US 20200410704A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2020/0410704 A1**

(43) **Pub. Date: Dec. 31, 2020**

CHOE et al.

(54) **SENSOR CALIBRATION SYSTEM FOR AUTONOMOUS DRIVING VEHICLES**

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(21) Appl. No.: **16/457,775**

(22) Filed: **Jun. 28, 2019**

Publication Classification

(51) **Int. Cl.**

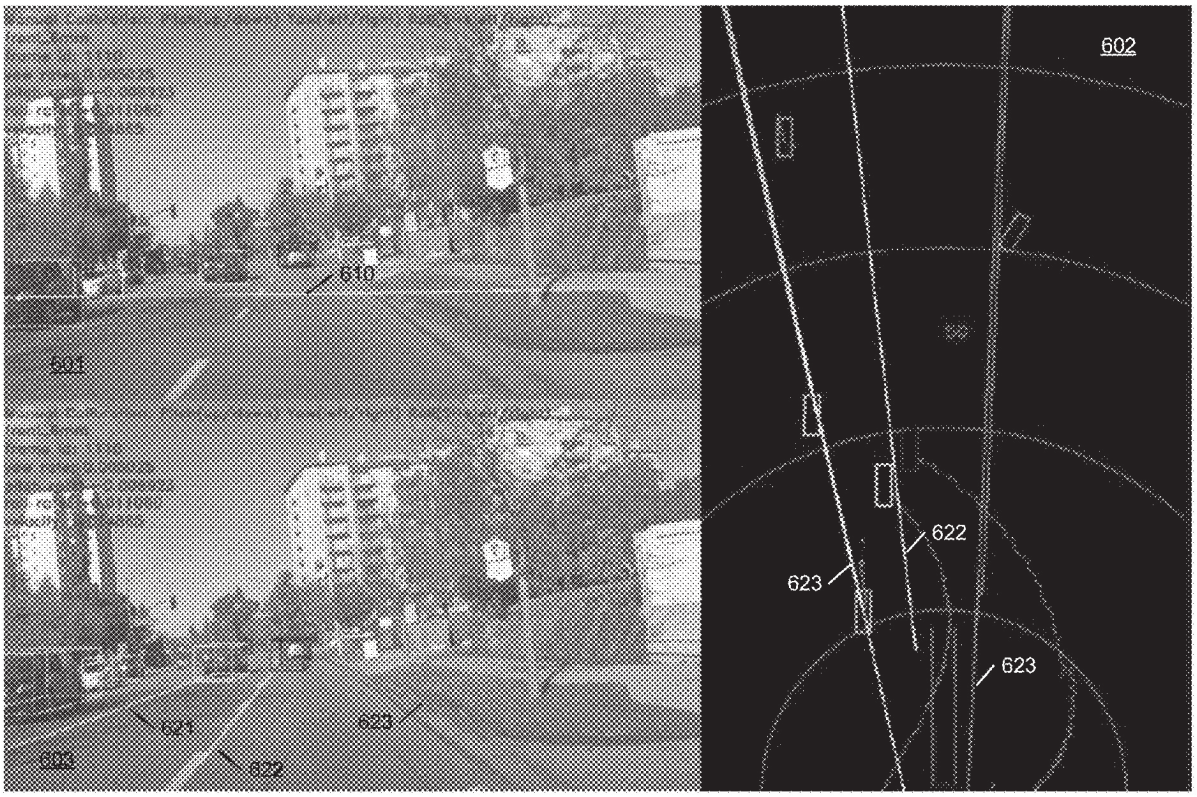
G06T 7/536	(2006.01)
G06K 9/00	(2006.01)
G06T 7/80	(2006.01)
G06T 7/55	(2006.01)
G06T 11/00	(2006.01)
G05D 1/02	(2006.01)

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

CPC ***G06T 7/536*** (2017.01); ***G06K 9/00798*** (2013.01); ***G06T 7/80*** (2017.01); ***G06T 7/55*** (2017.01); ***G06T 11/00*** (2013.01); *G05D 2201/0213* (2013.01); ***G05D 1/0257*** (2013.01); *G06T 2207/30256* (2013.01); *G06T 2207/10004* (2013.01); *G06T 2207/20081* (2013.01); ***G05D 1/0231*** (2013.01)

(57) **ABSTRACT**

In response to a first image captured by a camera of an ADV, a horizon line is determined based on the camera's hardware settings, representing a vanishing point based on an initial or default pitch angle of the camera. One or more lane lines are determined based on the first image via a perception process performed on the first image. In response to a first input signal received from an input device, a position of the horizon line is updated based on the first input signal and a position of at least one of the lane lines is updated based on the updated horizon line. The input signal may represent an incremental adjustment for adjusting the position of the horizon line. A first calibration factor or first correction value is determined for calibrating a pitch angle of the camera based on a difference between the initial horizon line and the updated horizon line.



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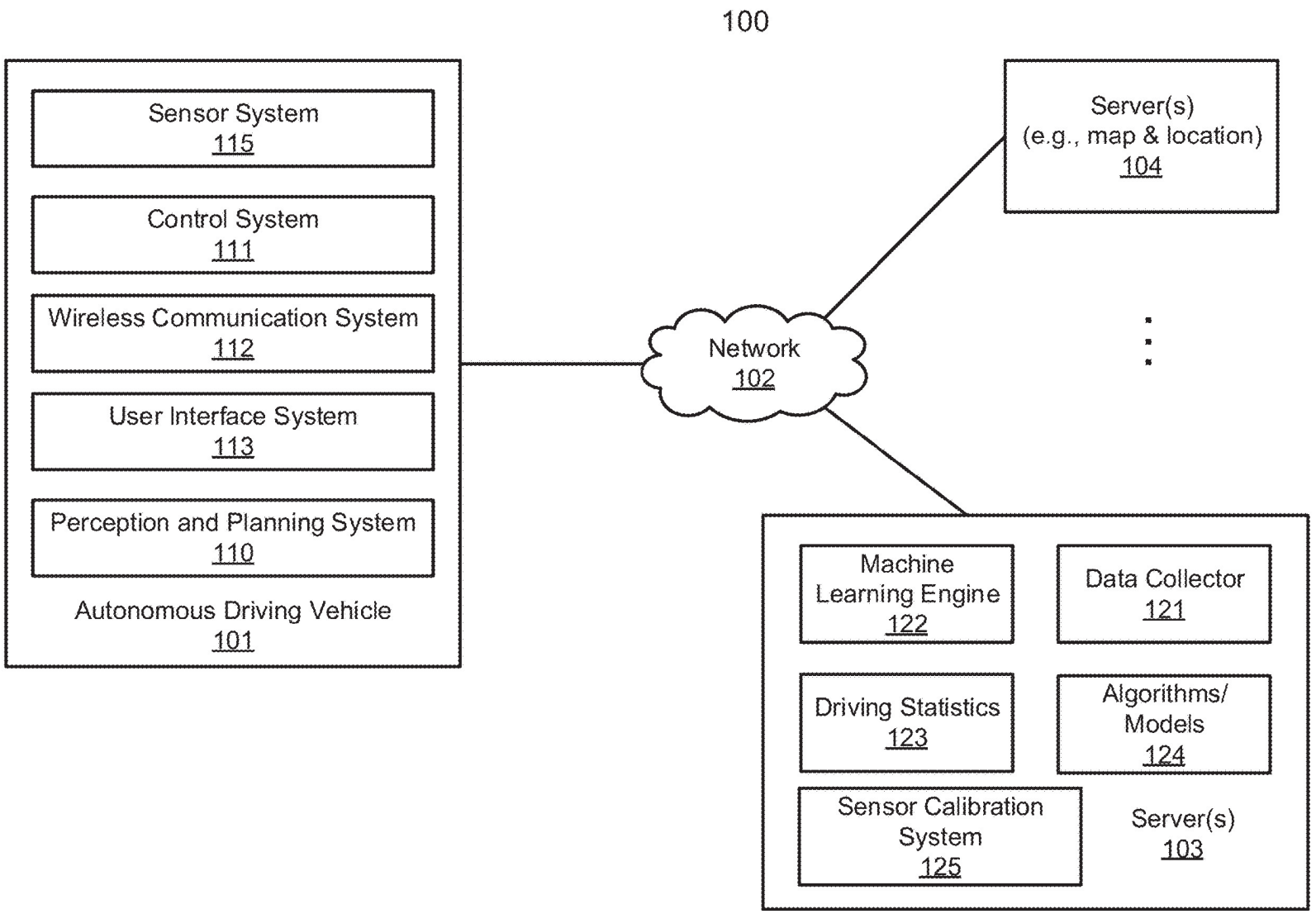

100
Sensor System
115
Control System
111
Wireless Communication System
112
User Interface System
113
Perception and Planning System
110
Autonomous Driving Vehicle
101
Network
102
Server(s)
(e.g., map & location)
104
Machine
Learning Engine
122
Data Collector
121
Driving Statistics
123
Algorithms/
Models
124
Sensor Calibration
System
125
Server(s)
103

