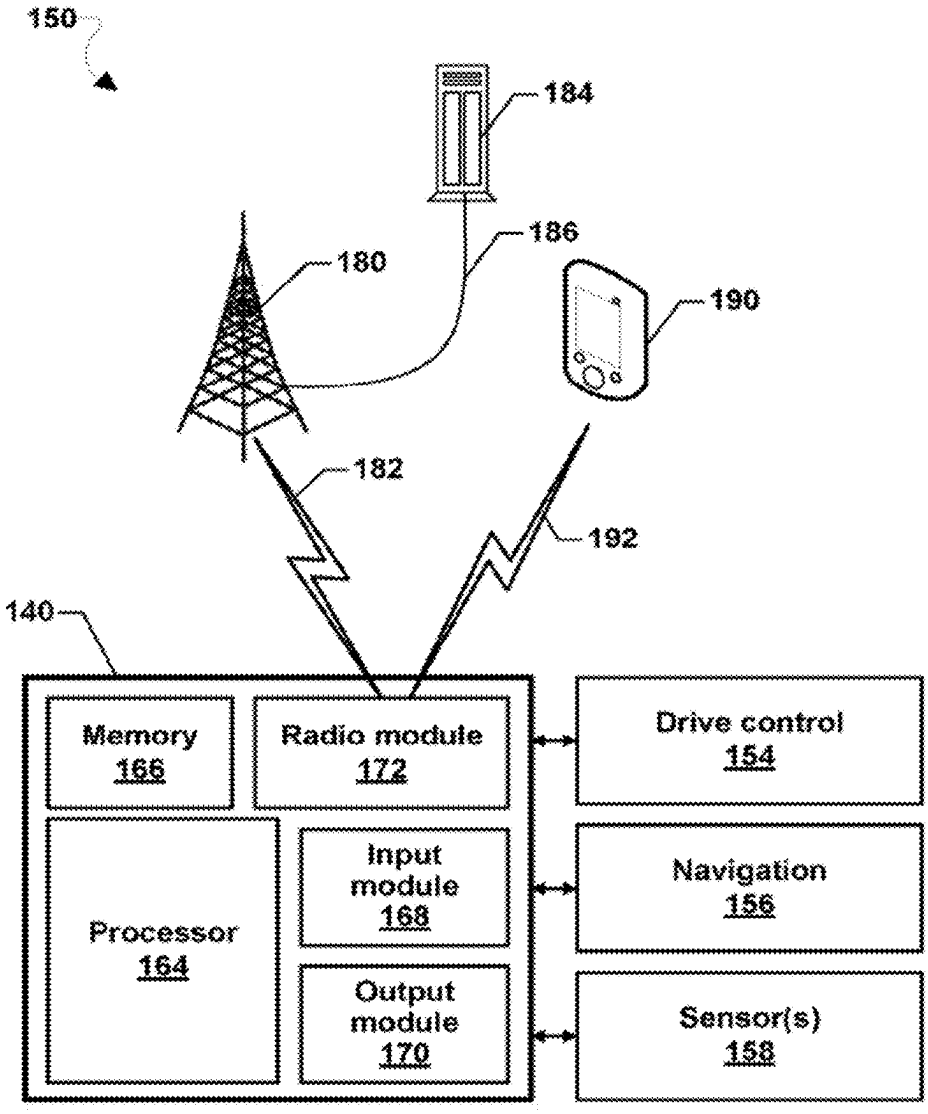

150
184
186
180
190
182
192
140
Memory
166
Radio module
172
Drive control
154
Processor
164
Input
module
168
Navigation
156
Output
module
170
Sensor(s)
158

FIG. 1C

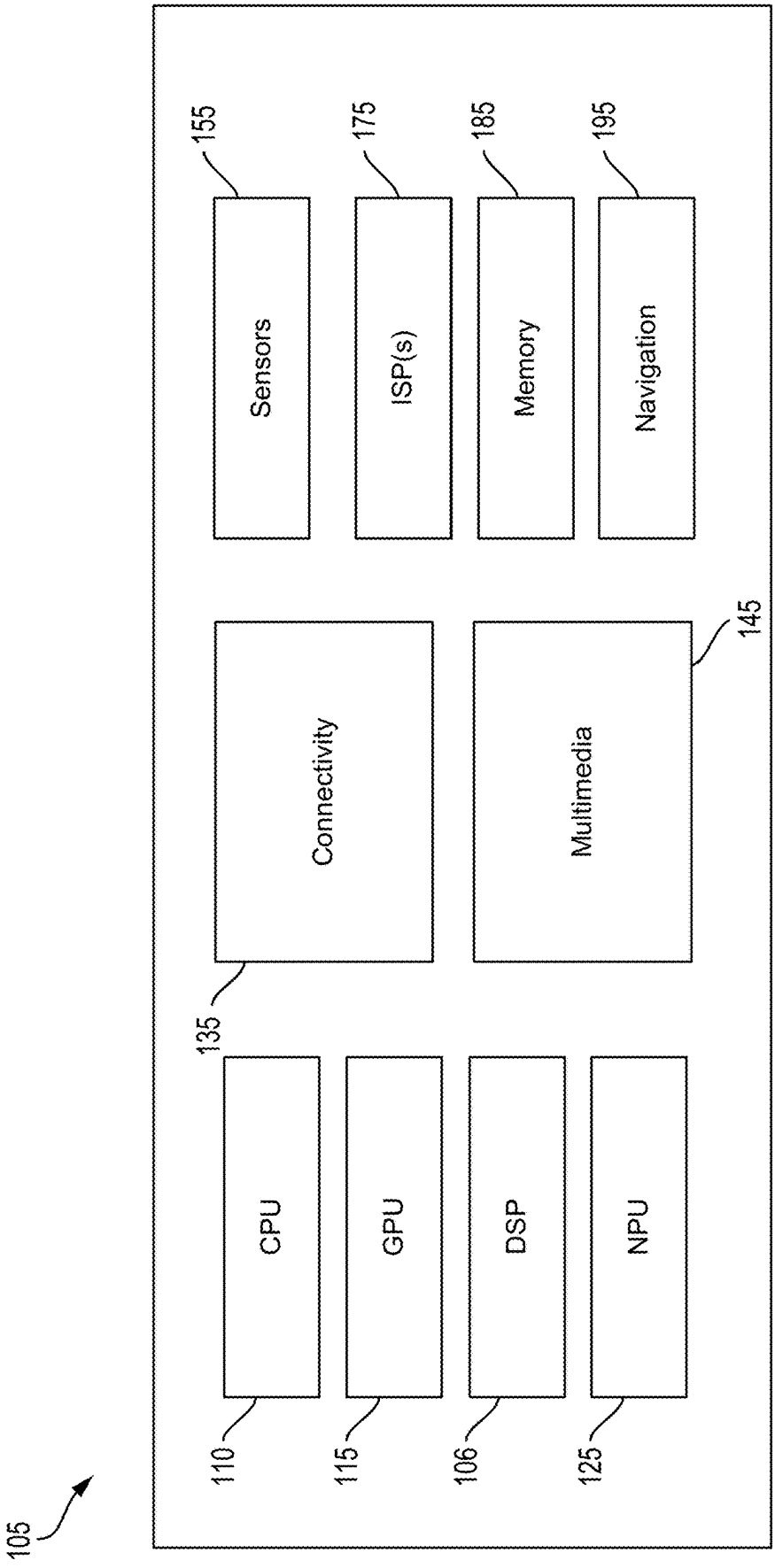

105
110
CPU
115
GPU
106
DSP
125
NPU
135
Connectivity
145
Multimedia
155
Sensors
175
ISP(s)
185
Memory
195
Navigation

FIG. 1D

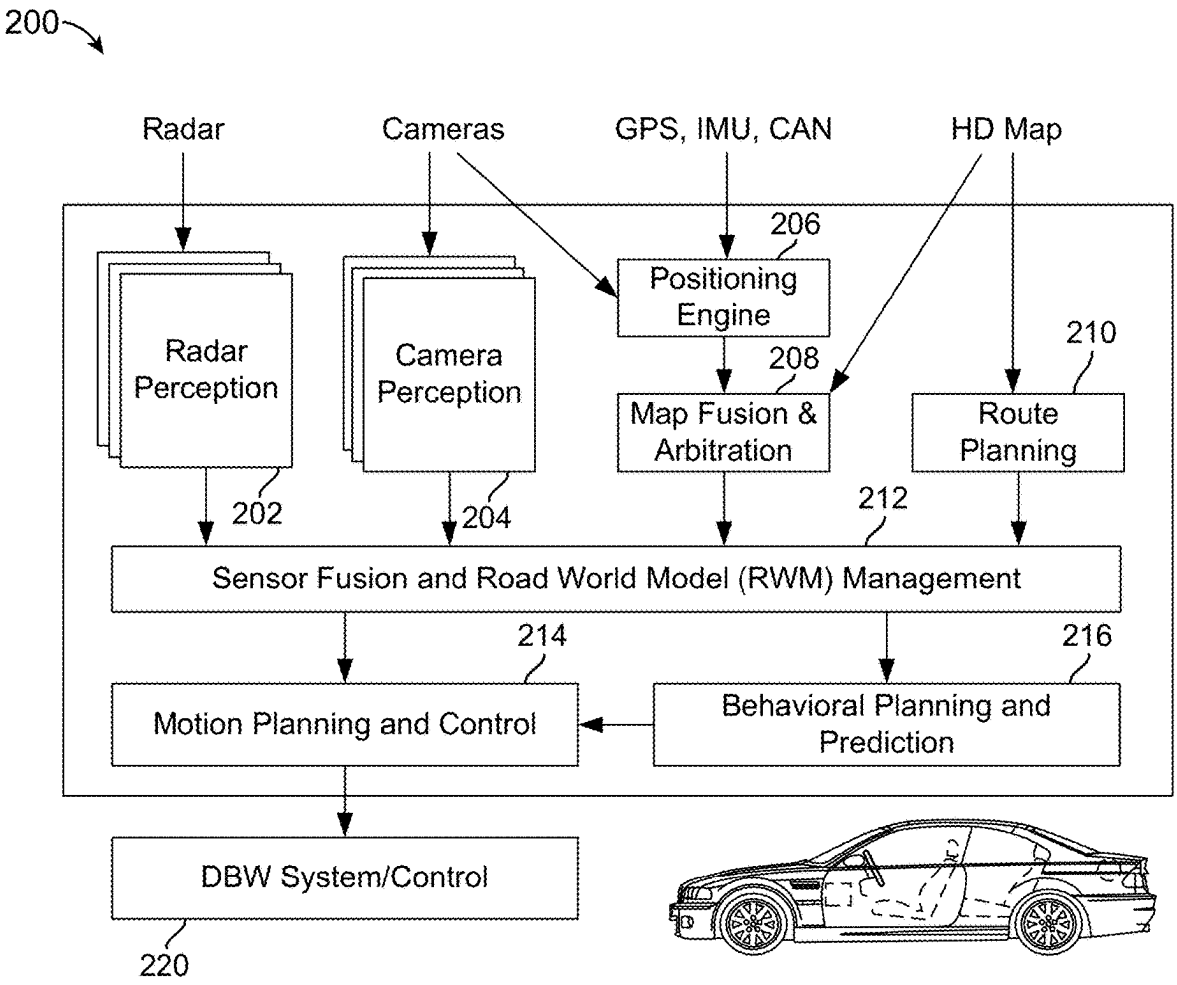

200
Radar
Cameras
GPS, IMU, CAN
HD Map
206
Positioning Engine
Radar Perception
Camera Perception
208
Map Fusion & Arbitration
210
Route Planning
202
204
212
Sensor Fusion and Road World Model (RWM) Management
214
216
Motion Planning and Control
Behavioral Planning and Prediction
DBW System/Control
220

FIG. 2A

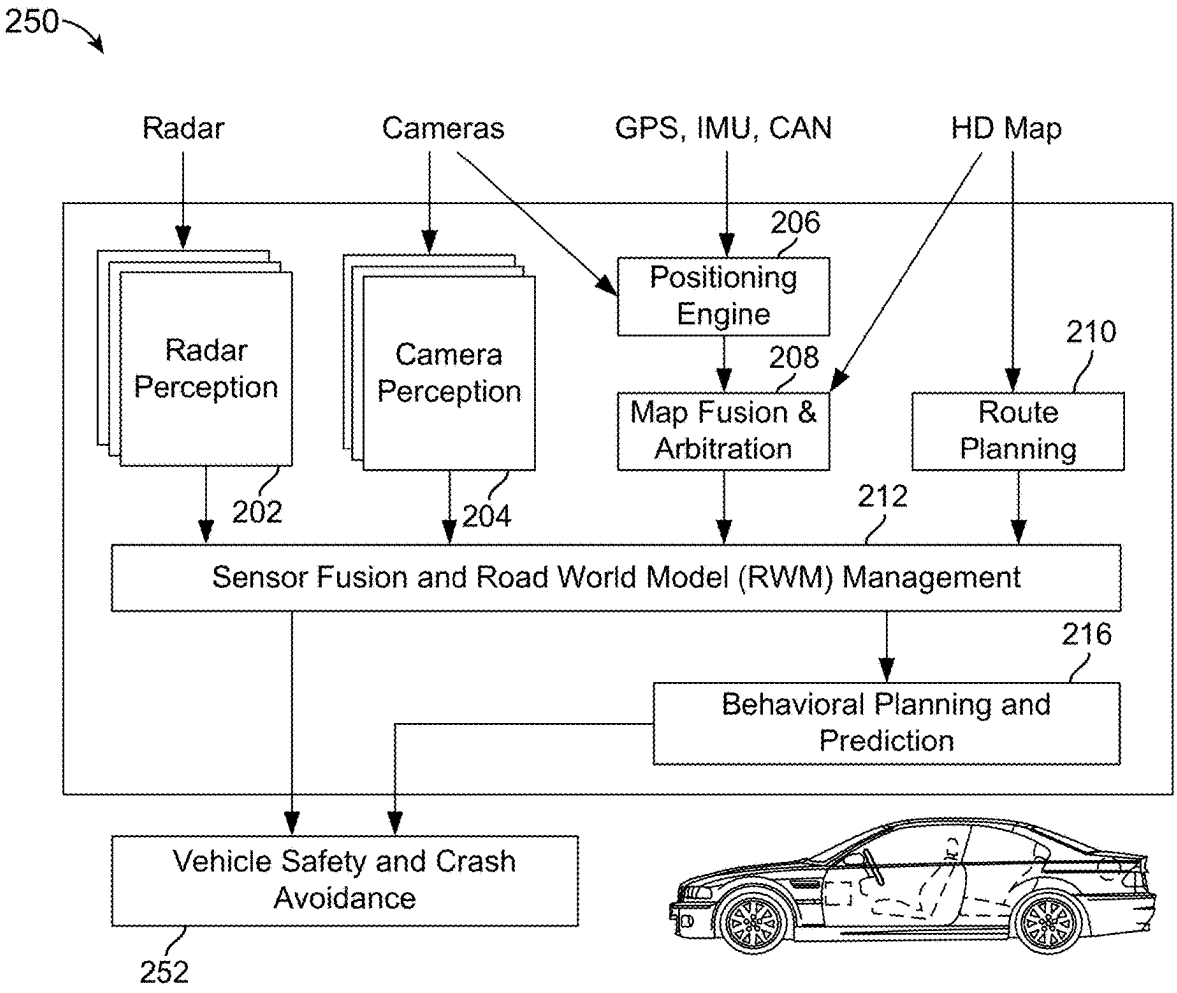

250
Radar
Cameras
GPS, IMU, CAN
HD Map
206
Positioning Engine
Radar Perception
Camera Perception
208
Map Fusion & Arbitration
210
Route Planning
202
204
212
Sensor Fusion and Road World Model (RWM) Management
216
Behavioral Planning and Prediction
Vehicle Safety and Crash Avoidance
252