FIG. 1

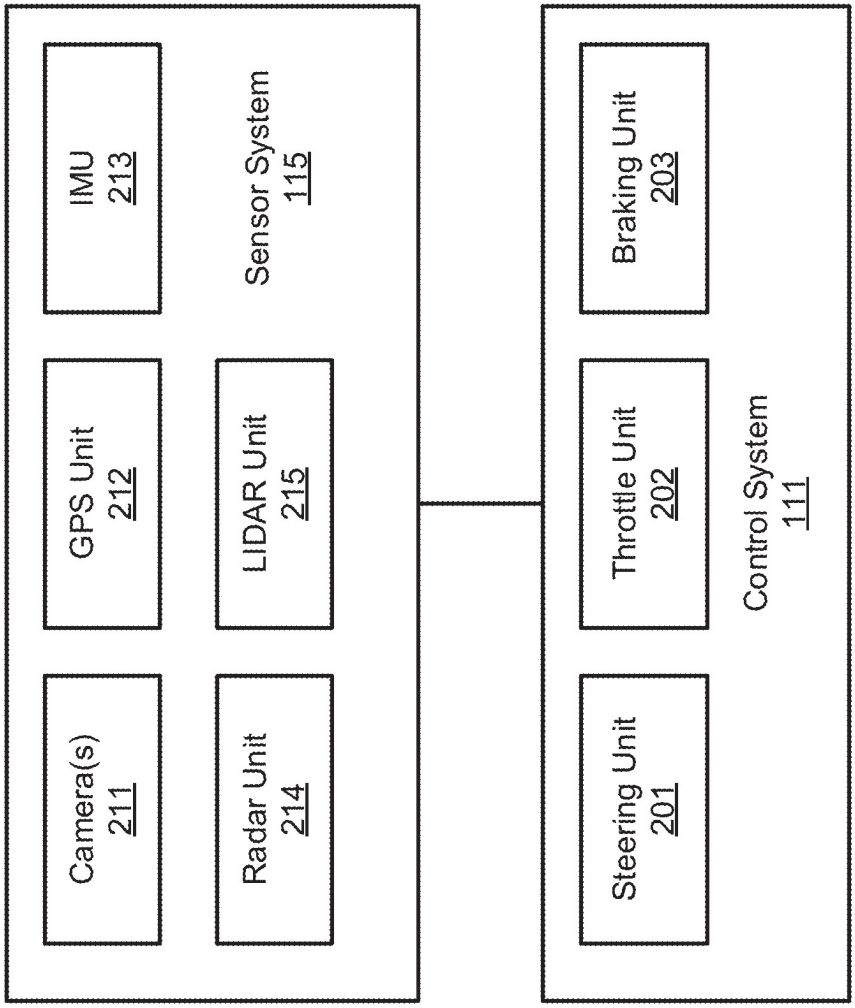

Sensor System
115
Camera(s)
211
GPS Unit
212
IMU
213
Radar Unit
214
LIDAR Unit
215
Control System
111
Steering Unit
201
Throttle Unit
202
Braking Unit
203

FIG. 2

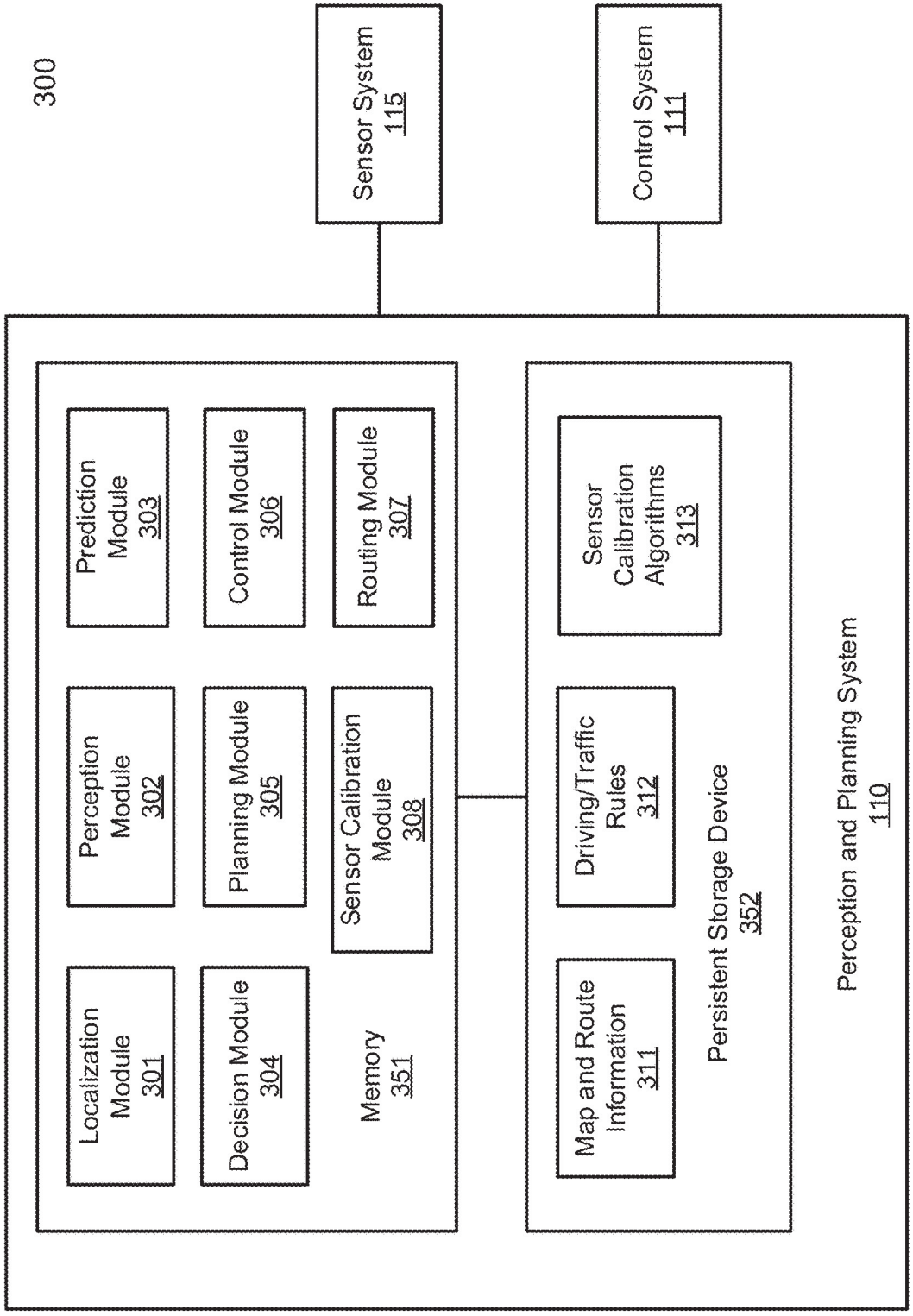

300
Sensor System 115
Control System 111
Perception and Planning System 110
Memory 351
Localization Module 301
Perception Module 302
Prediction Module 303
Decision Module 304
Planning Module 305
Control Module 306
Routing Module 307
Sensor Calibration Module 308
Persistent Storage Device 352
Map and Route Information 311
Driving/Traffic Rules 312
Sensor Calibration Algorithms 313

FIG. 3A

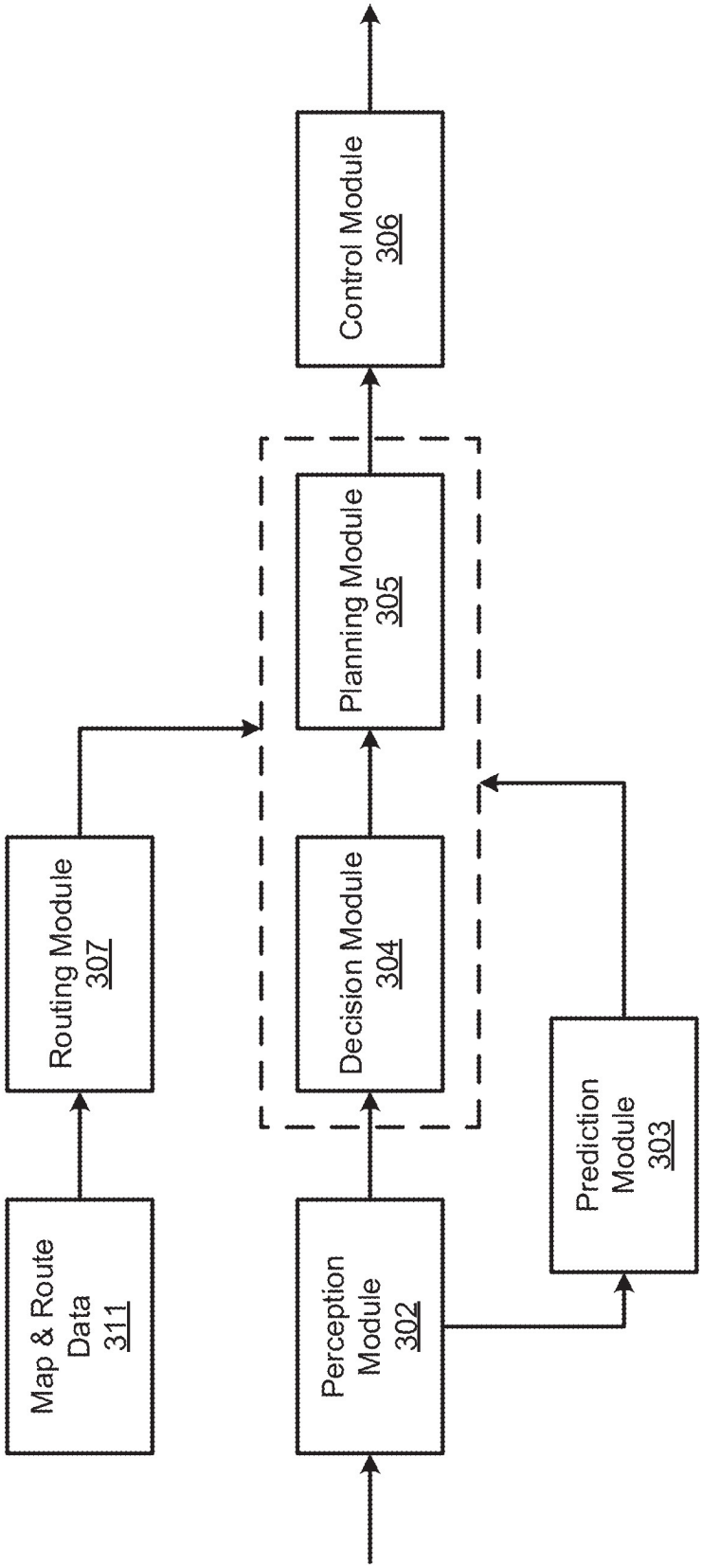

Map & Route Data 311
Routing Module 307
Perception Module 302
Decision Module 304
Prediction Module 303
Planning Module 305
Control Module 306

FIG. 3B

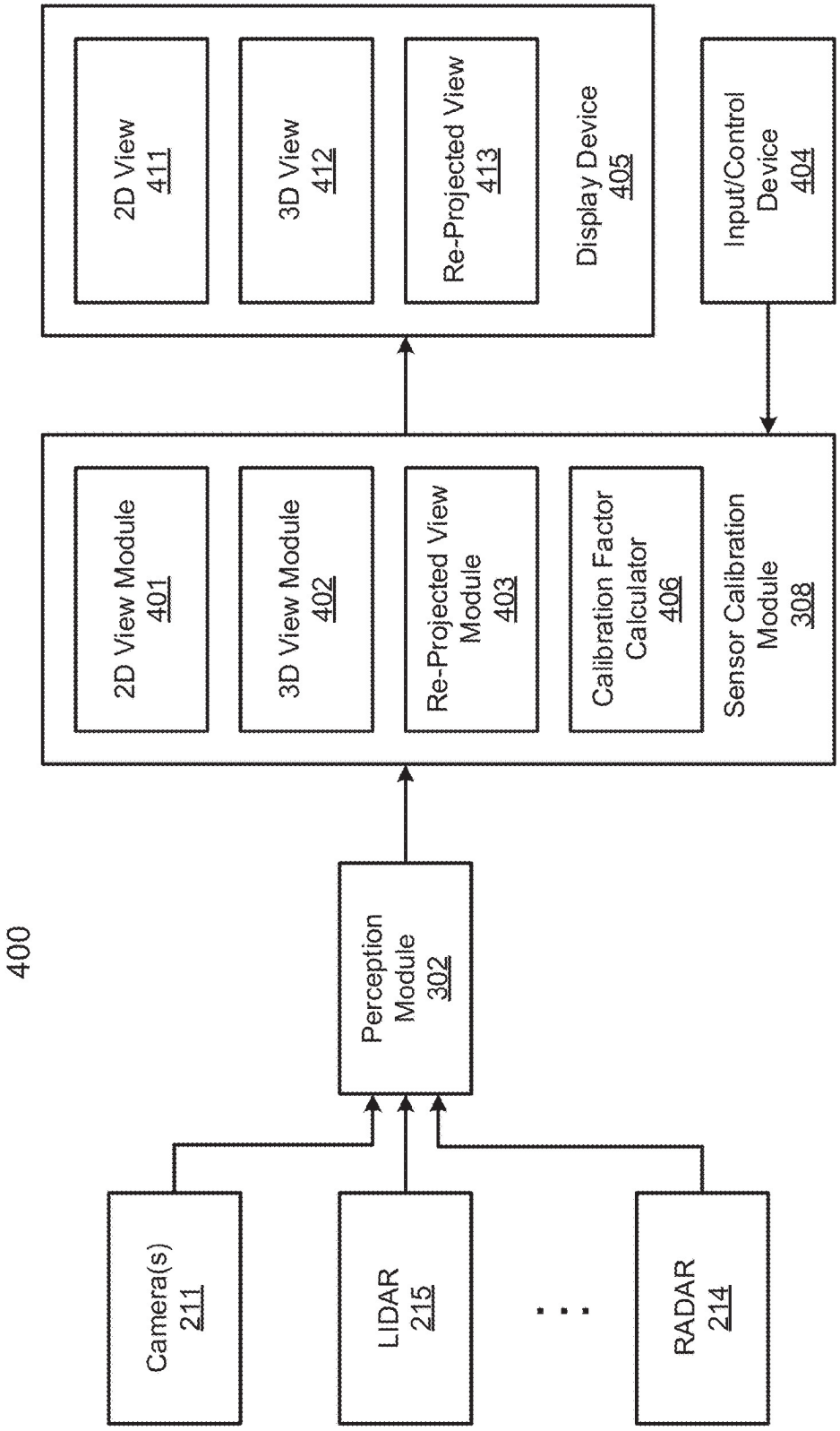

400
Camera(s)
211
LIDAR
215
. . .
RADAR
214
Perception
Module
302
2D View Module
401
3D View Module
402
Re-Projected View
Module
403
Calibration Factor
Calculator
406
Sensor Calibration
Module
308
2D View
411
3D View
412
Re-Projected View
413
Display Device
405
Input/Control
Device
404