FIG. 2B

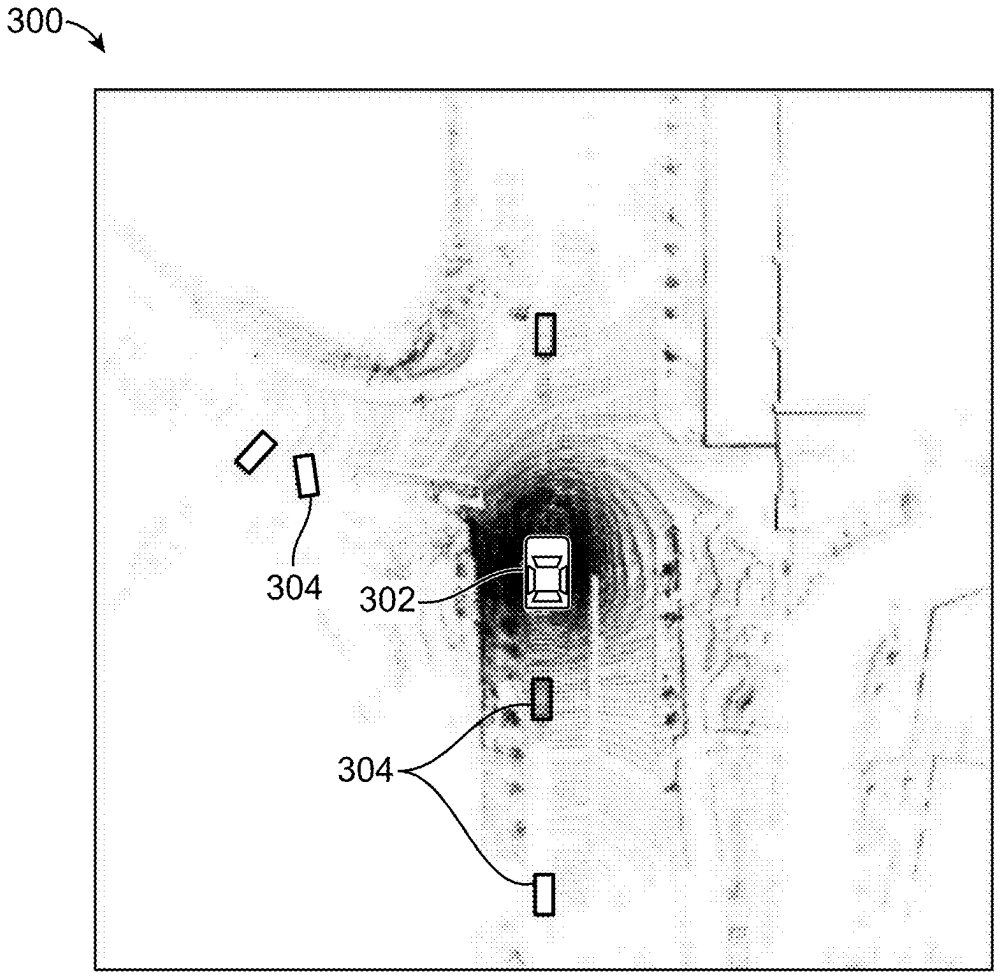


FIG. 3

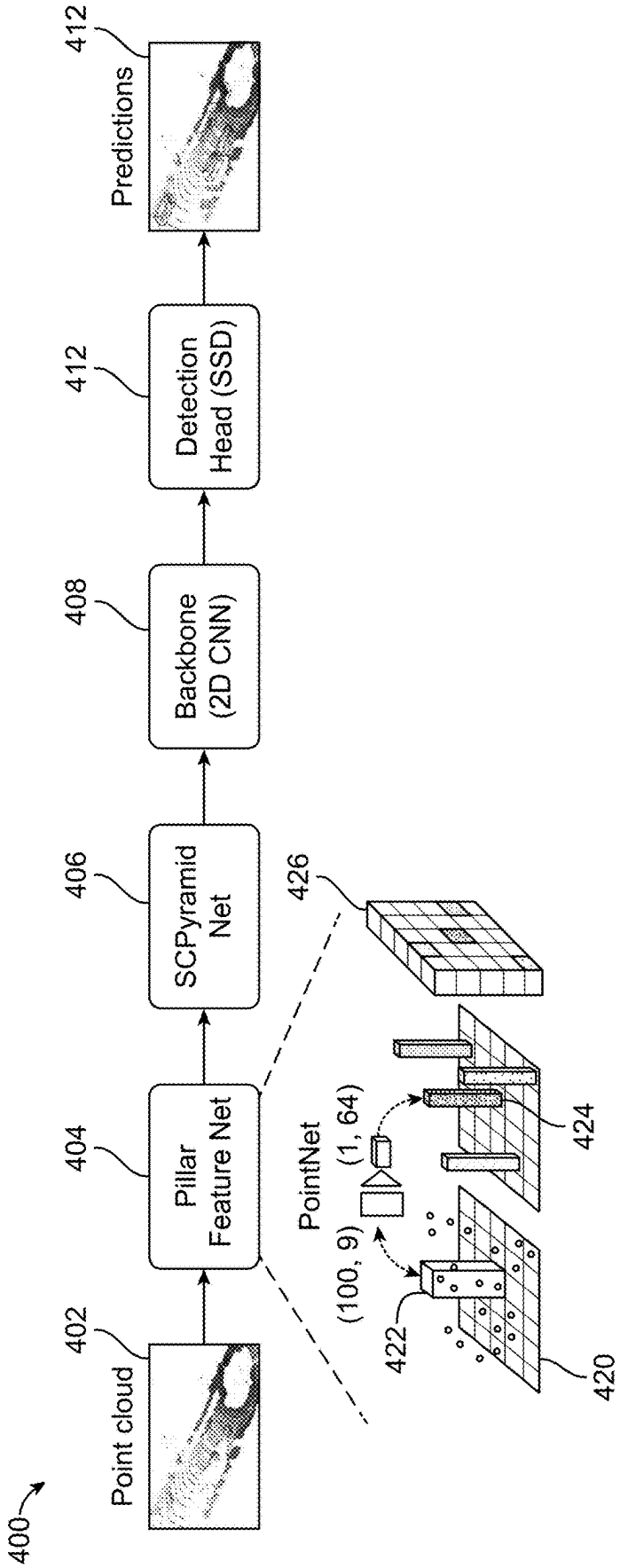

400
Point cloud
402
Pillar Feature Net
404
SCPyramid Net
406
Backbone (2D CNN)
408
Detection Head (SSD)
412
Predictions
412
PointNet
(100, 9)
(1, 64)
422
424
426
420

FIG. 4

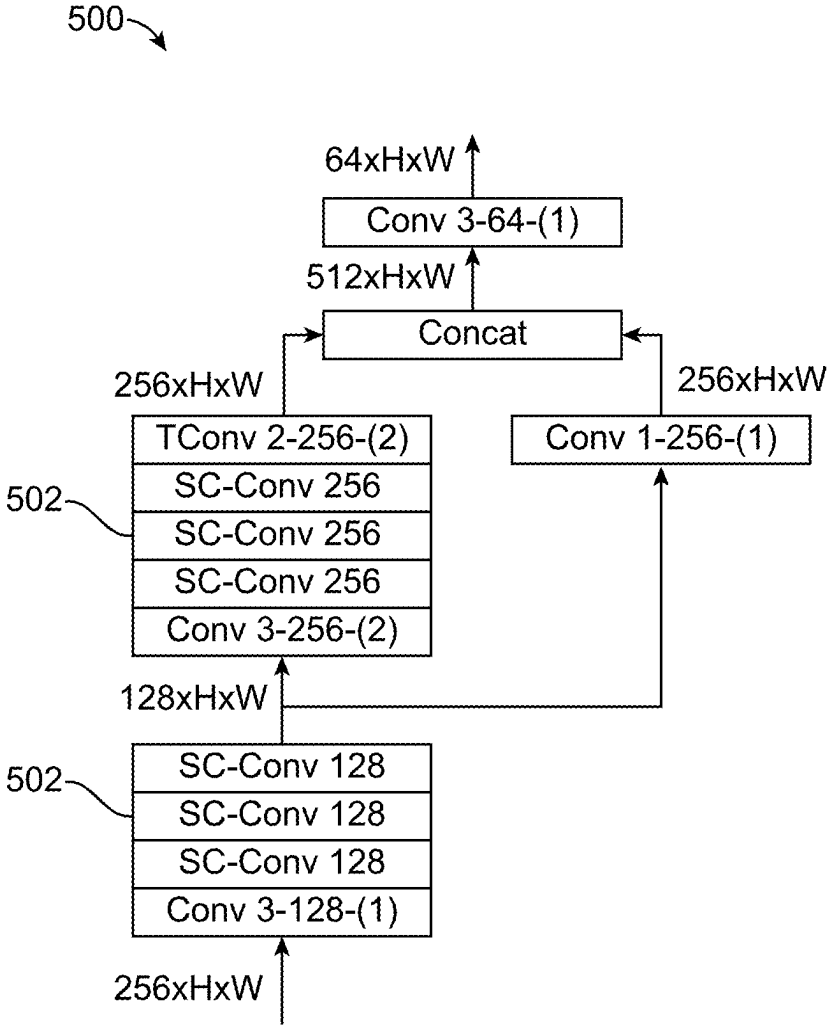

500
64xHxW
Conv 3-64-(1)
512xHxW
Concat
256xHxW
256xHxW
TConv 2-256-(2)
SC-Conv 256
SC-Conv 256
SC-Conv 256
Conv 3-256-(2)
Conv 1-256-(1)
502
128xHxW
SC-Conv 128
SC-Conv 128
SC-Conv 128
Conv 3-128-(1)
502
256xHxW

FIG. 5

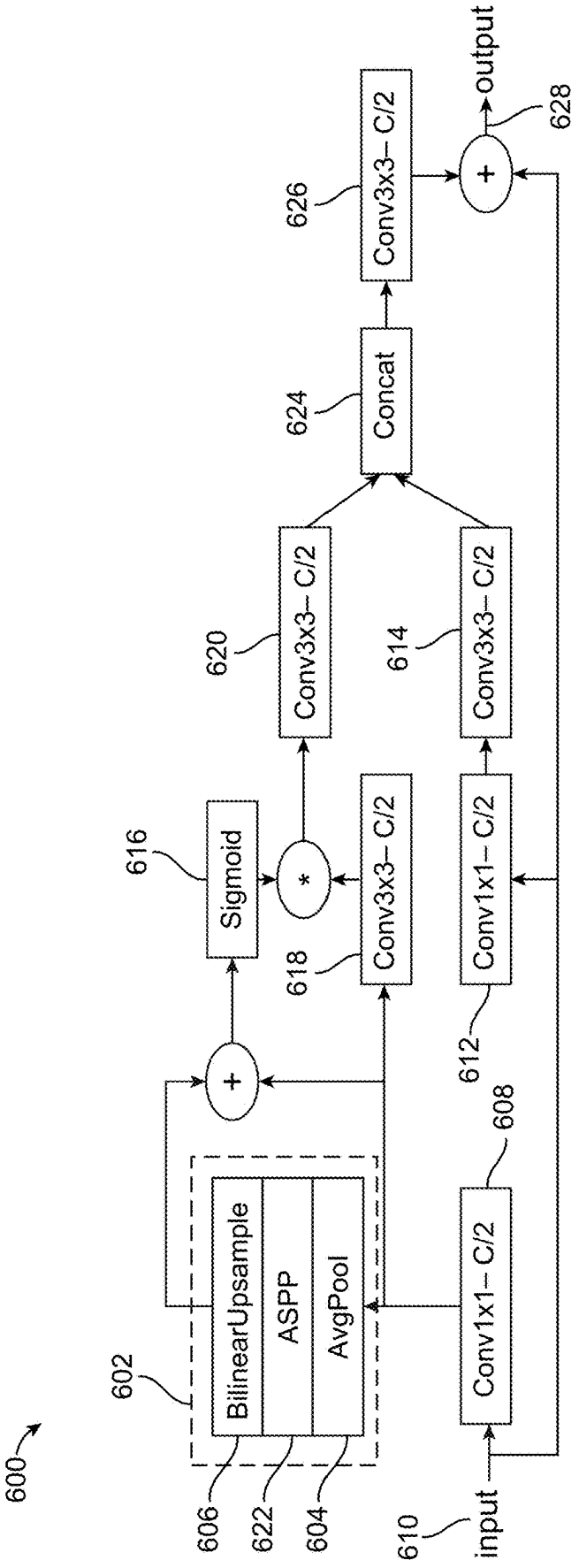

600
602
BilinearUpsample
ASPP
AvgPool
606
622
604
610
input
608
Conv1x1– C/2
612
Conv1x1– C/2
614
Conv3x3– C/2
618
Conv3x3– C/2
616
Sigmoid
620
Conv3x3– C/2
624
Concat
626
Conv3x3– C/2
628
output

FIG. 6

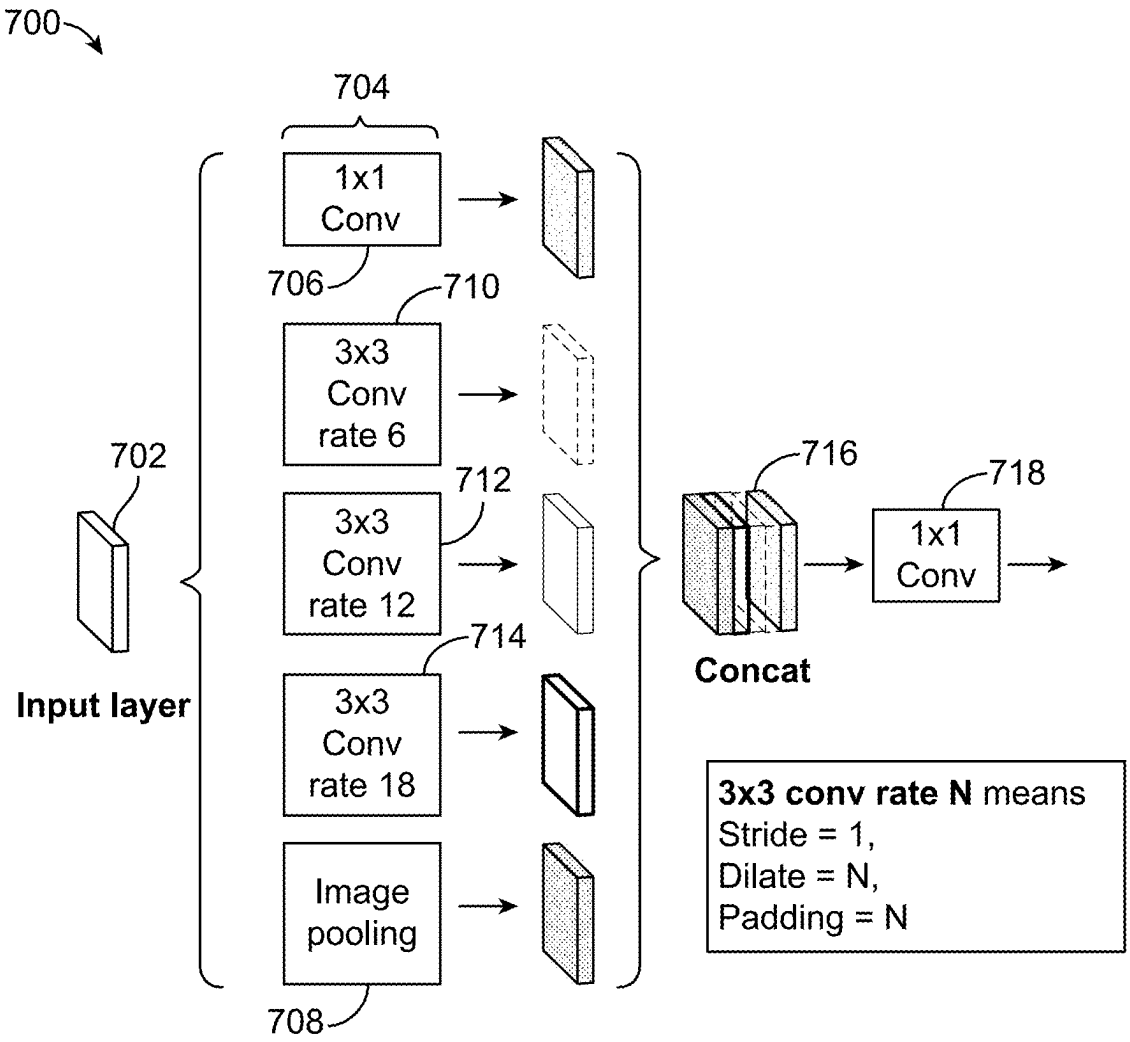

700
704
1x1 Conv
706
710
3x3 Conv rate 6
712
3x3 Conv rate 12
714
3x3 Conv rate 18
Image pooling
708
702
Input layer
716
Concat
718
1x1 Conv
3x3 conv rate N means
Stride = 1,
Dilate = N,
Padding = N

FIG. 7

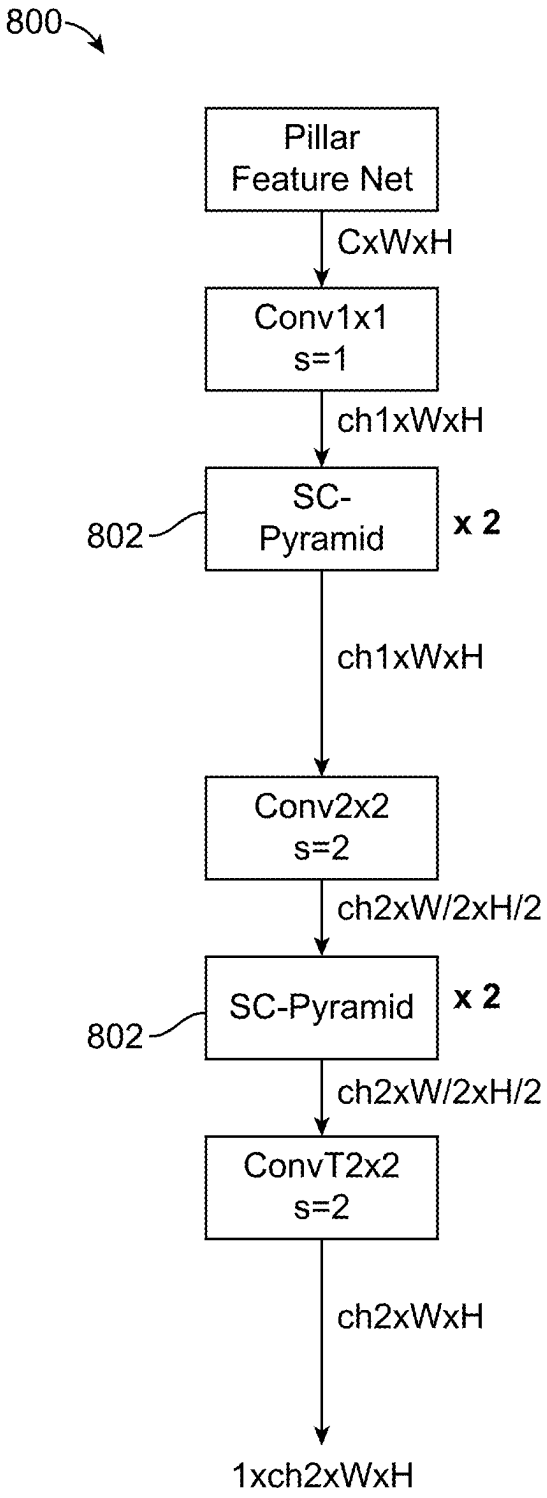

800
Pillar Feature Net
CxWxH
Conv1x1 s=1
ch1xWxH
802
SC-Pyramid
x 2
ch1xWxH
Conv2x2 s=2
ch2xW/2xH/2
802
SC-Pyramid
x 2
ch2xW/2xH/2
ConvT2x2 s=2
ch2xWxH
1xch2xWxH

FIG. 8

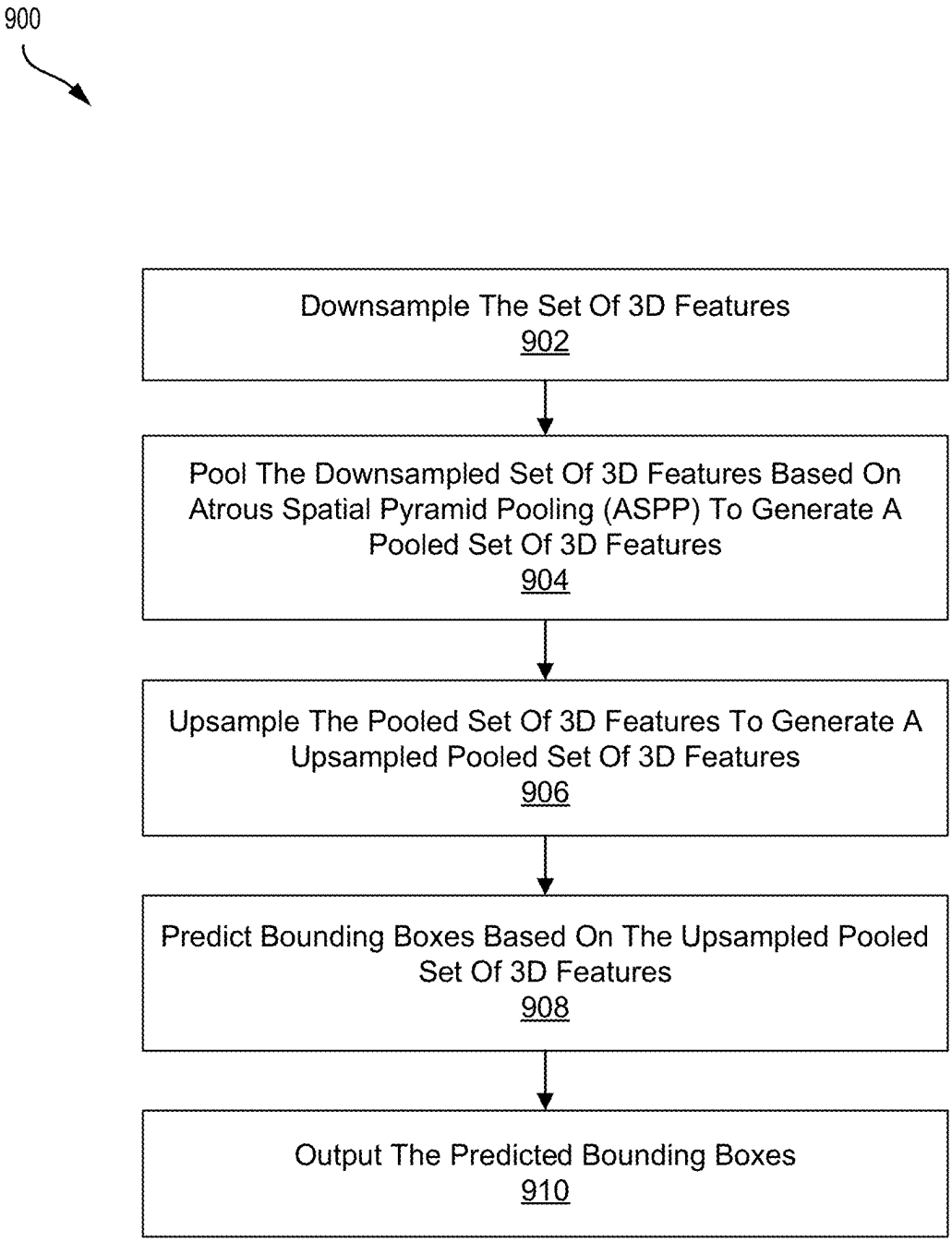

900
Downsample The Set Of 3D Features
902
Pool The Downsampled Set Of 3D Features Based On Atrous Spatial Pyramid Pooling (ASPP) To Generate A Pooled Set Of 3D Features
904
Upsample The Pooled Set Of 3D Features To Generate A Upsampled Pooled Set Of 3D Features
906
Predict Bounding Boxes Based On The Upsampled Pooled Set Of 3D Features
908
Output The Predicted Bounding Boxes
910

FIG. 9

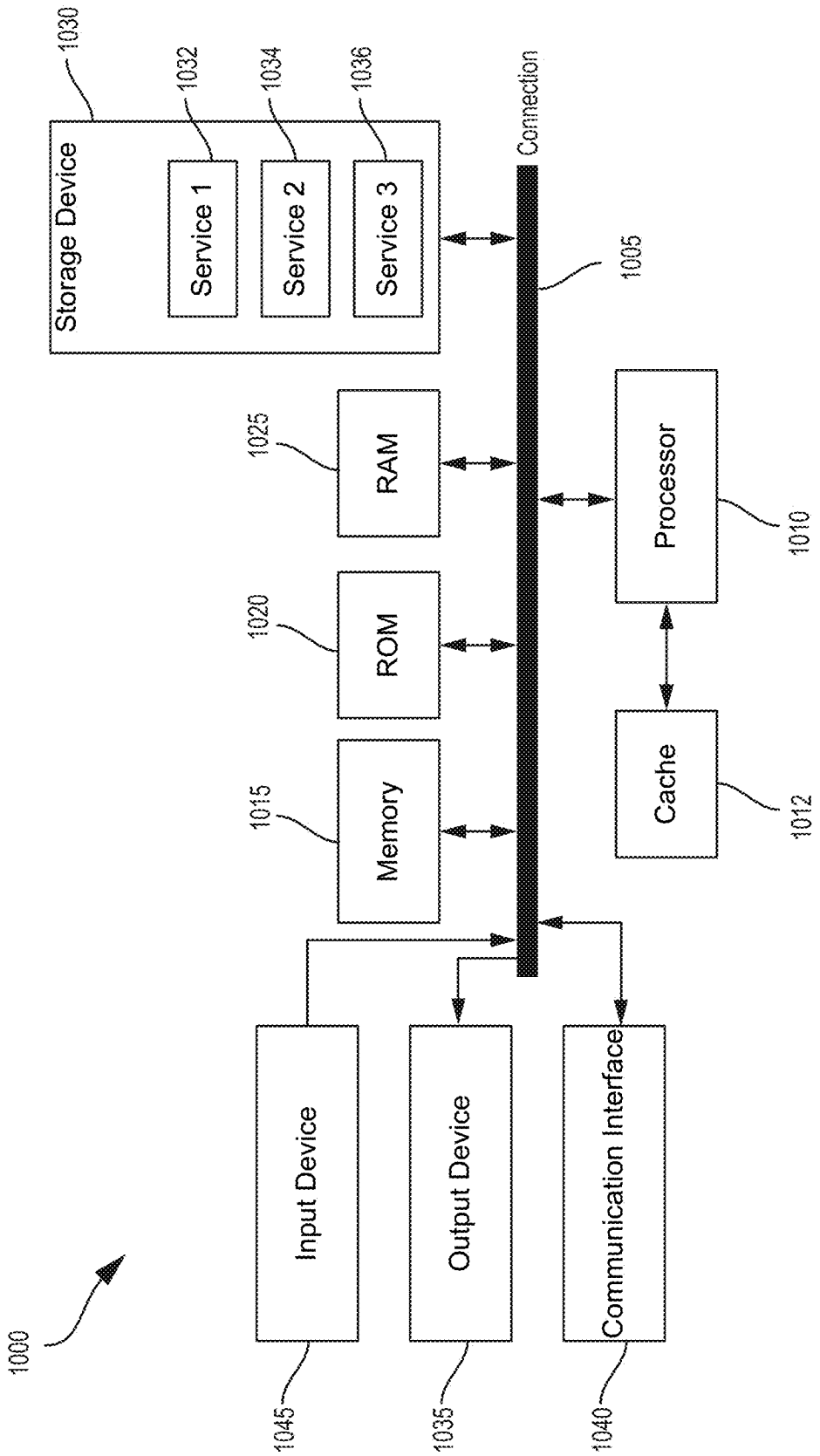

1000
Input Device
1045
Output Device
1035
Communication Interface
1040
Memory
1015
ROM
1020
RAM
1025
Cache
1012
Processor
1010
Connection
1005
Storage Device
1030
Service 1
1032
Service 2
1034
Service 3
1036

FIG. 10

SELF-CALIBRATED PYRAMID NETWORK FOR PILLAR-BASED DETECTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/554,765, filed Feb. 16, 2024, which is hereby incorporated by reference, in its entirety and for all purposes.

FIELD

[0002] The present disclosure generally relates to resource management for an advanced driver assistance system (ADAS). For example, aspects of the present disclosure are related to systems and techniques for a resources manager for an ADAS perception system.

BACKGROUND

[0003] Many devices or systems (e.g., autonomous vehicles, such as autonomous and semi-autonomous vehicles, drones or unmanned aerial vehicles (UAVs), mobile robots, mobile devices such as mobile phones, extended reality (XR) devices, and other suitable devices or systems) include multiple sensors to gather information about an environment. Such devices or systems may also include processing systems to process the sensor information for various purposes, such as route planning, navigation, collision avoidance, etc.

[0004] One example of a processing system is a perception system for devices. Perception systems may receiving data, such as from sensor of a device, and process the data to determine information (e.g., perceiving) about an environment around the device. In some cases, perception system may include object detection, such as 3-dimensional (3D) object detection. Generally, 3D object detection may be computer vision task for identifying and localizing objects in a 3D space. Techniques to improve 3D object detection may thus be useful to improve a device's ability to perceive the surrounding environment.