FIG. 4

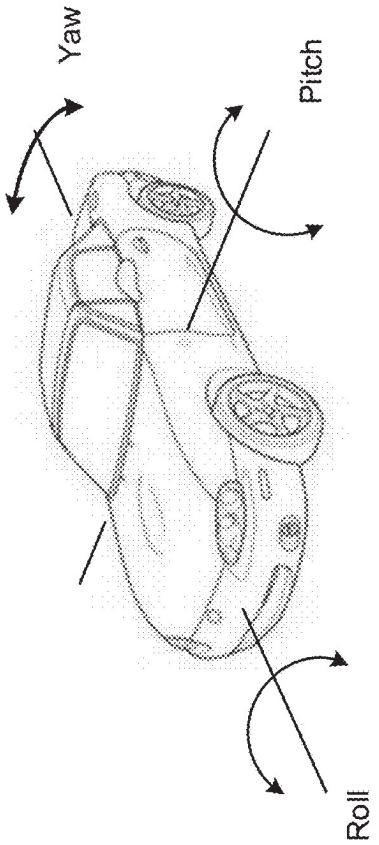


FIG. 5A

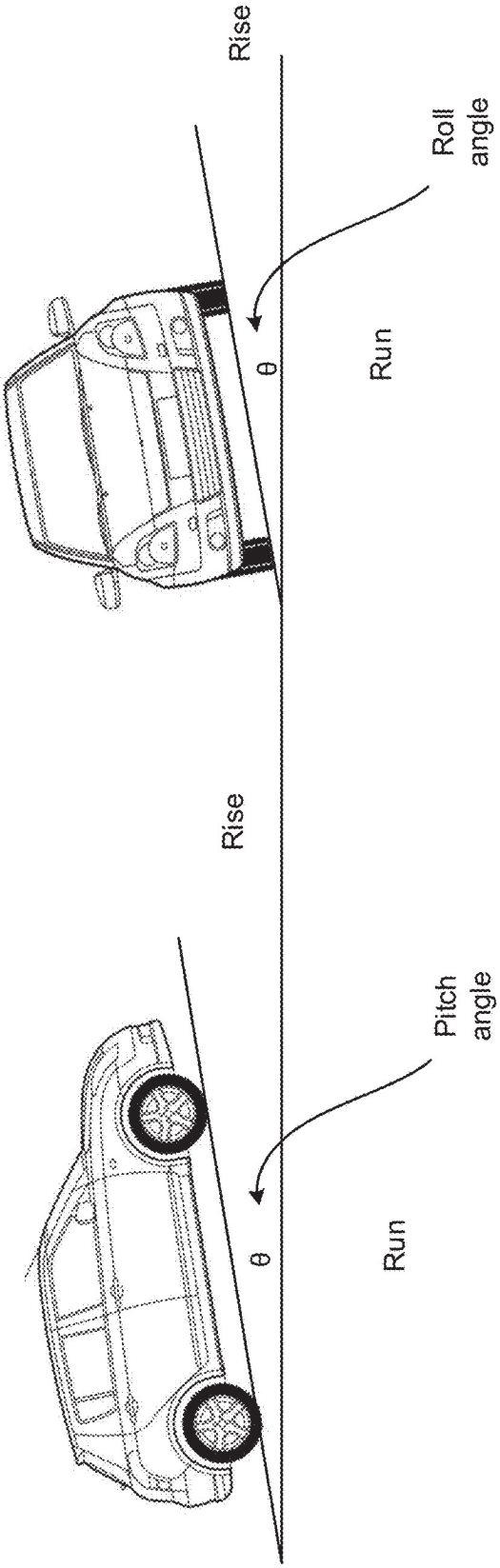


FIG. 5C

FIG. 5B

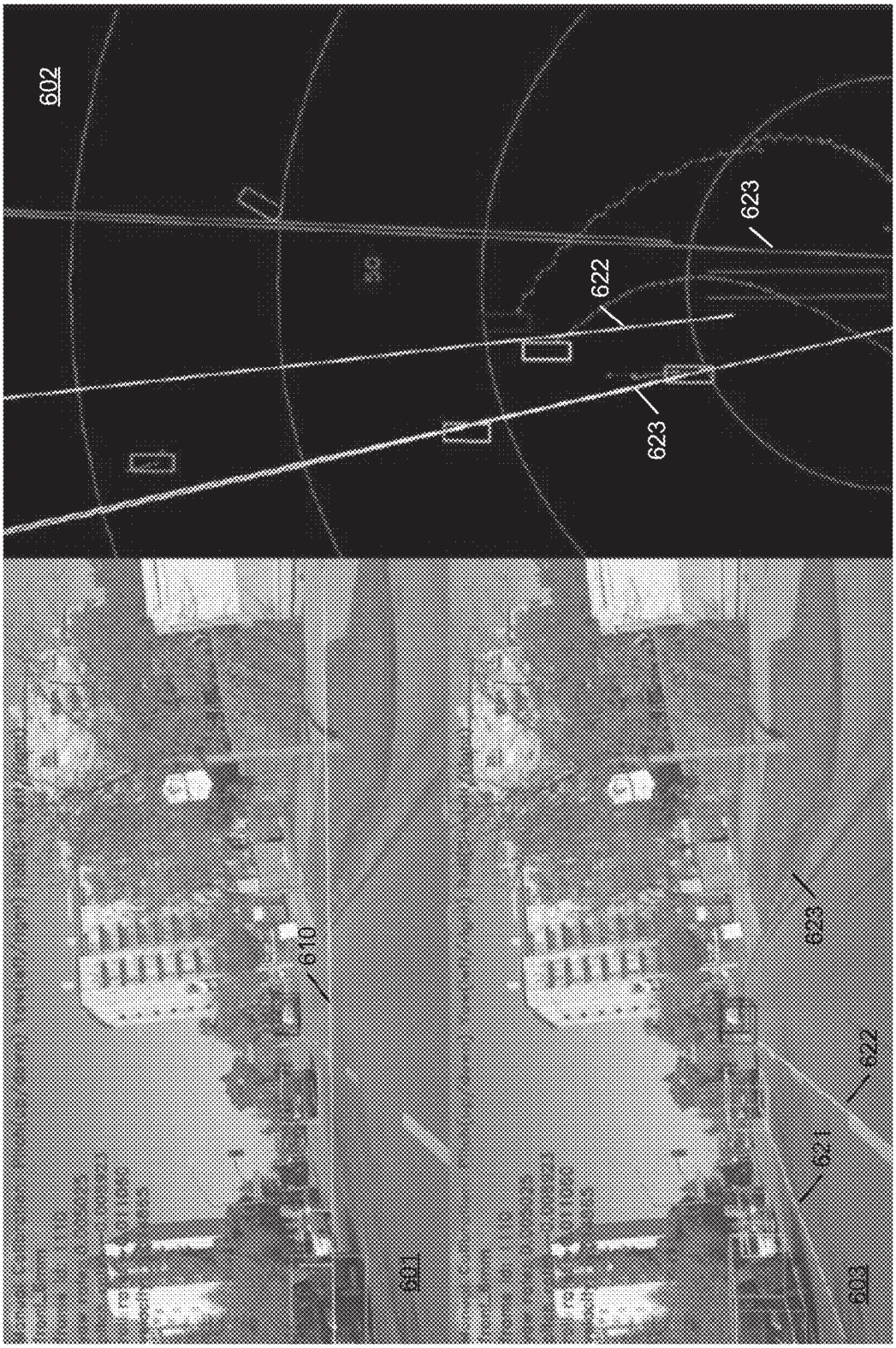


FIG. 6A

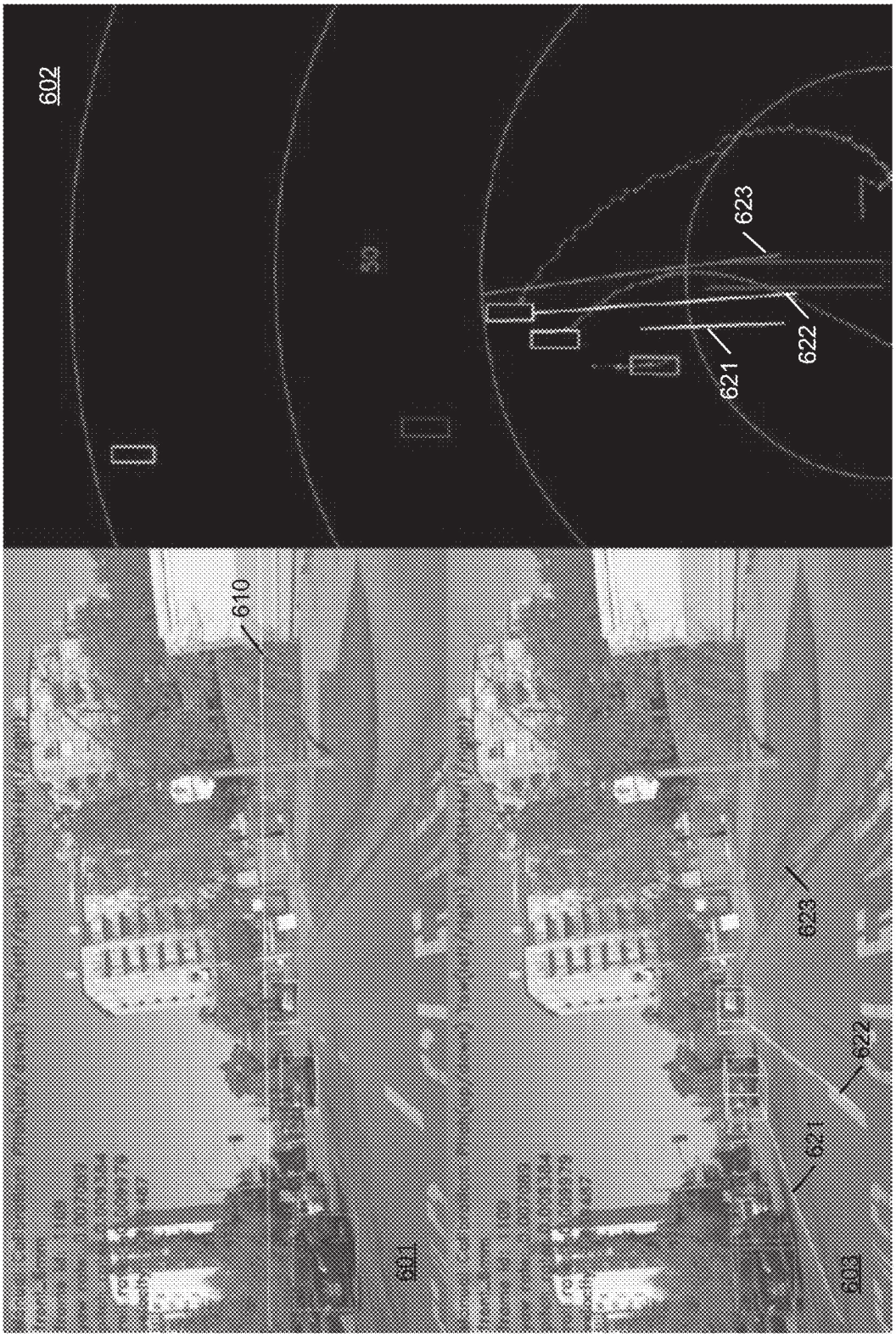


FIG. 6B

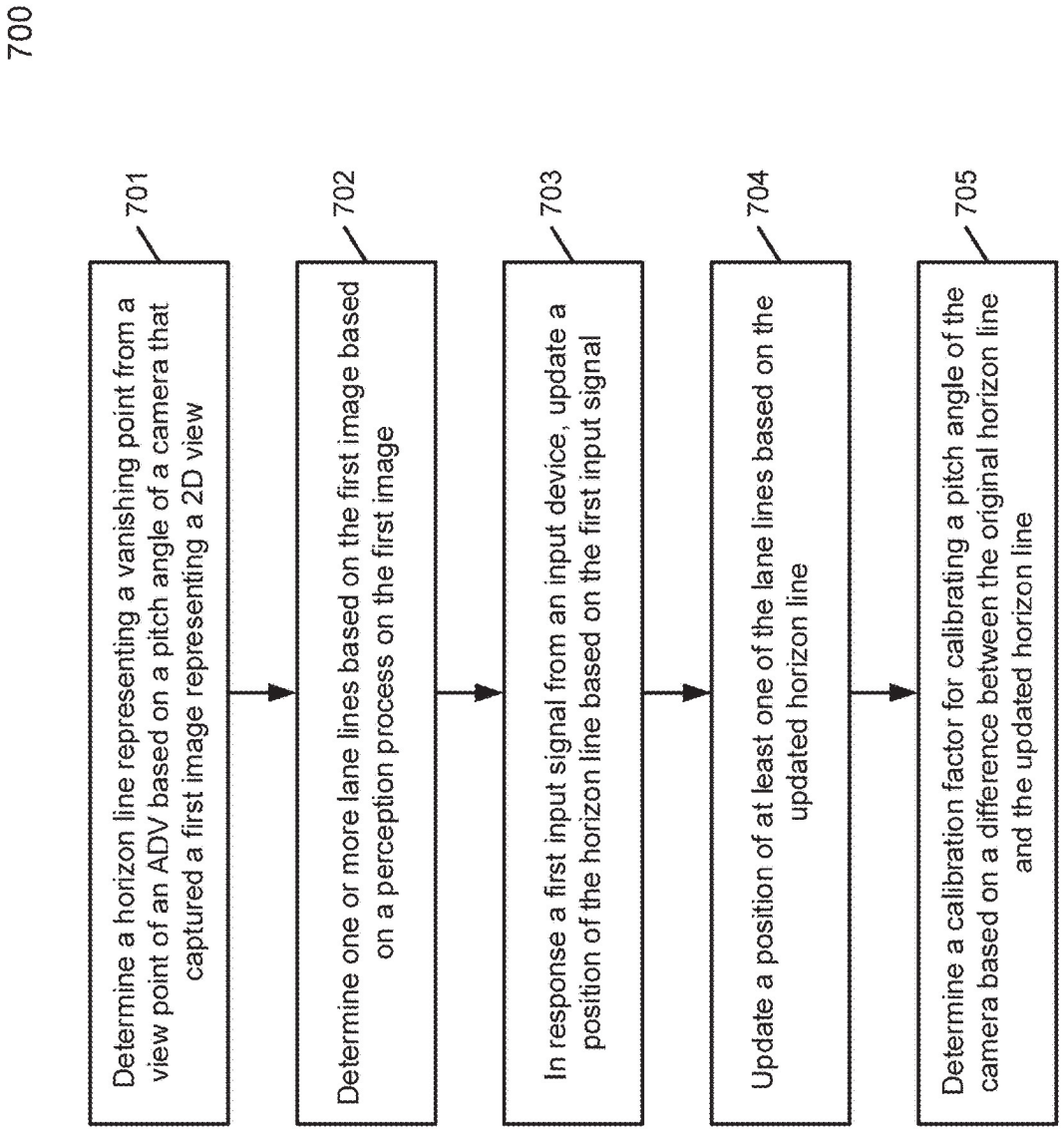

700
701
Determine a horizon line representing a vanishing point from a view point of an ADV based on a pitch angle of a camera that captured a first image representing a 2D view
702
Determine one or more lane lines based on the first image based on a perception process on the first image
703
In response a first input signal from an input device, update a position of the horizon line based on the first input signal
704
Update a position of at least one of the lane lines based on the updated horizon line
705
Determine a calibration factor for calibrating a pitch angle of the camera based on a difference between the original horizon line and the updated horizon line

FIG. 7

SENSOR CALIBRATION SYSTEM FOR AUTONOMOUS DRIVING VEHICLES

TECHNICAL FIELD

[0001] Embodiments of the present disclosure relate generally to operating autonomous vehicles. More particularly, embodiments of the disclosure relate to calibrating a sensor system of an autonomous driving vehicle.

BACKGROUND

[0002] Vehicles operating in an autonomous mode (e.g., driverless) can relieve occupants, especially the driver, from some driving-related responsibilities. When operating in an autonomous mode, the vehicle can navigate to various locations using onboard sensors, allowing the vehicle to travel with minimal human interaction or in some cases without any passengers.