SUMMARY

[0005] The following presents a simplified summary relating to one or more aspects disclosed herein. Thus, the following summary should not be considered an extensive overview relating to all contemplated aspects, nor should the following summary be considered to identify key or critical elements relating to all contemplated aspects or to delineate the scope associated with any particular aspect. Accordingly, the following summary presents certain concepts relating to one or more aspects relating to the mechanisms disclosed herein in a simplified form to precede the detailed description presented below.

[0006] In one illustrative example, an apparatus for object detection is provided. The apparatus includes at least one memory and at least one processor (e.g., configured in circuitry) coupled to the at least one memory. The at least one processor is configured to: receive a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; downsample the set of 3D features; pool the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; upsample the pooled set of 3D features to generate a upsampled pooled set of 3D features; predict bounding boxes based on the upsampled pooled set of 3D features; and output the predicted bounding boxes.

[0007] As another example, a method for object detection is provided. The method includes: receiving a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; downsampling the set of 3D features; pooling the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; upsampling the pooled set of 3D features to generate a upsampled pooled set of 3D features; predicting bounding boxes based on the upsampled pooled set of 3D features; and outputting the predicted bounding boxes.

[0008] In another example, a non-transitory computer-readable medium is provided. The non-transitory computer-readable medium includes instructions stored thereon, and the instructions, when executed by at least one processor, cause the at least one processor to: receive a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; downsample the set of 3D features; pool the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; upsample the pooled set of 3D features to generate a upsampled pooled set of 3D features; predict bounding boxes based on the upsampled pooled set of 3D features; and output the predicted bounding boxes.

[0009] As another example, an apparatus for object detection is provided. The apparatus includes means for receiving a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; means for downsampling the set of 3D features; means for pooling the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; means for upsampling the pooled set of 3D features to generate a upsampled pooled set of 3D features; means for predicting bounding boxes based on the upsampled pooled set of 3D features; and means for outputting the predicted bounding boxes.

[0010] In some aspects, the apparatus is, is part of, and/or includes a vehicle or a computing device or component of a vehicle (e.g., an autonomous vehicle), a camera, a mobile device (e.g., a mobile telephone or so-called "smart phone" or other mobile device), a wearable device, an extended reality device (e.g., a virtual reality (VR) device, an augmented reality (AR) device, or a mixed reality (MR) device), a personal computer, a laptop computer, a server computer, or other device. In some aspects, the apparatus(es) includes at least one camera for capturing one or more images or video frames. For example, the apparatus(es) can include a camera (e.g., an RGB camera) or multiple cameras for capturing one or more images and/or one or more videos including video frames. In some aspects, the apparatus further includes a display for displaying one or more images, notifications, and/or other displayable data. In some aspects, the apparatuses described above can include one or more sensors (e.g., one or more inertial measurement units (IMUs)), such as one or more gyrometers, one or more accelerometers, any combination thereof, and/or other sensor for obtaining information about the environment, such as a lidar, radar, etc. In some aspects, the at least one processor includes a neural processing unit (NPU), a neural signal processor (NSP), a central processing unit (CPU), a graphics processing unit (GPU), any combination thereof, and/or other processing device or component.

[0011] This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this patent, any or all drawings, and each claim.

[0012] The foregoing, together with other features and embodiments, will become more apparent upon referring to the following specification, claims, and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Illustrative embodiments of the present application are described in detail below with reference to the following figures:

[0014] FIGS. **1**A and **1**B are block diagrams illustrating a vehicle suitable for implementing various techniques described herein, in accordance with aspects of the present disclosure;

[0015] FIG. **1**C is a block diagram illustrating components of a vehicle suitable for implementing various techniques described herein, in accordance with aspects of the present disclosure;

[0016] FIG. **1**D illustrates an example implementation of a system-on-a-chip (SOC), in accordance with some examples;

[0017] FIG. **2**A is a component block diagram illustrating components of an example vehicle management system, in accordance with aspects of the present disclosure;

[0018] FIG. **2**B is a component block diagram illustrating components of another example vehicle management system, in accordance with aspects of the present disclosure;

[0019] FIG. **3** illustrates 3D object detection, in accordance with aspects of the present disclosure;

[0020] FIG. **4** is a block diagram illustrating a self-calibrated pyramid network for a pillar-based 3D object detector, in accordance with aspects of the present disclosure;

[0021] FIG. **5** illustrates a stack of self-calibrated convolution (SC-conv) blocks, in accordance with aspects of the present disclosure;

[0022] FIG. **6** is a block diagram illustrating an SC-pyramid block, in accordance with aspects of the present disclosure;

[0023] FIG. **7** is a block diagram illustrating operations of an ASPP block, in accordance with aspects of the present disclosure;

[0024] FIG. **8** illustrates a stack of SC-pyramid blocks, in accordance with aspects of the present disclosure;

[0025] FIG. **9** is a flow diagram illustrating a process for managing computing resources, in accordance with aspects of the present disclosure;

[0026] FIG. **10** illustrates an example computing device architecture of an example computing device which can implement techniques described herein.

DETAILED DESCRIPTION

[0027] Certain aspects of this disclosure are provided below. Some of these aspects may be applied independently and some of them may be applied in combination as would be apparent to those of skill in the art. In the following description, for the purposes of explanation, specific details are set forth in order to provide a thorough understanding of aspects of the application. However, it will be apparent that various aspects may be practiced without these specific details. The figures and description are not intended to be restrictive.

[0028] The ensuing description provides example aspects only, and is not intended to limit the scope, applicability, or configuration of the disclosure. Rather, the ensuing description of the example aspects will provide those skilled in the art with an enabling description for implementing an example aspect. It should be understood that various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the application as set forth in the appended claims.

[0029] Many devices or systems (e.g., vehicles, extended reality (XR) systems such as augmented reality (AR), virtual reality (VR), and/or mixed reality (MR) systems, robotic systems, etc.) utilize sensors to obtain information about an environment around the devices or systems. For example, an autonomous (e.g., semi-autonomous and/or fully autonomous) vehicle can use sensors to obtain information about an environment around the vehicle to help the vehicle navigate the environment. In another example, an extended reality (XR) system (e.g., an augmented reality (AR), virtual reality (VR), and/or mixed reality (MR) system) system can use sensors to obtain information in an environment of the XR system. A processing system of such a device or system (e.g., a vehicle such as an ego vehicle, an XR system, a robotic system, etc.) may be used to process the information for one or more operations, such as localization, route planning, navigation, collision avoidance, among others. For example, in some cases, the sensor data may be obtained from the one or more sensor (e.g., one or more images captured from one or more cameras, depth information captured or determined by one or more radar and/or lidar sensors, etc.), transformed, and analyzed to detect objects by one or more perception systems.

[0030] As a part of perceiving the environment, a device may perform three-dimensional (3D) object detection. Based on sensor data, objects may be detected and localized, such as by using a bounding box. In some cases, a 3D point cloud, such as one generated using lidar/radar data, may be divided into 2D pillars (e.g., where a pillar may be based on a dimension, such as distance) and object detection performed based on these 2D pillars to increase computational efficiency. However, these pillar-based techniques may sacrifice accuracy as compared to voxel-based techniques as existing pillar-based techniques may potentially not perform well with objects at multiple scales. In some cases, it may be useful to incorporate a self-calibrated pyramid network with a pillar based network to perform 3D object detection.

[0031] Systems and techniques are described that provide a self-calibrated pyramid network for pillar-based detection. In some cases, a self-calibrated pyramid network (SCPyramid net) may be added to pillar-based detection to enlarge a receptive field at multiple scales using a pyramid network and perform channel-wise and spatial wise attention to capture elements that may otherwise be missed. In some cases, an atrous spatial pyramid pooling (ASPP) block may be used as a part of a squeeze-and-excitation block in a SC-pyramid block (e.g., SCPyramid net) to provide the pyramid network and perform channel-wise and spatial wise attention.

[0032] Various aspects of the application will be described with respect to the figures.

[0033] The systems and techniques described herein may be implemented by any type of system or device. One illustrative example of a system that can be used to implement the systems and techniques described herein is a vehicle (e.g., an autonomous or semi-autonomous vehicle) or a system or component (e.g., an ADAS or other system or component) of the vehicle. FIGS. **1**A and **1**B are diagrams illustrating an example vehicle **100** that may implement the systems and techniques described herein. With reference to FIGS. **1**A and **1**B, a vehicle **100** may include a control unit **140** and a plurality of sensors **102-138**, including satellite geopositioning system receivers (e.g., sensors) **108**, occupancy sensors **112**, **116**, **118**, **126**, **128**, tire pressure sensors **114**, **120**, cameras **122**, **136**, microphones **124**, **134**, impact sensors **130**, radar **132**, and LIDAR **138**. The plurality of sensors **102-138**, disposed in or on the vehicle, may be used for various purposes, such as autonomous and semi-autonomous navigation and control, crash avoidance, position determination, etc., as well to provide sensor data regarding objects and people in or on the vehicle **100**. The sensors **102-138** may include one or more of a wide variety of sensors capable of detecting a variety of information useful for navigation and collision avoidance. Each of the sensors **102-138** may be in wired or wireless communication with a control unit **140**, as well as with each other. In particular, the sensors may include one or more cameras **122**, **136** or other optical sensors or photo optic sensors. The sensors may further include other types of object detection and ranging sensors, such as radar **132**, LIDAR **138**, IR sensors, and ultrasonic sensors. The sensors may further include tire pressure sensors **114**, **120**, humidity sensors, temperature sensors, satellite geopositioning sensors **108**, accelerometers, vibration sensors, gyroscopes, gravimeters, impact sensors **130**, force meters, stress meters, strain sensors, fluid sensors, chemical sensors, gas content analyzers, pH sensors, radiation sensors, Geiger counters, neutron detectors, biological material sensors, microphones **124**, **134**, occupancy sensors **112**, **116**, **118**, **126**, **128**, proximity sensors, and other sensors.

[0034] The vehicle control unit **140** may be configured with processor-executable instructions to perform various aspects using information received from various sensors, particularly the cameras **122**, **136**, radar **132**, and LIDAR **138**. In some aspects, the control unit **140** may supplement the processing of camera images using distance and relative position information (e.g., relative bearing angle) that may be obtained from radar **132** and/or LIDAR **138** sensors. The control unit **140** may further be configured to control steering, breaking and speed of the vehicle **100** when operating in an autonomous or semi-autonomous mode using information regarding other vehicles determined using various aspects.

[0035] FIG. **1**C is a component block diagram illustrating a system **150** of components and support systems suitable for implementing various aspects. With reference to FIGS. **1**A, **1**B, and **1**C, a vehicle **100** may include a control unit **140**, which may include various circuits and devices used to control the operation of the vehicle **100**. In the example illustrated in FIG. **1**C, the control unit **140** includes a processor **164**, memory **166**, an input module **168**, an output module **170** and a radio module **172**. The control unit **140** may be coupled to and configured to control drive control components **154**, navigation components **156**, and one or more sensors **158** of the vehicle **100**.

[0036] The control unit **140** may include a processor **164** that may be configured with processor-executable instructions to control maneuvering, navigation, and/or other operations of the vehicle **100**, including operations of various aspects. The processor **164** may be coupled to the memory **166**. The control unit **140** may include the input module **168**, the output module **170**, and the radio module **172**.

[0037] The radio module **172** may be configured for wireless communication. The radio module **172** may exchange signals **182** (e.g., command signals for controlling maneuvering, signals from navigation facilities, etc.) with a network node **180**, and may provide the signals **182** to the processor **164** and/or the navigation components **156**. In some aspects, the radio module **172** may enable the vehicle **100** to communicate with a wireless communication device **190** through a wireless communication link **92**. The wireless communication link **92** may be a bidirectional or unidirectional communication link and may use one or more communication protocols.

[0038] The input module **168** may receive sensor data from one or more vehicle sensors **158** as well as electronic signals from other components, including the drive control components **154** and the navigation components **156**. The output module **170** may be used to communicate with or activate various components of the vehicle **100**, including the drive control components **154**, the navigation components **156**, and the sensor(s) **158**.

[0039] The control unit **140** may be coupled to the drive control components **154** to control physical elements of the vehicle **100** related to maneuvering and navigation of the vehicle, such as the engine, motors, throttles, steering elements, other control elements, braking or deceleration elements, and the like. The drive control components **154** may also include components that control other devices of the vehicle, including environmental controls (e.g., air conditioning and heating), external and/or interior lighting, interior and/or exterior informational displays (which may include a display screen or other devices to display information), safety devices (e.g., haptic devices, audible alarms, etc.), and other similar devices.

[0040] The control unit **140** may be coupled to the navigation components **156** and may receive data from the navigation components **156**. The control unit **140** may be configured to use such data to determine the present position and orientation of the vehicle **100**, as well as an appropriate course toward a destination. In various aspects, the navigation components **156** may include or be coupled to a global navigation satellite system (GNSS) receiver system (e.g., one or more Global Positioning System (GPS) receivers) enabling the vehicle **100** to determine its current position using GNSS signals. Alternatively, or in addition, the navigation components **156** may include radio navigation receivers for receiving navigation beacons or other signals from radio nodes, such as Wi-Fi access points, cellular network sites, radio station, remote computing devices, other vehicles, etc. Through control of the drive control components **154**, the processor **164** may control the vehicle **100** to navigate and maneuver. The processor **164** and/or the navigation components **156** may be configured to communicate with a server **184** on a network **186** (e.g., the Internet) using wireless signals **182** exchanged over a cellular data network via network node **180** to receive commands to control

maneuvering, receive data useful in navigation, provide real-time position reports, and assess other data.

[0041] The control unit **140** may be coupled to one or more sensors **158**. The sensor(s) **158** may include the sensors **102-138** as described and may be configured to provide a variety of data to the processor **164** and/or the navigation components **156**. For example, the control unit **140** may aggregate and/or process data from the sensors **158** to produce information the navigation components **156** may use for localization. As a more specific example, the control unit **140** may process images from multiple camera sensors to generate a single semantically segmented image for the navigation components **156**. As another example, the control unit **140** may generate a fused point clouds from LIDAR and radar data for the navigation components **156**.

[0042] While the control unit **140** is described as including separate components, in some aspects some or all of the components (e.g., the processor **164**, the memory **166**, the input module **168**, the output module **170**, and the radio module **172**) may be integrated in a single device or module, such as a system-on-chip (SOC) processing device. Such an SOC processing device may be configured for use in vehicles and be configured, such as with processor-executable instructions executing in the processor **164**, to perform operations of various aspects when installed into a vehicle.

[0043] FIG. **1**D illustrates an example implementation of a system-on-a-chip (SOC) **105**, which may include a central processing unit (CPU) **110** or a multi-core CPU, configured to perform one or more of the functions described herein. In some cases, the SOC **105** may be based on an ARM instruction set. In some cases, CPU **110** may be similar to processor **164**. Parameters or variables (e.g., neural signals and synaptic weights), system parameters associated with a computational device (e.g., neural network with weights), delays, frequency bin information, task information, among other information may be stored in a memory block associated with a neural processing unit (NPU) **125**, in a memory block associated with a CPU **110**, in a memory block associated with a graphics processing unit (GPU) **115**, in a memory block associated with a digital signal processor (DSP) **106**, in a memory block **185**, and/or may be distributed across multiple blocks. Instructions executed at the CPU **110** may be loaded from a program memory associated with the CPU **110** or may be loaded from a memory block **185**.

[0044] The SOC **105** may also include additional processing blocks tailored to specific functions, such as a GPU **115**, a DSP **106**, a connectivity block **135**, which may include fifth generation (5G) connectivity, fourth generation long term evolution (4G LTE) connectivity, Wi-Fi connectivity, USB connectivity, Bluetooth connectivity, and the like, and a multimedia processor **145** that may, for example, detect and recognize gestures. In one implementation, the NPU is implemented in the CPU **110**, DSP **106**, and/or GPU **115**. The SOC **105** may also include a sensor processor **155**, image signal processors (ISPs) **175**, and/or navigation module **195**, which may include a global positioning system. In some cases, the navigation module **195** may be similar to navigation components **156** and sensor processor **155** may accept input from, for example, one or more sensors **158**. In some cases, the connectivity block **135** may be similar to the radio module **172**.

[0045] FIG. **2**A illustrates an example of vehicle applications, subsystems, computational elements, or units within a vehicle management system **200**, which may be utilized within a vehicle, such as vehicle **100** of FIG. **1**A. With reference to FIGS. **1**A-**2**A, in some aspects, the various vehicle applications, computational elements, or units within vehicle management system **200** may be implemented within a system of interconnected computing devices (i.e., subsystems), that communicate data and commands to each other. In other aspects, the vehicle management system **200** may be implemented as a plurality of vehicle applications executing within a single computing device, such as separate threads, processes, algorithms, or computational elements. However, the use of the term vehicle applications in describing various aspects are not intended to imply or require that the corresponding functionality is implemented within a single autonomous (or semi-autonomous) vehicle management system computing device, although that is a potential implementation aspect. Rather the use of the term vehicle applications is intended to encompass subsystems with independent processors, computational elements (e.g., threads, algorithms, subroutines, etc.) running in one or more computing devices, and combinations of subsystems and computational elements.

[0046] In various aspects, the vehicle applications executing in a vehicle management system **200** may include (but is not limited to) a radar perception vehicle application **202**, a camera perception vehicle application **204**, a positioning engine vehicle application **206**, a map fusion and arbitration vehicle application **208**, a route vehicle planning application **210**, sensor fusion and road world model (RWM) management vehicle application **212**, motion planning and control vehicle application **214**, and behavioral planning and prediction vehicle application **216**. The vehicle applications **202-216** are merely examples of some vehicle applications in one example configuration of the vehicle management system **200**. In other configurations consistent with various aspects, other vehicle applications may be included, such as additional vehicle applications for other perception sensors (e.g., LIDAR perception layer, etc.), additional vehicle applications for planning and/or control, additional vehicle applications for modeling, etc., and/or certain of the vehicle applications **202-216** may be excluded from the vehicle management system **200**. Each of the vehicle applications **202-216** may exchange data, computational results and commands.

[0047] The vehicle management system **200** may receive and process data from sensors (e.g., radar, LIDAR, cameras, inertial measurement units (IMU) etc.), navigation systems (e.g., GPS receivers, IMUs, etc.), vehicle networks (e.g., Controller Area Network (CAN) bus), and databases in memory (e.g., digital map data). The vehicle management system **200** may output vehicle control commands or signals to the drive by wire (DBW) system/control unit **220**, which is a system, subsystem or computing device that interfaces directly with vehicle steering, throttle and brake controls. The configuration of the vehicle management system **200** and DBW system/control unit **220** illustrated in FIG. **2**A is merely an example configuration and other configurations of a vehicle management system and other vehicle components may be used in the various aspects. As an example, the configuration of the vehicle management system **200** and DBW system/control unit **220** illustrated in FIG. **2**A may be used in a vehicle configured for autonomous or semi-autonomous operation while a different configuration may be used in a non-autonomous vehicle.

[0048] The radar perception vehicle application **202** may receive data from one or more detection and ranging sensors, such as radar (e.g., **132**) and/or LIDAR (e.g., **138**), and process the data to recognize and determine locations of other vehicles and objects within a vicinity of the vehicle **100**. The radar perception vehicle application **202** may include use of neural network processing and artificial intelligence methods to recognize objects and vehicles, and pass such information on to the sensor fusion and RWM management vehicle application **212**.

[0049] The camera perception vehicle application **204** may receive data from one or more cameras, such as cameras (e.g., **122**, **136**), and process the data to recognize and determine locations of other vehicles and objects within a vicinity of the vehicle **100**. The camera perception vehicle application **204** may include use of neural network processing and artificial intelligence methods to recognize objects and vehicles and pass such information on to the sensor fusion and RWM management vehicle application **212**.

[0050] The positioning engine vehicle application **206** may receive data from various sensors and process the data to determine a position of the vehicle **100**. The various sensors may include, but is not limited to, GPS sensor, an IMU, and/or other sensors connected via a CAN bus. The positioning engine vehicle application **206** may also utilize inputs from one or more cameras, such as cameras (e.g., **122**, **136**) and/or any other available sensor, such as radars, LIDARs, etc.

[0051] The map fusion and arbitration vehicle application **208** may access data within a high-definition (HD) map database and receive output received from the positioning engine vehicle application **206** and process the data to further determine the position of the vehicle **100** within the map, such as location within a lane of traffic, position within a street map, etc., using localization. The HD map database may be stored in a memory (e.g., memory **166**). For example, the map fusion and arbitration vehicle application **208** may convert latitude and longitude information from GPS into locations within a surface map of roads contained in the HD map database. GPS position fixes include errors, so the map fusion and arbitration vehicle application **208** may function to determine a best guess location of the vehicle **100** within a roadway based upon an arbitration between the GPS coordinates and the HD map data. For example, while GPS coordinates may place the vehicle **100** near the middle of a two-lane road in the HD map, the map fusion and arbitration vehicle application **208** may determine from the direction of travel that the vehicle **100** is most likely aligned with the travel lane consistent with the direction of travel. The map fusion and arbitration vehicle application **208** may pass map-based location information to the sensor fusion and RWM management vehicle application **212**.

[0052] The route planning vehicle application **210** may utilize the HD map, as well as inputs from an operator or dispatcher to plan a route to be followed by the vehicle **100** to a particular destination. The route planning vehicle application **210** may pass map-based location information to the sensor fusion and RWM management vehicle application **212**. However, the use of a prior map by other vehicle applications, such as the sensor fusion and RWM management vehicle application **212**, etc., is not required. For example, other stacks may operate and/or control the vehicle based on perceptual data alone without a provided map, constructing lanes, boundaries, and the notion of a local map as perceptual data is received.

[0053] The sensor fusion and RWM management vehicle application **212** may receive data and outputs produced by one or more of the radar perception vehicle application **202**, camera perception vehicle application **204**, map fusion and arbitration vehicle application **208**, and route planning vehicle application **210**, and use some or all of such inputs to estimate or refine the location and state of the vehicle **100** in relation to the road, other vehicles on the road, and other objects within a vicinity of the vehicle **100**. For example, the sensor fusion and RWM management vehicle application **212** may combine imagery data from the camera perception vehicle application **204** with arbitrated map location information from the map fusion and arbitration vehicle application **208** to refine the determined position of the vehicle within a lane of traffic. As another example, the sensor fusion and RWM management vehicle application **212** may combine object recognition and imagery data from the camera perception vehicle application **204** with object detection and ranging data from the radar perception vehicle application **202** to determine and refine the relative position of other vehicles and objects in the vicinity of the vehicle. As another example, the sensor fusion and RWM management vehicle application **212** may receive information from vehicle-to-vehicle (V2V) communications (such as via the CAN bus) regarding other vehicle positions and directions of travel and combine that information with information from the radar perception vehicle application **202** and the camera perception vehicle application **204** to refine the locations and motions of other vehicles. The sensor fusion and RWM management vehicle application **212** may output refined location and state information of the vehicle **100**, as well as refined location and state information of other vehicles and objects in the vicinity of the vehicle, to the motion planning and control vehicle application **214** and/or the behavior planning and prediction vehicle application **216**.

[0054] As a further example, the sensor fusion and RWM management vehicle application **212** may use dynamic traffic control instructions directing the vehicle **100** to change speed, lane, direction of travel, or other navigational element(s), and combine that information with other received information to determine refined location and state information. The sensor fusion and RWM management vehicle application **212** may output the refined location and state information of the vehicle **100**, as well as refined location and state information of other vehicles and objects in the vicinity of the vehicle **100**, to the motion planning and control vehicle application **214**, the behavior planning and prediction vehicle application **216** and/or devices remote from the vehicle **100**, such as a data server, other vehicles, etc., via wireless communications, such as through C-V2X connections, other wireless connections, etc.

[0055] As a still further example, the sensor fusion and RWM management vehicle application **212** may monitor perception data from various sensors, such as perception data from a radar perception vehicle application **202**, camera perception vehicle application **204**, other perception vehicle application, etc., and/or data from one or more sensors themselves to analyze conditions in the vehicle sensor data. The sensor fusion and RWM management vehicle application **212** may be configured to detect conditions in the sensor data, such as sensor measurements being at, above, or below

a threshold, certain types of sensor measurements occurring, etc., and may output the sensor data as part of the refined location and state information of the vehicle **100** provided to the behavior planning and prediction vehicle application **216** and/or devices remote from the vehicle **100**, such as a data server, other vehicles, etc., via wireless communications, such as through C-V2X connections, other wireless connections, etc.

[0056] The refined location and state information may include vehicle descriptors associated with the vehicle **100** and the vehicle owner and/or operator, such as: vehicle specifications (e.g., size, weight, color, on board sensor types, etc.); vehicle position, speed, acceleration, direction of travel, attitude, orientation, destination, fuel/power level (s), and other state information; vehicle emergency status (e.g., is the vehicle an emergency vehicle or private individual in an emergency); vehicle restrictions (e.g., heavy/wide load, turning restrictions, high occupancy vehicle (HOV) authorization, etc.); capabilities (e.g., all-wheel drive, four-wheel drive, snow tires, chains, connection types supported, on board sensor operating statuses, on board sensor resolution levels, etc.) of the vehicle; equipment problems (e.g., low tire pressure, weak breaks, sensor outages, etc.); owner/operator travel preferences (e.g., preferred lane, roads, routes, and/or destinations, preference to avoid tolls or highways, preference for the fastest route, etc.); permissions to provide sensor data to a data agency server (e.g., **184**); and/or owner/operator identification information.

[0057] The behavioral planning and prediction vehicle application **216** of the autonomous vehicle system **200** may use the refined location and state information of the vehicle **100** and location and state information of other vehicles and objects output from the sensor fusion and RWM management vehicle application **212** to predict future behaviors of other vehicles and/or objects. For example, the behavioral planning and prediction vehicle application **216** may use such information to predict future relative positions of other vehicles in the vicinity of the vehicle based on own vehicle position and velocity and other vehicle positions and velocity. Such predictions may take into account information from the HD map and route planning to anticipate changes in relative vehicle positions as host and other vehicles follow the roadway. The behavioral planning and prediction vehicle application **216** may output other vehicle and object behavior and location predictions to the motion planning and control vehicle application **214**.

[0058] Additionally, the behavior planning and prediction vehicle application **216** may use object behavior in combination with location predictions to plan and generate control signals for controlling the motion of the vehicle **100**. For example, based on route planning information, refined location in the roadway information, and relative locations and motions of other vehicles, the behavior planning and prediction vehicle application **216** may determine that the vehicle **100** needs to change lanes and accelerate, such as to maintain or achieve minimum spacing from other vehicles, and/or prepare for a turn or exit. As a result, the behavior planning and prediction vehicle application **216** may calculate or otherwise determine a steering angle for the wheels and a change to the throttle setting to be commanded to the motion planning and control vehicle application **214** and DBW system/control unit **220** along with such various parameters necessary to effectuate such a lane change and acceleration. One such parameter may be a computed steering wheel command angle.

[0059] The motion planning and control vehicle application **214** may receive data and information outputs from the sensor fusion and RWM management vehicle application **212** and other vehicle and object behavior as well as location predictions from the behavior planning and prediction vehicle application **216**, and use this information to plan and generate control signals for controlling the motion of the vehicle **100** and to verify that such control signals meet safety requirements for the vehicle **100**. For example, based on route planning information, refined location in the roadway information, and relative locations and motions of other vehicles, the motion planning and control vehicle application **214** may verify and pass various control commands or instructions to the DBW system/control unit **220**.

[0060] The DBW system/control unit **220** may receive the commands or instructions from the motion planning and control vehicle application **214** and translate such information into mechanical control signals for controlling wheel angle, brake, and throttle of the vehicle **100**. For example, DBW system/control unit **220** may respond to the computed steering wheel command angle by sending corresponding control signals to the steering wheel controller.

[0061] In various aspects, the vehicle management system **200** may include functionality that performs safety checks or oversight of various commands, planning or other decisions of various vehicle applications that could impact vehicle and occupant safety. Such safety checks or oversight functionality may be implemented within a dedicated vehicle application or distributed among various vehicle applications and included as part of the functionality. In some aspects, a variety of safety parameters may be stored in memory, and the safety checks or oversight functionality may compare a determined value (e.g., relative spacing to a nearby vehicle, distance from the roadway centerline, etc.) to corresponding safety parameter(s) and may issue a warning or command if the safety parameter is or will be violated. For example, a safety or oversight function in the behavior planning and prediction vehicle application **216** (or in a separate vehicle application) may determine the current or future separate distance between another vehicle (as refined by the sensor fusion and RWM management vehicle application **212**) and the vehicle **100** (e.g., based on the world model refined by the sensor fusion and RWM management vehicle application **212**), compare that separation distance to a safe separation distance parameter stored in memory, and issue instructions to the motion planning and control vehicle application **214** to speed up, slow down or turn if the current or predicted separation distance violates the safe separation distance parameter. As another example, safety or oversight functionality in the motion planning and control vehicle application **214** (or a separate vehicle application) may compare a determined or commanded steering wheel command angle to a safe wheel angle limit or parameter and may issue an override command and/or alarm in response to the commanded angle exceeding the safe wheel angle limit.

[0062] Some safety parameters stored in memory may be static (i.e., unchanging over time), such as maximum vehicle speed. Other safety parameters stored in memory may be dynamic in that the parameters are determined or updated continuously or periodically based on vehicle state information and/or environmental conditions. Non-limiting

examples of safety parameters include maximum safe speed, maximum brake pressure, maximum acceleration, and the safe wheel angle limit, all of which may be a function of roadway and weather conditions.