[0003] In order to accurately autonomously drive the vehicle, the system relies heavily on the sensor data obtained from the sensors such as cameras, LIDAR, and RADAR devices, etc. that are mounted on the vehicle. However, such sensors require periodically calibrated to make sure the accuracy of the sensors, such that the perception system of an autonomous driving system can accurately detect and recognize the objects and lane configuration of the driving environment. However, there has been a lack of efficient sensor calibration system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Embodiments of the disclosure are illustrated by way of example and not limitation in the figures of the accompanying drawings in which like references indicate similar elements.

[0005] FIG. **1** is a block diagram illustrating a networked system according to one embodiment.

[0006] FIG. **2** is a block diagram illustrating an example of an autonomous vehicle according to one embodiment.

[0007] FIGS. **3**A-**3**B are block diagrams illustrating an example of a perception and planning system used with an autonomous vehicle according to one embodiment.

[0008] FIG. **4** is a block diagram illustrating a sensor calibration system according to one embodiment.

[0009] FIGS. **5**A-**5**C show a pitch angle, a yaw angle, and a roll angle of a vehicle.

[0010] FIGS. **6**A and **6**B are screenshots illustrating an example of a graphical user interface for calibrating sensors according to one embodiment.

[0011] FIG. **7** is a flow diagram illustrating an example of a process for calibrating sensors of an autonomous driving vehicle according to one embodiment.

DETAILED DESCRIPTION

[0012] Various embodiments and aspects of the disclosures will be described with reference to details discussed below, and the accompanying drawings will illustrate the various embodiments. The following description and drawings are illustrative of the disclosure and are not to be construed as limiting the disclosure. Numerous specific details are described to provide a thorough understanding of various embodiments of the present disclosure. However, in certain instances, well-known or conventional details are not described in order to provide a concise discussion of embodiments of the present disclosures.

[0013] Reference in the specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in conjunction with the embodiment can be included in at least one embodiment of the disclosure. The appearances of the phrase "in one embodiment" in various places in the specification do not necessarily all refer to the same embodiment.

[0014] According to some embodiments, a calibration system with a visualizer is utilized to calibrate sensors (e.g., cameras, LIDAR, RADAR) of an autonomous driving vehicle (ADV). The visualizer includes a user interface to visually display a two-dimensional (2D) image captured by a camera and a three-dimensional (3D) image to allow a user visually calibrate the camera, a LIDAR device, and/or a RADAR device. A user can calibrate any of the sensors such as a pitch angle, a yaw angle, and/or a roll angle using an input device such as a keyboard or joystick to provide incremental calibration feedback, while displaying the calibration result on a display device concurrently. As a result, the user can visually "feel" the calibration result based on user feedback.

[0015] According to one embodiment, in response to a first image captured by a camera of an ADV, a horizon line is determined based on the camera's hardware settings. The horizon line represents a vanishing point from a view point of the ADV based on an initial or default pitch angle of the camera. One or more lane lines are determined based on the first image via a perception process performed on the first image. In response to a first input signal (e.g., an up or down arrow key) received from an input device (e.g., keyboard, joystick, voice interactive command), a position of the horizon line is updated based on the first input signal and a position of at least one of the lane lines is updated based on the updated horizon line. The input signal may represent an incremental adjustment for adjusting the position of the horizon line. A first calibration factor or first correction value is determined for calibrating a pitch angle of the camera based on a difference between the initial horizon line and the updated horizon line.

[0016] In one embodiment, the first image with the horizon line superimposed thereon is displayed within a first display area of a display device. When the position of the horizon line is updated, the first image is updated on the first display area to update the position of the horizon line to give a visual feedback to a user. In one embodiment, a second image is displayed within a second display area of the display device. The second image includes the lane lines superimposed thereon from a top view or a 3D view based on the 2D view of the first image. When the horizon line is updated, the positions of the lane lines are also updated on the second image on the second display area based on the pitch angle represented by the updated horizon line. In one embodiment, a third image is generated based on the first image and the second image, also referred to as a re-projected 2D view of the first image based on the 3D information associated with the second image. The third image is displayed within a third display area of the display device. When the lane lines are adjusted based on the input signal on the second image, the lane lines displayed on the third image are also adjusted to reflect the updates of the lane lines in a 2D view. The user can view the result of the lane lines based on the updated pitch angle of the camera.

[0017] According to one embodiment, in response to a second input signal received from the input device (e.g., left

or right arrow key), the position of at least one of the lane lines is modified based on the second input signal. The positions of the lane lines are updated on the second image displayed on the second display area. A second calibration factor for calibrating a yaw angle of the camera is determined based on the modification of the positions of the lane lines. Similarly, in response to a third signal received from the input device (e.g., shift-left or shift-right arrow key), the lane lines are modified and a third calibration factor for calibrating a roll angle of the camera is determined. The first, second, and third images are concurrently displayed within the first, second, and third display areas respectively. The processes similar to the above process can be implemented to determine calibration factors for LIDAR and/or RADAR devices. The above processes can be utilized online while the vehicle is driving and real-time images are captured to calibrate the sensors in real-time. Alternatively, the above processes can be performed offline based on the previously captured images or point clouds. The calibration factors can be utilized by software applications such as a perception module to adjust the image processing parameters such as pitch, yaw, and roll angles to compensate the hardware during the image processing.

[0018] FIG. **1** is a block diagram illustrating an autonomous vehicle network configuration according to one embodiment of the disclosure. Referring to FIG. **1**, network configuration **100** includes autonomous vehicle **101** that may be communicatively coupled to one or more servers **103-104** over a network **102**. Although there is one autonomous vehicle shown, multiple autonomous vehicles can be coupled to each other and/or coupled to servers **103-104** over network **102**. Network **102** may be any type of networks such as a local area network (LAN), a wide area network (WAN) such as the Internet, a cellular network, a satellite network, or a combination thereof, wired or wireless. Server(s) **103-104** may be any kind of servers or a cluster of servers, such as Web or cloud servers, application servers, backend servers, or a combination thereof. Servers **103-104** may be data analytics servers, content servers, traffic information servers, map and point of interest (MPOI) servers, or location servers, etc.

[0019] An autonomous vehicle refers to a vehicle that can be configured to in an autonomous mode in which the vehicle navigates through an environment with little or no input from a driver. Such an autonomous vehicle can include a sensor system having one or more sensors that are configured to detect information about the environment in which the vehicle operates. The vehicle and its associated controller(s) use the detected information to navigate through the environment. Autonomous vehicle **101** can operate in a manual mode, a full autonomous mode, or a partial autonomous mode.

[0020] In one embodiment, autonomous vehicle **101** includes, but is not limited to, perception and planning system **110**, vehicle control system **111**, wireless communication system **112**, user interface system **113**, infotainment system **114**, and sensor system **115**. Autonomous vehicle **101** may further include certain common components included in ordinary vehicles, such as, an engine, wheels, steering wheel, transmission, etc., which may be controlled by vehicle control system **111** and/or perception and planning system **110** using a variety of communication signals and/or commands, such as, for example, acceleration signals or commands, deceleration signals or commands, steering signals or commands, braking signals or commands, etc.

[0021] Components **110-115** may be communicatively coupled to each other via an interconnect, a bus, a network, or a combination thereof. For example, components **110-115** may be communicatively coupled to each other via a controller area network (CAN) bus. A CAN bus is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other in applications without a host computer. It is a message-based protocol, designed originally for multiplex electrical wiring within automobiles, but is also used in many other contexts.

[0022] Referring now to FIG. **2**, in one embodiment, sensor system **115** includes, but it is not limited to, one or more cameras **211**, global positioning system (GPS) unit **212**, inertial measurement unit (IMU) **213**, radar unit **214**, and a light detection and range (LIDAR) unit **215**. GPS system **212** may include a transceiver operable to provide information regarding the position of the autonomous vehicle. IMU unit **213** may sense position and orientation changes of the autonomous vehicle based on inertial acceleration. Radar unit **214** may represent a system that utilizes radio signals to sense objects within the local environment of the autonomous vehicle. In some embodiments, in addition to sensing objects, radar unit **214** may additionally sense the speed and/or heading of the objects. LIDAR unit **215** may sense objects in the environment in which the autonomous vehicle is located using lasers. LIDAR unit **215** could include one or more laser sources, a laser scanner, and one or more detectors, among other system components. Cameras **211** may include one or more devices to capture images of the environment surrounding the autonomous vehicle. Cameras **211** may be still cameras and/or video cameras. A camera may be mechanically movable, for example, by mounting the camera on a rotating and/or tilting a platform.

[0023] Sensor system **115** may further include other sensors, such as, a sonar sensor, an infrared sensor, a steering sensor, a throttle sensor, a braking sensor, and an audio sensor (e.g., microphone). An audio sensor may be configured to capture sound from the environment surrounding the autonomous vehicle. A steering sensor may be configured to sense the steering angle of a steering wheel, wheels of the vehicle, or a combination thereof. A throttle sensor and a braking sensor sense the throttle position and braking position of the vehicle, respectively. In some situations, a throttle sensor and a braking sensor may be integrated as an integrated throttle/braking sensor.

[0024] In one embodiment, vehicle control system **111** includes, but is not limited to, steering unit **201**, throttle unit **202** (also referred to as an acceleration unit), and braking unit **203**. Steering unit **201** is to adjust the direction or heading of the vehicle. Throttle unit **202** is to control the speed of the motor or engine that in turn controls the speed and acceleration of the vehicle. Braking unit **203** is to decelerate the vehicle by providing friction to slow the wheels or tires of the vehicle. Note that the components as shown in FIG. **2** may be implemented in hardware, software, or a combination thereof.

[0025] Referring back to FIG. **1**, wireless communication system **112** is to allow communication between autonomous vehicle **101** and external systems, such as devices, sensors, other vehicles, etc. For example, wireless communication system **112** can wirelessly communicate with one or more devices directly or via a communication network, such as

servers **103-104** over network **102**. Wireless communication system **112** can use any cellular communication network or a wireless local area network (WLAN), e.g., using WiFi to communicate with another component or system. Wireless communication system **112** could communicate directly with a device (e.g., a mobile device of a passenger, a display device, a speaker within vehicle **101**), for example, using an infrared link, Bluetooth, etc. User interface system **113** may be part of peripheral devices implemented within vehicle **101** including, for example, a keyboard, a touch screen display device, a microphone, and a speaker, etc.