[0063] FIG. **2**B illustrates an example of vehicle applications, subsystems, computational elements, or units within a vehicle management system **250**, which may be utilized within a vehicle **100**. With reference to FIGS. **1**A-**2**B, in some aspects, the vehicle applications **202**, **204**, **206**, **208**, **210**, **212**, and **216** of the vehicle management system **200** may be similar to those described with reference to FIG. **2**A and the vehicle management system **250** may operate similar to the vehicle management system **200**, except that the vehicle management system **250** may pass various data or instructions to a vehicle safety and crash avoidance system **252** rather than the DBW system/control unit **220**. For example, the configuration of the vehicle management system **250** and the vehicle safety and crash avoidance system **252** illustrated in FIG. **2**B may be used in a non-autonomous vehicle.

[0064] In various aspects, the behavioral planning and prediction vehicle application **216** and/or sensor fusion and RWM management vehicle application **212** may output data to the vehicle safety and crash avoidance system **252**. For example, the sensor fusion and RWM management vehicle application **212** may output sensor data as part of refined location and state information of the vehicle **100** provided to the vehicle safety and crash avoidance system **252**. The vehicle safety and crash avoidance system **252** may use the refined location and state information of the vehicle **100** to make safety determinations relative to the vehicle **100** and/or occupants of the vehicle **100**. As another example, the behavioral planning and prediction vehicle application **216** may output behavior models and/or predictions related to the motion of other vehicles to the vehicle safety and crash avoidance system **252**. The vehicle safety and crash avoidance system **252** may use the behavior models and/or predictions related to the motion of other vehicles to make safety determinations relative to the vehicle **100** and/or occupants of the vehicle **100**.

[0065] In various aspects, the vehicle safety and crash avoidance system **252** may include functionality that performs safety checks or oversight of various commands, planning, or other decisions of various vehicle applications, as well as human driver actions, that could impact vehicle and occupant safety. In some aspects, a variety of safety parameters may be stored in memory and the vehicle safety and crash avoidance system **252** may compare a determined value (e.g., relative spacing to a nearby vehicle, distance from the roadway centerline, etc.) to corresponding safety parameter(s), and issue a warning or command if the safety parameter is or will be violated. For example, a vehicle safety and crash avoidance system **252** may determine the current or future separate distance between another vehicle (as refined by the sensor fusion and RWM management vehicle application **212**) and the vehicle (e.g., based on the world model refined by the sensor fusion and RWM management vehicle application **212**), compare that separation distance to a safe separation distance parameter stored in memory, and issue instructions to a driver to speed up, slow down or turn if the current or predicted separation distance violates the safe separation distance parameter. As another example, a vehicle safety and crash avoidance system **252** may compare a human driver's change in steering wheel angle to a safe wheel angle limit or parameter and may issue an override command and/or alarm in response to the steering wheel angle exceeding the safe wheel angle limit.

[0066] Often, systems may use information about the environment to perform certain tasks. For example, systems that usefully (and in some cases autonomously or semi-autonomously) move through the environment, such as autonomous vehicles or semi-autonomous vehicles, may gather information (e.g., perceive) about the environment in which they operate. Similarly, extended reality (XR) systems or devices may gather information about the environment around them to provide virtual content to a user. This virtual content may combine real-world or physical environments and virtual environments (made up of virtual content) to provide users with XR experiences.

[0067] As a part of perceiving the environment, a device may perform 3D object detection. FIG. **3** illustrates 3D object detection. In 3D object detection, a device, such as vehicle **302** may sense the environment using a sensor, such as a lidar sensor, to generate a sensor data, such as a 3D point cloud, to capture information about the environment around the device. Based on the sensor data, objects **304** may be detected and localized, such as by using a one or more ML models to generate a bounding box around the objects **304**. In some cases, the point cloud may be divided into 3D voxels (x,y,z), and the voxels may be encoded by the lidar encoder to perform 3D object detection. However, such techniques may be relatively computationally inefficient as they are performed on 3D data. In some cases, it may be more computationally efficient to divide a 3D point cloud into 2D pillars and perform object detection based on these 2D pillars to increase computational efficiency. However, these pillar-based techniques may sacrifice accuracy as compared to voxel based techniques as existing pillar-based techniques may potentially not perform well with objects at multiple scales (e.g., due to different distances). In some cases, it may be useful to incorporate a self-calibrated pyramid network with a pillar based network to perform 3D object detection.

[0068] FIG. **4** is a block diagram illustrating a self-calibrated pyramid network for a pillar-based 3D object detector **400**, in accordance with aspects of the present disclosure. As shown in FIG. **4**, the 3D object detector **400** may receive a point cloud **402**, such as a lidar point cloud. The point cloud **402** may be processed by a pillar feature network **404**, then by a self-calibrated pyramid network (SCPyramid net **406**), then by a backbone **408**, and a detection head **410** to generate a prediction **412** of locations of detected objects from the point cloud **402**. The pillar feature network **404** may convert the point cloud **402** to a stacked pillar tensor and pillar index tensor and generate features of the pillars. The SCPyramid net **406** may enlarge a receptive field in multiple scales using a pyramid network and perform channel-wise and spatial wise attention to capture elements that may otherwise be missed. The receptive field may refer to a portion of an input set of features (e.g., of the tensor) a portion (e.g., neuron) of the ML network may be able to see for analysis. The backbone **408** may use the pillar features to learn a set of features, and the detection head **410** may use the features learned by the backbone **408** to predict bounding boxes for the prediction **412**.

[0069] Points in the point cloud **402** may be represented by with coordinates x, y, z and reflectance r. In some cases, to convert the point cloud **402**, the pillar feature network **404**

may discretize the point cloud **402** into an evenly spaced grid **420** in an x-y plane (e.g., width/height) create a set of pillars. Pillars (e.g., pillar **422**) of the set of pillars may be mostly empty due to sparsity of the point cloud, and the non-empty pillars may have few points in them. Points may be augmented based on a value c, which may stand for a distance to an arithmetic mean of all points in the pillar and a value p, which may represent an offset from a center of the pillar, resulting in 9 dimensions for each point. Points in each grid cell (e.g., corresponding to a pillar) may be represented by a single pillar (e.g., pillar **422**). Points in a grid cell may be converted into a feature **424**. As an example, 100 points with 9-dimensional information may be converted into a 1×64 dimensional feature **424**. In some cases, the conversion of the information into a feature **424** may be performed by a ML model such as a deep neural network. For example, the ML model may be based on PointNet and each point may be passed to a linear layer followed by a batch normalization layer and ReLU layer to generate a tensor. The pillar-wise features may then be projected into the W×H BEV grids to obtain a 3D pseudo-image **426** (e.g., 3D bird's eye view (BEV) features of the lidar point cloud). In some cases, the pseudo-image **426** may have a grid along with W/H axis and each pillar may include C number of values, thus the pseudo image may have dimensions of C×W×H.

[0070] The pseudo-image **426** may then be input to the SCPyramid net **406**. The SCPyramid net **406** may be used to recognize objects at different scales as a single image may contain objects with different scales (as certain objects may be further than others). In some cases, SCPyramid net **406** may be scale-invariant in that an object's scale change is offset by shifting its level in the pyramid. In SCPyramid net **406**, the features $F_1, F_2, \ldots, F_N$ from all pyramids $P_1, P_2, \ldots, P_N$ may be concatenated into a single feature Y, where $Y=\text{concat}(F_1, F_2, \ldots, F_N)$, and where $F_n=P_n(X)$, and X comprises the input into the pyramid (e.g., from an average pooling layer, such as average pooling layer **604** of FIG. **6**). An attention mechanism may be included in SCPyramid net **406** as the attention mechanism may allow the model to focus on the most relevant parts of the input. For example, lidar sensors may be highly sensitive and easily affected by noise. The attention mechanism may help neglect (e.g., giving less attention weight) to the noise data for non-object areas. The SCPyramid net **406** may be discussed in more detail below.

[0071] Output of the SCPyramid net **406** may be input to the backbone **408**. In some cases, the backbone **408** may include one or more CNNs operating on 2D data. In some cases, the backbone **408** may include two subnetworks. The first subnetwork may produce features at increasingly small spatial resolution and a second subnetwork may performs upsampling and concatenation of the top-down features to generate output features. The output features may be input to the detection head **410**. The detection head **410** may be a single shot detector (SSD) detector head setup to perform 3D object detection trained to match priorboxes (e.g., detected objects) to ground truth images using 2D intersection over union (IoU).

[0072] FIG. **5** is a block diagram **500** illustrating stacks of self-calibrated convolution (SC-conv) blocks. In some cases, pillar-based detectors may include stacked SC-cony blocks **502** following the pillar feature network (e.g., pillar feature network **404**), before the backbone (e.g., backbone **408**), and/or integrated into the backbone. In some cases, SC-cony blocks **502** may contribute to incorporating richer information and generating more discriminative representations. However, while SC-cony blocks **502** may act to enlarge a receptive field, the SC-cony blocks **502** may have difficulties with multi-scale objects. In some cases, it may be useful to enhance an SC-cony block to better handle objects at different scales. For example, it may be useful to replace the SC-cony block with an SC-pyramid block.

[0073] FIG. **6** is a block diagram illustrating an SC-pyramid block **600**, in accordance with aspects of the present disclosure. In some cases, SC-pyramid block **600**, like an SC-cony block, may provide a long-range spatial dependency through an SE (Squeeze-and-Excitation) block **602**. Traditionally, an SE block may include an average pooling (AvgPooling) layer **604**, followed by a 2D convolution layer, and then an upsampling layer **606** acting on spatially pooled features (e.g., obtained by convolving, via convolution layer **608**, the input **610** BEV features of the pseudo image) help to enlarge the receptive field. In some cases, the average pooling layer **604** may downsample a feature map by determining an average value for a portion of feature map and then downsampling (e.g., pooling) the feature map using the average value for that portion of the feature map.

[0074] The SC-pyramid block **600** may also apply spatial attention and channel attention (e.g., by multiplying the sigmoid **616** output and a tensor from the convolutional layer **618**) to highly rely on important elements. For example, the sigmoid **616** may be applied to tensors from convolution layer **618** to determine which tensors are more relevant and which tensors are less relevant. In some cases, the sigmoid **616** may be used to generate the attention weight as its ranges is from **0** to **1**. A smaller weight may then be assigned to less relevant areas. After spatial attention and channel attention are applied, the results may be further encoded (e.g., via concatenation layer **624** and convolutional layers **612**, **614**, and **626**) and output **628** along with the input **610**.

[0075] In some cases, the SE block **602** of the SC-pyramid block **600** may be enhanced by replacing the convolution layer of a traditional SE block with an atrous spatial pyramid pooling (ASPP) block **622**, as shown in SE block **602**. In some cases, the ASPP block **622** acts to enlarge the receptive field at different rates with a pyramid structure to help capture different object scales.

[0076] FIG. **7** is a block diagram illustrating operations of an ASPP block **700**, in accordance with aspects of the present disclosure. In some cases, the ASPP block **700** may be substantially similar to ASPP block **622** of FIG. **6**. As shown in FIG. **7**, output from an average pooling block, such as average pooling layer **604** of FIG. **6**, may be passed to an input layer **702** of the ASPP block **700**. The ASPP block **700** may enlarge the receptive field at different rates using a pyramid structure **704** by performing different operations on the input using multiple paths through the pyramid structure **704**. For example, a top **706** path through the pyramid structure **704** may perform a 1×1 convolution on the input feature and the bottom path **708** may perform a 1×1 convolution on the globally pooled feature. Other paths through the pyramid structure **704** may perform a 3×3 convolution with different dilation rates (e.g., **6** in the second path **710**, **12** in the third path **712**, and **18** in the fourth path **714**) to generate different sets of convolved 3D features. Different dilation rates may expand the convolutional kernel by insert-

ing holes between consecutive elements to expand the features at different rates. The different rates of expansion may make the different paths sensitive to different object scales. The output (e.g., sets of convolved 3D features) of the different paths through the pyramid structure **704** may then be concatenated to generate a concatenated set of convolved 3D features **716**. The concatenated sets of convolved 3D features **716** may be convolved **718** (e.g., encoded) for output. In some cases, the SC-pyramid block, such as SC-pyramid block **600** of FIG. **6**, may be more computational expensive as compared to a single SC-conv block. However, the SC-pyramid block **600** may encode the input data more effectively as compared to the SC-cony block. In some cases, fewer SC-pyramid blocks **600** may be used as compared to the number of SC-cony block used to achieve an equivalent accuracy. For example, 4 SC-pyramid blocks may be equivalent to 6 SC-cony blocks.

[0077] FIG. **8** illustrates a stack **800** of SC-pyramid blocks, in accordance with aspects of the present disclosure. In some cases, the stack **800** of SC-pyramid blocks may be used as a part of a pillar-based detector following the pillar feature network (e.g., pillar feature network **404** of FIG. **4**), before the backbone (e.g., backbone **408** of FIG. **4**), and/or integrated into the backbone. For example, the stack **800** of SC-pyramid blocks may form the SCPyramid net **406** of FIG. **4**. As shown in FIG. **8**, a fewer number of SC-pyramid blocks **802**, here two SC-pyramid blocks **802**, may replace a larger number of SC-cony blocks, as shown in FIG. **5**. In some cases, using a same number of SC-pyramid blocks **802** as SC-cony blocks in a traditional pillar-based detector may yield increased accuracy. Additionally, as SC-pyramid blocks **802** may operate at multiple scales, a concatenation across multiple scales of blocks (e.g., SC-cony blocks, as shown in FIG. **5**) may be omitted. Omitting this concatenation step may lead to a decreased channel dimension as the multiple scales (e.g., channels) are not concatenated, which helps reduce computation costs for following layers.

[0078] FIG. **9** is a flow diagram illustrating a process **900** for managing computing resources, in accordance with aspects of the present disclosure. The process **900** may be performed by a computing device (or apparatus) (e.g., vehicle **100** of FIG. **1**A-**1**C, wireless communication device **190** of FIG. **1**C, computing system **1000** of FIG. **10**, etc.) or a component (e.g., a chipset, codec, etc., such as control unit **140** of FIGS. **1**A-**1**C, SOC **105** of FIG. **1**D, processor **1010** of FIG. **10**, etc.) of the computing device. The computing device may be a mobile device (e.g., a vehicle, mobile phone, etc.), a network-connected wearable such as a watch, an extended reality (XR) device such as a virtual reality (VR) device or augmented reality (AR) device, a vehicle or component or system of a vehicle, or other type of computing device. The operations of the process **900** may be implemented as software components that are executed and run on one or more processors.

[0079] At block **902**, the computing device (or component thereof) may downsample the set of 3D features (e.g., by an average pooling layer). In some cases, the computing device (or component thereof) may downsample the set of 3D features by determining an average value for a portion of the set of 3D features; and downsampling the set of 3D features based on the average value for the portion of the set of 3D features. In some examples, the set of 3D features are generated based on an obtained 3D point cloud. In some cases, the set of 3D features may be a pseudo-image. In some examples, the set of 3D features may be a set of 3D BEV images. In some cases, the 3D point cloud comprises a lidar point cloud. In some examples, to generate the set of 3D features (e.g., by pillar feature net **404** of FIG. **4**), the at least one processor is configured to: discretize the 3D point cloud into an evenly spaced grid; represent points in a cell of the grid as a pillar; and generate a feature based on the pillar.

[0080] At block **904**, the computing device (or component thereof) may pool the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) (e.g., by an ASPP layer) to generate a pooled set of 3D features. In some cases, the computing device (or component thereof) may pool the downsampled set of 3D features based on ASPP by convolving the set of 3D features using a pyramid structure (e.g., pyramid structure **704**). In some examples, the pyramid structure convolves the set of 3D features at multiple dilation rates (e.g., none, 6, 12, 18, as illustrated in FIG. **7**) to generate sets of convolved 3D features. In some cases, to pool the downsampled set of 3D features based on ASPP, the at least one processor is configured to: concatenate the sets of convolved 3D features to generate a concatenated set of convolved 3D features (e.g., concatenated **716** of FIG. **7**); and convolve (e.g., convolved **718** of FIG. **7**) the concatenated set of convolved 3D features. In some cases, the computing device or component thereof may apply channel attention and spatial attention to the set of 3D features (e.g., via sigmoid **616** and convolutional layer **618**).

[0081] At block **906**, the computing device (or component thereof) may upsample the pooled set of 3D features (e.g., by a bilinear upsampling layer) to generate a upsampled pooled set of 3D features.

[0082] At block **908**, the computing device (or component thereof) may predict bounding boxes (e.g., by a detection head) based on the upsampled pooled set of 3D features.

[0083] At block **910**, the computing device (or component thereof) may output the predicted bounding boxes.

[0084] In some examples, the processes described herein (e.g., process **900** and/or other process described herein) may be performed by the vehicle **100** of FIG. **1**A.

[0085] In some examples, the techniques or processes described herein may be performed by a computing device, an apparatus, and/or any other computing device. In some cases, the computing device or apparatus may include a processor, microprocessor, microcomputer, or other component of a device that is configured to carry out the steps of processes described herein. In some examples, the computing device or apparatus may include a camera configured to capture video data (e.g., a video sequence) including video frames. For example, the computing device may include a camera device, which may or may not include a video codec. As another example, the computing device may include a mobile device with a camera (e.g., a camera device such as a digital camera, an IP camera or the like, a mobile phone or tablet including a camera, or other type of device with a camera). In some cases, the computing device may include a display for displaying images. In some examples, a camera or other capture device that captures the video data is separate from the computing device, in which case the computing device receives the captured video data. The computing device may further include a network interface, transceiver, and/or transmitter configured to communicate the video data. The network interface, transceiver, and/or

transmitter may be configured to communicate Internet Protocol (IP) based data or other network data.

[0086] The processes described herein can be implemented in hardware, computer instructions, or a combination thereof. In the context of computer instructions, the operations represent computer-executable instructions stored on one or more computer-readable storage media that, when executed by one or more processors, perform the recited operations. Generally, computer-executable instructions include routines, programs, objects, components, data structures, and the like that perform particular functions or implement particular data types. The order in which the operations are described is not intended to be construed as a limitation, and any number of the described operations can be combined in any order and/or in parallel to implement the processes.

[0087] In some cases, the devices or apparatuses configured to perform the operations of the process **900** and/or other processes described herein may include a processor, microprocessor, micro-computer, or other component of a device that is configured to carry out the steps of the process **900** and/or other process. In some examples, such devices or apparatuses may include one or more sensors configured to capture image data and/or other sensor measurements. In some examples, such computing device or apparatus may include one or more sensors and/or a camera configured to capture one or more images or videos. In some cases, such device or apparatus may include a display for displaying images. In some examples, the one or more sensors and/or camera are separate from the device or apparatus, in which case the device or apparatus receives the sensed data. Such device or apparatus may further include a network interface configured to communicate data.

[0088] The components of the device or apparatus configured to carry out one or more operations of the process **900** and/or other processes described herein can be implemented in circuitry. For example, the components can include and/or can be implemented using electronic circuits or other electronic hardware, which can include one or more programmable electronic circuits (e.g., microprocessors, graphics processing units (GPUs), digital signal processors (DSPs), central processing units (CPUs), and/or other suitable electronic circuits), and/or can include and/or be implemented using computer software, firmware, or any combination thereof, to perform the various operations described herein. The computing device may further include a display (as an example of the output device or in addition to the output device), a network interface configured to communicate and/or receive the data, any combination thereof, and/or other component(s). The network interface may be configured to communicate and/or receive Internet Protocol (IP) based data or other type of data.

[0089] The process **900** is illustrated as a logical flow diagram, the operations of which represent sequences of operations that can be implemented in hardware, computer instructions, or a combination thereof. In the context of computer instructions, the operations represent computer-executable instructions stored on one or more computer-readable storage media that, when executed by one or more processors, perform the recited operations. Generally, computer-executable instructions include routines, programs, objects, components, data structures, and the like that perform particular functions or implement particular data types. The order in which the operations are described is not intended to be construed as a limitation, and any number of the described operations can be combined in any order and/or in parallel to implement the processes.

[0090] Additionally, the processes described herein (e.g., the process **900** and/or other processes) may be performed under the control of one or more computer systems configured with executable instructions and may be implemented as code (e.g., executable instructions, one or more computer programs, or one or more applications) executing collectively on one or more processors, by hardware, or combinations thereof. As noted above, the code may be stored on a computer-readable or machine-readable storage medium, for example, in the form of a computer program including a plurality of instructions executable by one or more processors. The computer-readable or machine-readable storage medium may be non-transitory.

[0091] FIG. **10** is a diagram illustrating an example of a system for implementing certain aspects of the present technology. In particular, FIG. **10** illustrates an example of computing system **1000**, which may be for example any computing device making up internal computing system, a remote computing system, a camera, or any component thereof in which the components of the system are in communication with each other using connection **1005**. Connection **1005** may be a physical connection using a bus, or a direct connection into processor **1010**, such as in a chipset architecture. Connection **1005** may also be a virtual connection, networked connection, or logical connection.

[0092] In some embodiments, computing system **1000** is a distributed system in which the functions described in this disclosure may be distributed within a datacenter, multiple data centers, a peer network, etc. In some embodiments, one or more of the described system components represents many such components each performing some or all of the function for which the component is described. In some embodiments, the components may be physical or virtual devices.

[0093] Example system **1000** includes at least one processing unit (CPU or processor) **1010** and connection **1005** that communicatively couples various system components including system memory **1015**, such as read-only memory (ROM) **1020** and random access memory (RAM) **1025** to processor **1010**. Computing system **1000** may include a cache **1012** of high-speed memory connected directly with, in close proximity to, or integrated as part of processor **1010**.

[0094] Processor **1010** may include any general purpose processor and a hardware service or software service, such as services **1032**, **1034**, and **1036** stored in storage device **1030**, configured to control processor **1010** as well as a special-purpose processor where software instructions are incorporated into the actual processor design. Processor **1010** may essentially be a completely self-contained computing system, containing multiple cores or processors, a bus, memory controller, cache, etc. A multi-core processor may be symmetric or asymmetric.

[0095] To enable user interaction, computing system **1000** includes an input device **1045**, which may represent any number of input mechanisms, such as a microphone for speech, a touch-sensitive screen for gesture or graphical input, keyboard, mouse, motion input, speech, etc. Computing system **1000** may also include output device **1035**, which may be one or more of a number of output mechanisms. In

some instances, multimodal systems may enable a user to provide multiple types of input/output to communicate with computing system **1000**.

[0096] Computing system **1000** may include communications interface **1040**, which may generally govern and manage the user input and system output. The communication interface may perform or facilitate receipt and/or transmission wired or wireless communications using wired and/or wireless transceivers, including those making use of an audio jack/plug, a microphone jack/plug, a universal serial bus (USB) port/plug, an Apple™ Lightning™ port/plug, an Ethernet port/plug, a fiber optic port/plug, a proprietary wired port/plug, 3G, 4G, 5G and/or other cellular data network wireless signal transfer, a Bluetooth™ wireless signal transfer, a Bluetooth™ low energy (BLE) wireless signal transfer, an IBEACON™ wireless signal transfer, a radio-frequency identification (RFID) wireless signal transfer, near-field communications (NFC) wireless signal transfer, dedicated short range communication (DSRC) wireless signal transfer, 802.11 Wi-Fi wireless signal transfer, wireless local area network (WLAN) signal transfer, Visible Light Communication (VLC), Worldwide Interoperability for Microwave Access (WiMAX), Infrared (IR) communication wireless signal transfer, Public Switched Telephone Network (PSTN) signal transfer, Integrated Services Digital Network (ISDN) signal transfer, ad-hoc network signal transfer, radio wave signal transfer, microwave signal transfer, infrared signal transfer, visible light signal transfer, ultraviolet light signal transfer, wireless signal transfer along the electromagnetic spectrum, or some combination thereof. The communications interface **1040** may also include one or more Global Navigation Satellite System (GNSS) receivers or transceivers that are used to determine a location of the computing system **1000** based on receipt of one or more signals from one or more satellites associated with one or more GNSS systems. GNSS systems include, but are not limited to, the US-based Global Positioning System (GPS), the Russia-based Global Navigation Satellite System (GLONASS), the China-based BeiDou Navigation Satellite System (BDS), and the Europe-based Galileo GNSS. There is no restriction on operating on any particular hardware arrangement, and therefore the basic features here may easily be substituted for improved hardware or firmware arrangements as they are developed.

[0097] Storage device **1030** may be a non-volatile and/or non-transitory and/or computer-readable memory device and may be a hard disk or other types of computer readable media which may store data that are accessible by a computer, such as magnetic cassettes, flash memory cards, solid state memory devices, digital versatile disks, cartridges, a floppy disk, a flexible disk, a hard disk, magnetic tape, a magnetic strip/stripe, any other magnetic storage medium, flash memory, memristor memory, any other solid-state memory, a compact disc read only memory (CD-ROM) optical disc, a rewritable compact disc (CD) optical disc, digital video disk (DVD) optical disc, a blu-ray disc (BDD) optical disc, a holographic optical disk, another optical medium, a secure digital (SD) card, a micro secure digital (microSD) card, a Memory Stick® card, a smartcard chip, a EMV chip, a subscriber identity module (SIM) card, a mini/micro/nano/pico SIM card, another integrated circuit (IC) chip/card, random access memory (RAM), static RAM (SRAM), dynamic RAM (DRAM), read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), flash EPROM (FLASHEPROM), cache memory (e.g., Level 1 (L1) cache, Level 2 (L2) cache, Level 3 (L3) cache, Level 4 (L4) cache, Level 5 (L5) cache, or other (L#) cache), resistive random-access memory (RRAM/ReRAM), phase change memory (PCM), spin transfer torque RAM (STT-RAM), another memory chip or cartridge, and/or a combination thereof.

[0098] The storage device **1030** may include software services, servers, services, etc., that when the code that defines such software is executed by the processor **1010**, it causes the system to perform a function. In some embodiments, a hardware service that performs a particular function may include the software component stored in a computer-readable medium in connection with the necessary hardware components, such as processor **1010**, connection **1005**, output device **1035**, etc., to carry out the function. The term "computer-readable medium" includes, but is not limited to, portable or non-portable storage devices, optical storage devices, and various other mediums capable of storing, containing, or carrying instruction(s) and/or data. A computer-readable medium may include a non-transitory medium in which data may be stored and that does not include carrier waves and/or transitory electronic signals propagating wirelessly or over wired connections. Examples of a non-transitory medium may include, but are not limited to, a magnetic disk or tape, optical storage media such as compact disk (CD) or digital versatile disk (DVD), flash memory, memory or memory devices. A computer-readable medium may have stored thereon code and/or machine-executable instructions that may represent a procedure, a function, a subprogram, a program, a routine, a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements. A code segment may be coupled to another code segment or a hardware circuit by passing and/or receiving information, data, arguments, parameters, or memory contents. Information, arguments, parameters, data, etc. may be passed, forwarded, or transmitted via any suitable means including memory sharing, message passing, token passing, network transmission, or the like.

[0099] Specific details are provided in the description above to provide a thorough understanding of the embodiments and examples provided herein, but those skilled in the art will recognize that the application is not limited thereto. Thus, while illustrative embodiments of the application have been described in detail herein, it is to be understood that the inventive concepts may be otherwise variously embodied and employed, and that the appended claims are intended to be construed to include such variations, except as limited by the prior art. Various features and aspects of the above-described application may be used individually or jointly. Further, embodiments may be utilized in any number of environments and applications beyond those described herein without departing from the broader scope of the specification. The specification and drawings are, accordingly, to be regarded as illustrative rather than restrictive. For the purposes of illustration, methods were described in a particular order. It should be appreciated that in alternate embodiments, the methods may be performed in a different order than that described.

[0100] For clarity of explanation, in some instances the present technology may be presented as including individual

functional blocks comprising devices, device components, steps or routines in a method embodied in software, or combinations of hardware and software. Additional components may be used other than those shown in the figures and/or described herein. For example, circuits, systems, networks, processes, and other components may be shown as components in block diagram form in order not to obscure the embodiments in unnecessary detail. In other instances, well-known circuits, processes, algorithms, structures, and techniques may be shown without unnecessary detail in order to avoid obscuring the embodiments.

[0101] Further, those of skill in the art will appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the aspects disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure.

[0102] Individual embodiments may be described above as a process or method which is depicted as a flowchart, a flow diagram, a data flow diagram, a structure diagram, or a block diagram. Although a flowchart may describe the operations as a sequential process, many of the operations may be performed in parallel or concurrently. In addition, the order of the operations may be re-arranged. A process is terminated when its operations are completed but could have additional steps not included in a figure. A process may correspond to a method, a function, a procedure, a subroutine, a subprogram, etc. When a process corresponds to a function, its termination may correspond to a return of the function to the calling function or the main function.

[0103] Processes and methods according to the above-described examples may be implemented using computer-executable instructions that are stored or otherwise available from computer-readable media. Such instructions may include, for example, instructions and data which cause or otherwise configure a general purpose computer, special purpose computer, or a processing device to perform a certain function or group of functions. Portions of computer resources used may be accessible over a network. The computer executable instructions may be, for example, binaries, intermediate format instructions such as assembly language, firmware, source code. Examples of computer-readable media that may be used to store instructions, information used, and/or information created during methods according to described examples include magnetic or optical disks, flash memory, USB devices provided with non-volatile memory, networked storage devices, and so on.

[0104] In some embodiments the computer-readable storage devices, mediums, and memories may include a cable or wireless signal containing a bitstream and the like. However, when mentioned, non-transitory computer-readable storage media expressly exclude media such as energy, carrier signals, electromagnetic waves, and signals per se.

[0105] Those of skill in the art will appreciate that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof, in some cases depending in part on the particular application, in part on the desired design, in part on the corresponding technology, etc.

[0106] The various illustrative logical blocks, modules, and circuits described in connection with the aspects disclosed herein may be implemented or performed using hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof, and may take any of a variety of form factors. When implemented in software, firmware, middleware, or microcode, the program code or code segments to perform the necessary tasks (e.g., a computer-program product) may be stored in a computer-readable or machine-readable medium. A processor(s) may perform the necessary tasks. Examples of form factors include laptops, smart phones, mobile phones, tablet devices or other small form factor personal computers, personal digital assistants, rackmount devices, standalone devices, and so on. Functionality described herein also may be embodied in peripherals or add-in cards. Such functionality may also be implemented on a circuit board among different chips or different processes executing in a single device, by way of further example.