[0026] Some or all of the functions of autonomous vehicle **101** may be controlled or managed by perception and planning system **110**, especially when operating in an autonomous driving mode. Perception and planning system **110** includes the necessary hardware (e.g., processor(s), memory, storage) and software (e.g., operating system, planning and routing programs) to receive information from sensor system **115**, control system **111**, wireless communication system **112**, and/or user interface system **113**, process the received information, plan a route or path from a starting point to a destination point, and then drive vehicle **101** based on the planning and control information. Alternatively, perception and planning system **110** may be integrated with vehicle control system **111**.

[0027] For example, a user as a passenger may specify a starting location and a destination of a trip, for example, via a user interface. Perception and planning system **110** obtains the trip related data. For example, perception and planning system **110** may obtain location and route information from an MPOI server, which may be a part of servers **103-104**. The location server provides location services and the MPOI server provides map services and the POIs of certain locations. Alternatively, such location and MPOI information may be cached locally in a persistent storage device of perception and planning system **110**.

[0028] While autonomous vehicle **101** is moving along the route, perception and planning system **110** may also obtain real-time traffic information from a traffic information system or server (TIS). Note that servers **103-104** may be operated by a third party entity. Alternatively, the functionalities of servers **103-104** may be integrated with perception and planning system **110**. Based on the real-time traffic information, MPOI information, and location information, as well as real-time local environment data detected or sensed by sensor system **115** (e.g., obstacles, objects, nearby vehicles), perception and planning system **110** can plan an optimal route and drive vehicle **101**, for example, via control system **111**, according to the planned route to reach the specified destination safely and efficiently.

[0029] Server **103** may be a data analytics system to perform data analytics services for a variety of clients. In one embodiment, data analytics system **103** includes data collector **121** and machine learning engine **122**. Data collector **121** collects driving statistics **123** from a variety of vehicles, either autonomous vehicles or regular vehicles driven by human drivers. Driving statistics **123** include information indicating the driving commands (e.g., throttle, brake, steering commands) issued and responses of the vehicles (e.g., speeds, accelerations, decelerations, directions) captured by sensors of the vehicles at different points in time. Driving statistics **123** may further include information describing the driving environments at different points in time, such as, for example, routes (including starting and destination locations), MPOIs, road conditions, weather conditions, etc.

[0030] Based on driving statistics **123**, machine learning engine **122** generates or trains a set of rules, algorithms, and/or predictive models **124** for a variety of purposes. In one embodiment, algorithms **124** may include algorithms for autonomous driving a vehicle as described further below. Algorithms **124** may further include sensor calibration algorithms, which will be described further below. Algorithms **124** can then be uploaded on ADVs to be utilized during autonomous driving in real-time.

[0031] In one embodiment, sensor calibration system **125** may be hosted by server **103** to calibrate sensors such as cameras, LIDAR, and/or RADAR devices offline based on the images and/or point clouds captured by the sensors. The sensor calibration process may be performed offline based on the previously captured sensor data captured by the targeted sensors of ADVs. The calibration parameters can then be uploaded to the corresponding vehicles and utilized by autonomous driving software to calibrate and compensate the corresponding sensors. The calibration process will be described in details further below.

[0032] FIGS. **3**A and **3**B are block diagrams illustrating an example of a perception and planning system used with an autonomous vehicle according to one embodiment. System **300** may be implemented as a part of autonomous vehicle **101** of FIG. **1** including, but is not limited to, perception and planning system **110**, control system **111**, and sensor system **115**. Referring to FIGS. **3**A-**3**B, perception and planning system **110** includes, but is not limited to, localization module **301**, perception module **302**, prediction module **303**, decision module **304**, planning module **305**, control module **306**, routing module **307**, and sensor calibration module or system **308**.

[0033] Some or all of modules **301-308** may be implemented in software, hardware, or a combination thereof. For example, these modules may be installed in persistent storage device **352**, loaded into memory **351**, and executed by one or more processors (not shown). Note that some or all of these modules may be communicatively coupled to or integrated with some or all modules of vehicle control system **111** of FIG. **2**. Some of modules **301-308** may be integrated together as an integrated module.

[0034] Localization module **301** determines a current location of autonomous vehicle **300** (e.g., leveraging GPS unit **212**) and manages any data related to a trip or route of a user. Localization module **301** (also referred to as a map and route module) manages any data related to a trip or route of a user. A user may log in and specify a starting location and a destination of a trip, for example, via a user interface. Localization module **301** communicates with other components of autonomous vehicle **300**, such as map and route information **311**, to obtain the trip related data. For example, localization module **301** may obtain location and route information from a location server and a map and POI (MPOI) server. A location server provides location services and an MPOI server provides map services and the POIs of certain locations, which may be cached as part of map and route information **311**. While autonomous vehicle **300** is moving along the route, localization module **301** may also obtain real-time traffic information from a traffic information system or server.

[0035] Based on the sensor data provided by sensor system **115** and localization information obtained by localization module **301**, a perception of the surrounding environment is determined by perception module **302**. The perception information may represent what an ordinary driver would perceive surrounding a vehicle in which the driver is driving. The perception can include the lane configuration, traffic light signals, a relative position of another vehicle, a pedestrian, a building, crosswalk, or other traffic related signs (e.g., stop signs, yield signs), etc., for example, in a form of an object. The lane configuration includes information describing a lane or lanes, such as, for example, a shape of the lane (e.g., straight or curvature), a width of the lane, how many lanes in a road, one-way or two-way lane, merging or splitting lanes, exiting lane, etc.

[0036] Perception module **302** may include a computer vision system or functionalities of a computer vision system to process and analyze images captured by one or more cameras in order to identify objects and/or features in the environment of autonomous vehicle. The objects can include traffic signals, road way boundaries, other vehicles, pedestrians, and/or obstacles, etc. The computer vision system may use an object recognition algorithm, video tracking, and other computer vision techniques. In some embodiments, the computer vision system can map an environment, track objects, and estimate the speed of objects, etc. Perception module **302** can also detect objects based on other sensors data provided by other sensors such as a radar and/or LIDAR.

[0037] For each of the objects, prediction module **303** predicts what the object will behave under the circumstances. The prediction is performed based on the perception data perceiving the driving environment at the point in time in view of a set of map/rout information **311** and traffic rules **312**. For example, if the object is a vehicle at an opposing direction and the current driving environment includes an intersection, prediction module **303** will predict whether the vehicle will likely move straight forward or make a turn. If the perception data indicates that the intersection has no traffic light, prediction module **303** may predict that the vehicle may have to fully stop prior to enter the intersection. If the perception data indicates that the vehicle is currently at a left-turn only lane or a right-turn only lane, prediction module **303** may predict that the vehicle will more likely make a left turn or right turn respectively.

[0038] For each of the objects, decision module **304** makes a decision regarding how to handle the object. For example, for a particular object (e.g., another vehicle in a crossing route) as well as its metadata describing the object (e.g., a speed, direction, turning angle), decision module **304** decides how to encounter the object (e.g., overtake, yield, stop, pass). Decision module **304** may make such decisions according to a set of rules such as traffic rules or driving rules **312**, which may be stored in persistent storage device **352**.

[0039] Routing module **307** is configured to provide one or more routes or paths from a starting point to a destination point. For a given trip from a start location to a destination location, for example, received from a user, routing module **307** obtains route and map information **311** and determines all possible routes or paths from the starting location to reach the destination location. Routing module **307** may generate a reference line in a form of a topographic map for each of the routes it determines from the starting location to reach the destination location. A reference line refers to an ideal route or path without any interference from others such as other vehicles, obstacles, or traffic condition. That is, if there is no other vehicle, pedestrians, or obstacles on the road, an ADV should exactly or closely follows the reference line. The topographic maps are then provided to decision module **304** and/or planning module **305**. Decision module **304** and/or planning module **305** examine all of the possible routes to select and modify one of the most optimal routes in view of other data provided by other modules such as traffic conditions from localization module **301**, driving environment perceived by perception module **302**, and traffic condition predicted by prediction module **303**. The actual path or route for controlling the ADV may be close to or different from the reference line provided by routing module **307** dependent upon the specific driving environment at the point in time.

[0040] Based on a decision for each of the objects perceived, planning module **305** plans a path or route for the autonomous vehicle, as well as driving parameters (e.g., distance, speed, and/or turning angle), using a reference line provided by routing module **307** as a basis. That is, for a given object, decision module **304** decides what to do with the object, while planning module **305** determines how to do it. For example, for a given object, decision module **304** may decide to pass the object, while planning module **305** may determine whether to pass on the left side or right side of the object. Planning and control data is generated by planning module **305** including information describing how vehicle **300** would move in a next moving cycle (e.g., next route/path segment). For example, the planning and control data may instruct vehicle **300** to move 10 meters at a speed of 30 mile per hour (mph), then change to a right lane at the speed of 25 mph.

[0041] Based on the planning and control data, control module **306** controls and drives the autonomous vehicle, by sending proper commands or signals to vehicle control system **111**, according to a route or path defined by the planning and control data. The planning and control data include sufficient information to drive the vehicle from a first point to a second point of a route or path using appropriate vehicle settings or driving parameters (e.g., throttle, braking, steering commands) at different points in time along the path or route.

[0042] In one embodiment, the planning phase is performed in a number of planning cycles, also referred to as driving cycles, such as, for example, in every time interval of 100 milliseconds (ms). For each of the planning cycles or driving cycles, one or more control commands will be issued based on the planning and control data. That is, for every 100 ms, planning module **305** plans a next route segment or path segment, for example, including a target position and the time required for the ADV to reach the target position. Alternatively, planning module **305** may further specify the specific speed, direction, and/or steering angle, etc. In one embodiment, planning module **305** plans a route segment or path segment for the next predetermined period of time such as 5 seconds. For each planning cycle, planning module **305** plans a target position for the current cycle (e.g., next 5 seconds) based on a target position planned in a previous cycle. Control module **306** then generates one or more control commands (e.g., throttle, brake, steering control commands) based on the planning and control data of the current cycle.

[0043] Note that decision module **304** and planning module **305** may be integrated as an integrated module. Decision module **304**/planning module **305** may include a navigation system or functionalities of a navigation system to determine a driving path for the autonomous vehicle. For example, the navigation system may determine a series of speeds and directional headings to affect movement of the autonomous vehicle along a path that substantially avoids perceived obstacles while generally advancing the autonomous vehicle along a roadway-based path leading to an ultimate destination. The destination may be set according to user inputs via user interface system **113**. The navigation system may update the driving path dynamically while the autonomous vehicle is in operation. The navigation system can incorporate data from a GPS system and one or more maps so as to determine the driving path for the autonomous vehicle.

[0044] According to one embodiment, sensor calibration module or system **308** is configured to calibrate, using sensor calibration algorithms **313**, a sensor based on an image or point cloud captured by the sensor to determine a set of calibration parameters. The calibration parameters can be utilized by the software to compensate the hardware settings of the sensors during a perception process. Sensor calibration module **308** may be implemented as a part of perception module **302** or communicatively coupled to perception module **302**. The functionalities of sensor calibration module **308** may be maintained in a data analytics system such as server **103** to perform a sensor calibration of a sensor offline based on the images captured by the corresponding sensor. The calibration result can then be uploaded onto the vehicle to be utilized online during the image processing as a part of the perception process.

[0045] FIG. **4** is a block diagram illustrating a sensor calibration system according to one embodiment. Referring to FIG. **4**, as described above, perception module **302** receives sensor data from a variety of sensors such as camera **211**, LIDAR **215**, and RADAR **214**. For camera **211**, sensor data may include an image and for LIDAR **215**, the corresponding sensor data may include a point cloud image. The sensor data is then processed by perception module **302** such as image processing, including detecting an object within the image and determining a horizon line representing a vanishing point of a road. The result of the perception processing can be utilized by other modules such as prediction module **303** and planning module **305** for autonomous driving.

[0046] In addition, an image processed by perception module **302** may be utilized by sensor calibration module **308** for sensor calibration. According to one embodiment, sensor calibration module **308** includes a 2D rendering module **401**, a 3D rendering module **402**, and a 2D re-projecting module **403**. In response to an image captured by camera **211** and processed by perception module **302**, 2D rendering module **401** is configured to render a 2D view including superimposing a horizon line onto the image according to the camera setting (e.g., hardware preset pitch angle). The 2D view image is then displayed on display device **405** as part of 2D view **411**. Based on the 2D view image, 3D rendering module **412** is configured to render a 3D view such as a top-down view using other 3D information such as sensor data obtained from LIDAR **215** and RADAR **214**. The 3D view image is then displayed on display device **405** as part of 3D view **412**. The 2D re-projecting module **403** is configured to render or reconstruct a 2D view from 3D view image. Note that the 2D re-projecting module **403** may be integrated with 2D rendering module **401**.

[0047] The re-projected 2D view is then displayed on display device **405** as part of 2D re-projected view **413**. A user can then enter feedback or adjustment using input device **404** such as a keyboard or joystick. In response to the input provided by the user, modules **411-413** adjust certain parameters, render the images again, and display the updated images on display device **405**. As a result, the user can calibrate the sensors until the calibration results as shown on display device **405** are satisfied. Once the calibration results are satisfied, calibration factor calculator **406** determines the calibration factor **410** and feeds back to perception module **302** or other software modules such that the software modules can perform proper adjustment at the software level to compensate the hardware settings of the sensors.

[0048] According to one embodiment, in response to a first image captured by a camera of an ADV, perception module **302** determines a horizon line based on the camera's hardware settings. The horizon line represents a vanishing point from a view point of the ADV based on an initial or default pitch angle of the camera. Perception module **302** may include an object detector to detect an object within the image and a lane detector to detect one or more lanes. One or more lane lines are determined based on the first image by perception module **302**. The processed first image having the detected objects, lane lines, and the horizon line is provided to sensor calibration module **308**.

[0049] In response to a first input signal (e.g., an up or down arrow keypress) received from an input device (e.g., a keyboard, a joystick, a microphone to receive voice interactive commands), a position of the horizon line is updated based on the first input signal and a position of at least one of the lane lines is updated based on the updated horizon line. The input signal may represent an incremental value for adjusting the position of the horizon line. A first calibration factor or first correction value is determined for calibrating a pitch angle of the camera based on a difference between the initial horizon line and the updated horizon line. A pitch angle may be represented by a pitch slope angle or a pitch grade/slope percentage as shown in FIGS. **5**A and **5**B. A positive pitch angle represents an uphill road and a negative pitch angle represents a downhill road, or vice versa.

[0050] In one embodiment, the first image with the horizon line superimposed thereon is rendered by 2D module **401** and displayed within a first display area of display device **405** as part of 2D view **411**. When the position of the horizon line is updated, the first image is rendered again in view of the input signal and updated on the first display area as part of 2D view **411** to update the position of the horizon line to give a visual feedback to a user. In one embodiment, a second image is rendered by 3D rendering module **402** and displayed within a second display area of display device **405** as part of 3D view **412**. The second image includes the lane lines superimposed thereon from a top view or a 3D view corresponding to the 2D view of the first image. When the horizon line is updated, the positions of the lane lines are also updated on the second image (e.g., 3D view **412**) on the second display area based on the pitch angle represented by the updated horizon line.

[0051] In one embodiment, an optional third image is generated by 2D re-projecting module **403** based on the first

image **411** and the second image **412**, also referred to as a re-projected 2D view of the first image based on the 3D information associated with the second image. The third image is displayed within a third display area of display device **405** as part of 2D re-projected view **413**. When the lane lines are adjusted based on the input signal on the second image, the lane lines displayed on the third image are also adjusted to reflect the updates of the lane lines in a 2D view. The user can view the result of the lane lines based on the updated pitch angle of the camera.

[0052] According to one embodiment, in response to a second input signal received from the input device **404** (e.g., left or right arrow key), the position of at least one of the lane lines is modified based on the second input signal. The positions of the lane lines are updated on the second image **412** displayed on the second display area. A second calibration factor for calibrating a yaw angle of the camera is determined based on the modification of the positions of the lane lines. A yaw angle represents a horizontal turning left and right of an object.

[0053] Similarly, in response to a third signal received from the input device (e.g., shift-left or shift-right arrow key), the lane lines are modified and a third calibration factor for calibrating a roll angle of the camera is determined. A roll angle refers to whether an object is tilted or rolled left or right. The roll angle may be represented by a roll slope angle or a roll grade/slope percentage as shown in FIGS. **5**A and **5**C. A positive roll angle represents a road tilted left and a negative roll angle represents a road tilted right, or vice versa.

[0054] The first, second, and third images are concurrently displayed within the first, second, and third display areas respectively. The processes similar to the above process can be implemented to determine calibration factors for LIDAR and/or RADAR devices. The above processes can be utilized online while the vehicle is driving and real-time images are captured to calibrate the sensors in real-time. Alternatively, the above processes can be performed offline based on the previously captured images or point clouds. The calibration factors can be utilized by software applications such as a perception module to adjust the image processing parameters such as pitch, yaw, and roll angles to compensate the hardware during the image processing.

[0055] FIGS. **6**A-**6**B are screenshots illustrating a graphical user interface of a sensor calibration system according to one embodiment. Referring to FIG. **6**A, in this example, the system is calibrating a pitch angle of a camera. Image **601** was captured by a camera to be calibrated and processed by perception module **302**, including detecting objects shown on the image indicated by the bounding boxes in this example. In addition, horizon line **610** is determined and placed on a location within image **601** based on the hardware setting of the targeted camera. Image **601** may be rendered by 2D rendering module **401** and displayed within a first display area of a display device as a 2D view.

[0056] Based on the image **601**, image **602** representing a 3D view, in this example, a top-down view, is generated based on the image **601** and other 3D information, for example, provided by a LIDAR device and/or RADAR device. Image **602** may be rendered by 3D rendering module **402** and displayed within a second display area of the display device. Image **402** includes one or more lane lines **621-623** positioned based on the position of horizon line **610**. In addition, optional image **603**, referred to herein as a 2D re-projected view, is generated based on 2D view image **601** and 3D view image **602**, including projecting lane lines **621-623** onto the 2D view.

[0057] From the top-down view, when a pitch angle of a camera has been calibrated, lane lines **621-623** should be relatively or substantially parallel. In this example, assuming horizon line **610** is too low, which causes lane lines to be diverged. Similarly, if the horizon line **610** is too high, as shown in FIG. **6**B, lane lines **621-623** shown in 3D view **602** would be converged. By displaying the top-down view based on the position of horizon line **610**, a user can calibrate the pitch angle by adjusting the position horizon line **610**, for example, using an up-arrow key or a down-arrow key of a keyboard as an input device, until lane lines **621-623** are relatively parallel on the 3D view **602**. An input device can also be a joystick or a microphone that can receive a voice interactive command from a user. Similarly, the yaw angle and the roll angle of a camera can also be calibrated using the techniques as described above.

[0058] LIDAR device and RADAR device can also be calibrated in a similar manner as described above. In one embodiment, in order to calibrate a LIDAR device or a RADAR device, a camera needs to be calibrated accurately first. Based on the images provided by the camera, a LIDAR device or a RADAR device can be calibrated.

[0059] FIG. **7** is a flow diagram illustrating an example of a process for calibrating sensors according to one embodiment. Process **700** may be performed by processing logic which may include software, hardware, or a combination thereof. For example, process **700** may be performed by sensor calibration module **308** or sensor calibration system **125**. Referring to FIG. **7**, at block **701**, processing logic determines a horizon line representing a vanishing point from a view point of the ADV based on a pitch angle of a camera that captured a first image. The first image represents a 2D view from the view point of the ADV. At block **702**, processing logic determines one or more lane lines based on the first image based on a perception process on the first image. In response to a first input signal received from an input device, at block **703**, the position of the horizon line is updated based on the first input signal. At block **704**, a position of at least one of the lane lines is updated based on the updated horizon line. At block **705**, processing logic determines a calibration factor or parameter for calibrating a pitch angle of the camera based on the difference between the initial horizon line and the updated horizon line.