[0107] The instructions, media for conveying such instructions, computing resources for executing them, and other structures for supporting such computing resources are example means for providing the functions described in the disclosure.

[0108] The techniques described herein may also be implemented in electronic hardware, computer software, firmware, or any combination thereof. Such techniques may be implemented in any of a variety of devices such as general purposes computers, wireless communication device handsets, or integrated circuit devices having multiple uses including application in wireless communication device handsets and other devices. Any features described as modules or components may be implemented together in an integrated logic device or separately as discrete but interoperable logic devices. If implemented in software, the techniques may be realized at least in part by a computer-readable data storage medium comprising program code including instructions that, when executed, performs one or more of the methods, algorithms, and/or operations described above. The computer-readable data storage medium may form part of a computer program product, which may include packaging materials. The computer-readable medium may comprise memory or data storage media, such as random access memory (RAM) such as synchronous dynamic random access memory (SDRAM), read-only memory (ROM), non-volatile random access memory (NVRAM), electrically erasable programmable read-only memory (EEPROM), FLASH memory, magnetic or optical data storage media, and the like. The techniques additionally, or alternatively, may be realized at least in part by a computer-readable communication medium that carries or communicates program code in the form of instructions or

data structures and that may be accessed, read, and/or executed by a computer, such as propagated signals or waves.

[0109] The program code may be executed by a processor, which may include one or more processors, such as one or more digital signal processors (DSPs), general purpose microprocessors, an application specific integrated circuits (ASICs), field programmable logic arrays (FPGAs), or other equivalent integrated or discrete logic circuitry. Such a processor may be configured to perform any of the techniques described in this disclosure. A general-purpose processor may be a microprocessor; but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. Accordingly, the term "processor," as used herein may refer to any of the foregoing structure, any combination of the foregoing structure, or any other structure or apparatus suitable for implementation of the techniques described herein.

[0110] One of ordinary skill will appreciate that the less than ("<") and greater than (">") symbols or terminology used herein may be replaced with less than or equal to ("≤") and greater than or equal to ("≥") symbols, respectively, without departing from the scope of this description.

[0111] Where components are described as being "configured to" perform certain operations, such configuration may be accomplished, for example, by designing electronic circuits or other hardware to perform the operation, by programming programmable electronic circuits (e.g., microprocessors, or other suitable electronic circuits) to perform the operation, or any combination thereof.

[0112] The phrase "coupled to" or "communicatively coupled to" refers to any component that is physically connected to another component either directly or indirectly, and/or any component that is in communication with another component (e.g., connected to the other component over a wired or wireless connection, and/or other suitable communication interface) either directly or indirectly.

[0113] Claim language or other language reciting "at least one of" a set and/or "one or more" of a set indicates that one member of the set or multiple members of the set (in any combination) satisfy the claim. For example, claim language reciting "at least one of A and B" or "at least one of A or B" means A, B, or A and B. In another example, claim language reciting "at least one of A, B, and C" or "at least one of A, B, or C" means A, B, C, or A and B, or A and C, or B and C, A and B and C, or any duplicate information or data (e.g., A and A, B and B, C and C, A and A and B, and so on), or any other ordering, duplication, or combination of A, B, and C. The language "at least one of" a set and/or "one or more" of a set does not limit the set to the items listed in the set. For example, claim language reciting "at least one of A and B" or "at least one of A or B" may mean A, B, or A and B, and may additionally include items not listed in the set of A and B. The phrases "at least one" and "one or more" are used interchangeably herein.

[0114] Claim language or other language reciting "at least one processor configured to," "at least one processor being configured to," "one or more processors configured to," "one or more processors being configured to," or the like indicates that one processor or multiple processors (in any combination) can perform the associated operation(s). For example, claim language reciting "at least one processor configured to: X, Y, and Z" means a single processor can be used to perform operations X, Y, and Z; or that multiple processors are each tasked with a certain subset of operations X, Y, and Z such that together the multiple processors perform X, Y, and Z; or that a group of multiple processors work together to perform operations X, Y, and Z. In another example, claim language reciting "at least one processor configured to: X, Y, and Z" can mean that any single processor may only perform at least a subset of operations X, Y, and Z.

[0115] Where reference is made to one or more elements performing functions (e.g., steps of a method), one element may perform all functions, or more than one element may collectively perform the functions. When more than one element collectively performs the functions, each function need not be performed by each of those elements (e.g., different functions may be performed by different elements) and/or each function need not be performed in whole by only one element (e.g., different elements may perform different sub-functions of a function). Similarly, where reference is made to one or more elements configured to cause another element (e.g., an apparatus) to perform functions, one element may be configured to cause the other element to perform all functions, or more than one element may collectively be configured to cause the other element to perform the functions.

[0116] Where reference is made to an entity (e.g., any entity or device described herein) performing functions or being configured to perform functions (e.g., steps of a method), the entity may be configured to cause one or more elements (individually or collectively) to perform the functions. The one or more components of the entity may include at least one memory, at least one processor, at least one communication interface, another component configured to perform one or more (or all) of the functions, and/or any combination thereof. Where reference to the entity performing functions, the entity may be configured to cause one component to perform all functions, or to cause more than one component to collectively perform the functions. When the entity is configured to cause more than one component to collectively perform the functions, each function need not be performed by each of those components (e.g., different functions may be performed by different components) and/or each function need not be performed in whole by only one component (e.g., different components may perform different sub-functions of a function).

[0117] Illustrative aspects of the disclosure include:

[0118] Aspect 1. A method for object detection comprising: receiving a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; downsampling the set of 3D features; pooling the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; upsampling the pooled set of 3D features to generate a upsampled pooled set of 3D features; predicting bounding boxes based on the upsampled pooled set of 3D features; and outputting the predicted bounding boxes.

[0119] Aspect 2. The method of Aspect 1, wherein pooling the downsampled set of 3D features based on ASPP comprises convolving the set of 3D features using a pyramid structure.

[0120] Aspect 3. The method of Aspect 2, wherein the pyramid structure convolves the set of 3D features at multiple dilation rates to generate sets of convolved 3D features.

[0121] Aspect 4. The method of Aspect 3, wherein pooling the downsampled set of 3D features based on ASPP further comprises: concatenating the sets of convolved 3D features to generate a concatenated set of convolved 3D features; and convolving the concatenated set of convolved 3D features.

[0122] Aspect 5. The method of any of Aspects 1-4, wherein downsampling the set of 3D features comprises: determining an average value for a portion of the set of 3D features; and downsampling the set of 3D features based on the average value for the portion of the set of 3D features.

[0123] Aspect 6. The method of any of Aspects 1-5, wherein the 3D point cloud comprises a lidar point cloud.

[0124] Aspect 7. The method of any of Aspects 1-6, wherein the set of 3D features are generated by: discretizing the 3D point cloud into an evenly spaced grid; representing points in a cell of the grid as a pillar; and generating a feature based on the pillar.

[0125] Aspect 8. The method of any of Aspects 1-7, further comprising applying channel attention and spatial attention to the set of 3D features.

[0126] Aspect 9. An apparatus for object detection, comprising: at least one memory; and at least one processor coupled to the at least one memory and configured to: receive a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; downsample the set of 3D features; pool the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; upsample the pooled set of 3D features to generate a upsampled pooled set of 3D features; predict bounding boxes based on the upsampled pooled set of 3D features; and output the predicted bounding boxes.

[0127] Aspect 10. The apparatus of Aspect 9, wherein, to pool the downsampled set of 3D features based on ASPP, the at least one processor is configured to convolve the set of 3D features using a pyramid structure.

[0128] Aspect 11. The apparatus of Aspect 10, wherein the pyramid structure convolves the set of 3D features at multiple dilation rates to generate sets of convolved 3D features.

[0129] Aspect 12. The apparatus of Aspect 11, wherein, to pool the downsampled set of 3D features based on ASPP, the at least one processor is configured to: concatenate the sets of convolved 3D features to generate a concatenated set of convolved 3D features; and convolve the concatenated set of convolved 3D features.

[0130] Aspect 13. The apparatus of any of Aspects 9-12, wherein, to downsample the set of 3D features, the at least one processor is configured to: determine an average value for a portion of the set of 3D features; and downsample the set of 3D features based on the average value for the portion of the set of 3D features.

[0131] Aspect 14. The apparatus of any of Aspects 9-13, wherein the 3D point cloud comprises a lidar point cloud.

[0132] Aspect 15. The apparatus of any of Aspects 9-14, wherein, to generate the set of 3D features, the at least one processor is configured to: discretize the 3D point cloud into an evenly spaced grid; represent points in a cell of the grid as a pillar; and generate a feature based on the pillar.

[0133] Aspect 16. The apparatus of any of Aspects 9-15, wherein the at least one processor is further configured to apply channel attention and spatial attention to the set of 3D features.

[0134] Aspect 17. A non-transitory computer-readable medium having stored thereon instructions that, when executed by at least one processor, cause the at least one processor to: receive a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud; downsample the set of 3D features; pool the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features; upsample the pooled set of 3D features to generate a upsampled pooled set of 3D features; predict bounding boxes based on the upsampled pooled set of 3D features; and output the predicted bounding boxes.

[0135] Aspect 18. The non-transitory computer-readable medium of Aspect 17, wherein, to pool the downsampled set of 3D features based on ASPP, the instructions cause the at least one processor to convolve the set of 3D features using a pyramid structure.

[0136] Aspect 19. The non-transitory computer-readable medium of Aspect 18, wherein the pyramid structure convolves the set of 3D features at multiple dilation rates to generate sets of convolved 3D features.

[0137] Aspect 20. The non-transitory computer-readable medium of Aspect 19, wherein, to pool the downsampled set of 3D features based on ASPP, the instructions cause the at least one processor to: concatenate the sets of convolved 3D features to generate a concatenated set of convolved 3D features; and convolve the concatenated set of convolved 3D features.

[0138] Aspect 21. The non-transitory computer-readable medium of any of Aspects 17-20, wherein, to downsample the set of 3D features, the instructions cause the at least one processor to: determine an average value for a portion of the set of 3D features; and downsample the set of 3D features based on the average value for the portion of the set of 3D features.

[0139] Aspect 22. The non-transitory computer-readable medium of any of Aspects 17-21 wherein the 3D point cloud comprises a lidar point cloud.

[0140] Aspect 23. The non-transitory computer-readable medium of any of Aspects 17-22, wherein, to generate the set of 3D features, the instructions cause the at least one processor to: discretize the 3D point cloud into an evenly spaced grid; represent points in a cell of the grid as a pillar; and generate a feature based on the pillar.

[0141] Aspect 24. The non-transitory computer-readable medium of any of Aspects 17-23, wherein the instructions cause the at least one processor to apply channel attention and spatial attention to the set of 3D features.

[0142] Aspect 25: An apparatus for object detection, comprising one or more means for performing operations according to any of Aspects 1 to 8.

What is claimed is:

1. A method for object detection comprising:

downsampling a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud;

pooling the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features;

upsampling the pooled set of 3D features to generate a upsampled pooled set of 3D features;

predicting bounding boxes based on the upsampled pooled set of 3D features; and

outputting the predicted bounding boxes.

2. The method of claim **1**, wherein pooling the downsampled set of 3D features based on ASPP comprises convolving the set of 3D features using a pyramid structure.

3. The method of claim **2**, wherein the pyramid structure convolves the set of 3D features at multiple dilation rates to generate sets of convolved 3D features.

4. The method of claim **3**, wherein pooling the downsampled set of 3D features based on ASPP further comprises:

concatenating the sets of convolved 3D features to generate a concatenated set of convolved 3D features; and

convolving the concatenated set of convolved 3D features.

5. The method of claim **1**, wherein downsampling the set of 3D features comprises:

determining an average value for a portion of the set of 3D features; and

downsampling the set of 3D features based on the average value for the portion of the set of 3D features.

6. The method of claim **1**, wherein the 3D point cloud comprises a lidar point cloud.

7. The method of claim **1**, wherein the set of 3D features are generated by:

discretizing the 3D point cloud into an evenly spaced grid;

representing points in a cell of the grid as a pillar; and

generating a feature based on the pillar.

8. The method of claim **1**, further comprising applying channel attention and spatial attention to the set of 3D features.

9. An apparatus for object detection, comprising:

at least one memory; and

at least one processor coupled to the at least one memory and configured to:

downsample a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud;

pool the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features;

upsample the pooled set of 3D features to generate a upsampled pooled set of 3D features;

predict bounding boxes based on the upsampled pooled set of 3D features; and

output the predicted bounding boxes.

10. The apparatus of claim **9**, wherein, to pool the downsampled set of 3D features based on ASPP, the at least one processor is configured to convolve the set of 3D features using a pyramid structure.

11. The apparatus of claim **10**, wherein the pyramid structure convolves the set of 3D features at multiple dilation rates to generate sets of convolved 3D features.

12. The apparatus of claim **11**, wherein, to pool the downsampled set of 3D features based on ASPP, the at least one processor is configured to:

concatenate the sets of convolved 3D features to generate a concatenated set of convolved 3D features; and

convolve the concatenated set of convolved 3D features.

13. The apparatus of claim **9**, wherein, to downsample the set of 3D features, the at least one processor is configured to:

determine an average value for a portion of the set of 3D features; and

downsample the set of 3D features based on the average value for the portion of the set of 3D features.

14. The apparatus of claim **9**, wherein the 3D point cloud comprises a lidar point cloud.

15. The apparatus of claim **9**, wherein, to generate the set of 3D features, the at least one processor is configured to:

discretize the 3D point cloud into an evenly spaced grid;

represent points in a cell of the grid as a pillar; and

generate a feature based on the pillar.

16. The apparatus of claim **9**, wherein the at least one processor is further configured to apply channel attention and spatial attention to the set of 3D features.

17. A non-transitory computer-readable medium having stored thereon instructions that, when executed by at least one processor, cause the at least one processor to:

downsample a set of 3D features, wherein the set of 3D features are generated based on an obtained 3D point cloud;

pool the downsampled set of 3D features based on Atrous Spatial Pyramid Pooling (ASPP) to generate a pooled set of 3D features;

upsample the pooled set of 3D features to generate a upsampled pooled set of 3D features;

predict bounding boxes based on the upsampled pooled set of 3D features; and

output the predicted bounding boxes.

18. The non-transitory computer-readable medium of claim **17**, wherein, to pool the downsampled set of 3D features based on ASPP, the instructions cause the at least one processor to convolve the set of 3D features using a pyramid structure.

19. The non-transitory computer-readable medium of claim **18**, wherein the pyramid structure convolves the set of 3D features at multiple dilation rates to generate sets of convolved 3D features.

20. The non-transitory computer-readable medium of claim **19**, wherein, to pool the downsampled set of 3D features based on ASPP, the instructions cause the at least one processor to:

concatenate the sets of convolved 3D features to generate a concatenated set of convolved 3D features; and

convolve the concatenated set of convolved 3D features.

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