[0060] Note that some or all of the components as shown and described above may be implemented in software, hardware, or a combination thereof. For example, such components can be implemented as software installed and stored in a persistent storage device, which can be loaded and executed in a memory by a processor (not shown) to carry out the processes or operations described throughout this application. Alternatively, such components can be implemented as executable code programmed or embedded into dedicated hardware such as an integrated circuit (e.g., an application specific IC or ASIC), a digital signal processor (DSP), or a field programmable gate array (FPGA), which can be accessed via a corresponding driver and/or operating system from an application. Furthermore, such components can be implemented as specific hardware logic in a processor or processor core as part of an instruction set accessible by a software component via one or more specific instructions.

[0061] Some portions of the preceding detailed descriptions have been presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the ways used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of operations leading to a desired result. The operations are those requiring physical manipulations of physical quantities.

[0062] It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the above discussion, it is appreciated that throughout the description, discussions utilizing terms such as those set forth in the claims below, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

[0063] Embodiments of the disclosure also relate to an apparatus for performing the operations herein. Such a computer program is stored in a non-transitory computer readable medium. A machine-readable medium includes any mechanism for storing information in a form readable by a machine (e.g., a computer). For example, a machine-readable (e.g., computer-readable) medium includes a machine (e.g., a computer) readable storage medium (e.g., read only memory ("ROM"), random access memory ("RAM"), magnetic disk storage media, optical storage media, flash memory devices).

[0064] The processes or methods depicted in the preceding figures may be performed by processing logic that comprises hardware (e.g. circuitry, dedicated logic, etc.), software (e.g., embodied on a non-transitory computer readable medium), or a combination of both. Although the processes or methods are described above in terms of some sequential operations, it should be appreciated that some of the operations described may be performed in a different order. Moreover, some operations may be performed in parallel rather than sequentially.

[0065] Embodiments of the present disclosure are not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of embodiments of the disclosure as described herein.

[0066] In the foregoing specification, embodiments of the disclosure have been described with reference to specific exemplary embodiments thereof. It will be evident that various modifications may be made thereto without departing from the broader spirit and scope of the disclosure as set forth in the following claims. The specification and drawings are, accordingly, to be regarded in an illustrative sense rather than a restrictive sense.

1. A computer-implemented method for calibrating a sensor of an autonomous driving vehicle (ADV), the method comprising:

determining a horizon line representing a vanishing point from a view point of the ADV based on a pitch angle of a camera that captured a first image representing a two-dimensional (2D) view from the viewpoint of the ADV;

displaying, on a first display area of a display device, the horizon line superimposed on a location within the first image that is based on a setting of the camera;

displaying, on a second display area of the display device, a second image that is a three-dimensional (3D) view based on the first image and 3D information obtained from one or more other sensors of the ADV;

determining one or more lane lines based on the first image based on a perception process performed on the first image and projecting the one or more lane lines onto the second image;

in response to a first input signal received from an input device,

updating a position of the horizon line superimposed on the first image, based on the first input signal, and

updating a position of at least one of the lane lines projected onto the second image, based on the updated position of the horizon line superimposed on the first image; and

determining a first calibration factor for calibrating the pitch angle of the camera based on a difference between the horizon line and the updated horizon line in view of the one or more lane lines and the updated position of the at least one of the one or more lane lines.

2. The method of claim **1**, further comprising:

repeating the receiving of an input signal from an input device and the updating a position of the horizon line and updating the position of the least one of the one or more lane lines until the one or more lane lines projected onto the second image are substantially parallel.

3. The method of claim **1**, wherein the 3D view of the second image comprises a top-down view based on the first image and the 3D information obtained from the one or more other sensors of the ADV.

4. The method of claim **1**, further comprising:

generating a third image based on the first image and the second image, the third image representing a reconstructed 2D view of the first image based on 3D information associated with the second image; and

displaying the third image within a third display area of the display device.

5. The method of claim **4**, wherein updating a position of at least one of the lane lines comprises updating the position of the at least one lane line superimposed on the third image displayed within the third display area.

6. The method of claim **1**, further comprising:

in response to a second input signal received from the input device, modifying a position of at least one of the lane lines based on the second input signal;

updating the position of the at least one of the lane lines superimposed on the second image displayed within the second display area; and

determining a second calibration factor for calibrating a yaw angle of the camera based on a modification of the position of the at least one of the lane lines.

7. The method of claim **1**, further comprising:

in response to a third input signal received from the input device, modifying a position of at least one of the lane lines based on the third input signal;

updating the position of the at least one of the lane lines superimposed on the second image displayed within the second display area; and

determining a third calibration factor for calibrating a roll angle of the camera based on a modification of the position of the at least one of the lane lines.

8. The method of claim **1**, further comprising:

in response to a fourth signal received from the input device, generating a light detection and ranging (LIDAR) point cloud image in a top-down view based on LIDAR data obtained from a LIDAR device of the ADV and the first image;

displaying the LIDAR point cloud within the second display area of the display device; and

determining a fourth calibration factor for calibrating the LIDAR device.

9. The method of claim **3**, further comprising:

in response to a fifth signal received from the input device, generating a radio detection and ranging (RADAR) image in a top-down view based on RADAR sensor data obtained from a RADAR device of the ADV and the first image;

displaying the RADAR image within the second display area of the display device; and

determining a fifth calibration factor for calibrating the RADAR device.

10. The method of claim **4**, wherein the first, second, and third images are concurrently displayed in the first, second, and third display areas of the display device.

11. A non-transitory machine-readable medium having instructions stored therein, which when executed by a processor, cause the processor to perform operations for calibrating a sensor of an autonomous driving vehicle (ADV), the operations comprising:

determining a horizon line representing a vanishing point from a view point of the ADV based on a pitch angle of a camera that captured a first image representing a two-dimensional (2D) view from the viewpoint of the ADV;

displaying, on a first display area of a display device, the horizon line superimposed on a location within the first image that is based on a setting of the camera;

displaying, on a second display area of the display device, a second image that is a three-dimensional (3D) view based on the first image and 3D information obtained from one or more other sensors of the ADV;

determining one or more lane lines based on the first image based on a perception process performed on the first image and projecting the one or more lane lines onto the second image;

in response to a first input signal received from an input device,

updating a position of the horizon line superimposed on the first image, based on the first input signal, and

updating a position of at least one of the lane lines projected onto the second image, based on the updated position of the horizon line superimposed on the first image; and

determining a first calibration factor for calibrating the pitch angle of the camera based on a difference between the horizon line and the updated horizon line in view of the one or more lane lines and the updated position of the at least one of the one or more lane lines.

12. The machine-readable medium of claim **11**, wherein the operations further comprise:

repeating the receiving of an input signal from an input device and the updating of the position of the horizon line and updating the position of the least one of the one or more lane lines until the one or more lane lines projected onto the second image are substantially parallel.

13. The machine-readable medium of claim **11**, wherein the 3D view of the second image comprises a top-down view based on the first image and 3D information obtained from one or more other sensors of the ADV.

14. The machine-readable medium of claim **11**, wherein the operations further comprise:

generating a third image based on the first image and the second image, the third image representing a reconstructed 2D view of the first image based on 3D information associated with the second image; and

displaying the third image within a third display area of the display device.

15. The machine-readable medium of claim **14**, wherein updating a position of at least one of the lane lines comprises updating the position of the at least one lane line superimposed on the third image displayed within the third display area.

16. The machine-readable medium of claim **11**, wherein the operations further comprise:

in response to a second input signal received from the input device, modifying a position of at least one of the lane lines based on the second input signal;

updating the position of the at least one of the lane lines superimposed on the second image displayed within the second display area; and

determining a second calibration factor for calibrating a yaw angle of the camera based on a modification of the position of the at least one of the lane lines.

17. The machine-readable medium of claim **11**, wherein the operations further comprise:

in response to a third input signal received from the input device, modifying a position of at least one of the lane lines based on the third input signal;

updating the position of the at least one of the lane lines superimposed on the second image displayed within the second display area; and

determining a third calibration factor for calibrating a roll angle of the camera based on a modification of the position of the at least one of the lane lines.

18. The machine-readable medium of claim **11**, wherein the operations further comprise:

in response to a fourth signal received from the input device, generating a light detection and ranging (LIDAR) point cloud image in a top-down view based on LIDAR data obtained from a LIDAR device of the ADV and the first image;

displaying the LIDAR point cloud within the second display area of the display device; and

determining a fourth calibration factor for calibrating the LIDAR device.

19. The machine-readable medium of claim **13**, wherein the operations further comprise:

in response to a fifth signal received from the input device, generating a radio detection and ranging (RA-

DAR) image in a top-down view based on RADAR sensor data obtained from a RADAR device of the ADV and the first image;

displaying the RADAR image within the second display area of the display device; and

determining a fifth calibration factor for calibrating the RADAR device.

20. A data processing system, comprising:

a processor; and

a memory coupled to the processor to store instructions, which when executed by the processor, cause the processor to perform operations for calibrating a sensor of an autonomous driving vehicle (ADV), the operations including

determining a horizon line representing a vanishing point from a view point of the ADV based on a pitch angle of a camera that captured a first image representing a two-dimensional (2D) view from the viewpoint of the ADV,

displaying, on a first display area of a display device, the horizon line superimposed on a location within the first image that is based on a setting of the camera,

displaying, on a second display area of the display device, a second image that is a three-dimensional (3D) view based on the first image and 3D information obtained from one or more other sensors of the ADV,

determining one or more lane lines based on the first image based on a perception process performed on the first image and projecting the one or more lane lines onto the second image,

in response to a first input signal received from an input device,

updating a position of the horizon line superimposed on the first image based on the first input signal, and

updating a position of at least one of the lane lines projected onto the second image, based on the updated position of the horizon line superimposed on the first image, and

determining a first calibration factor for calibrating the pitch angle of the camera based on a difference between the horizon line and the updated horizon line in view of the one or more lane lines and the updated position of the at least one of the one or more lane lines.

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