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(54) SYSTEM AND METHOD FOR REMOTE NON-CONTACT CALIBRATION OF ROADSIDE SENSORS

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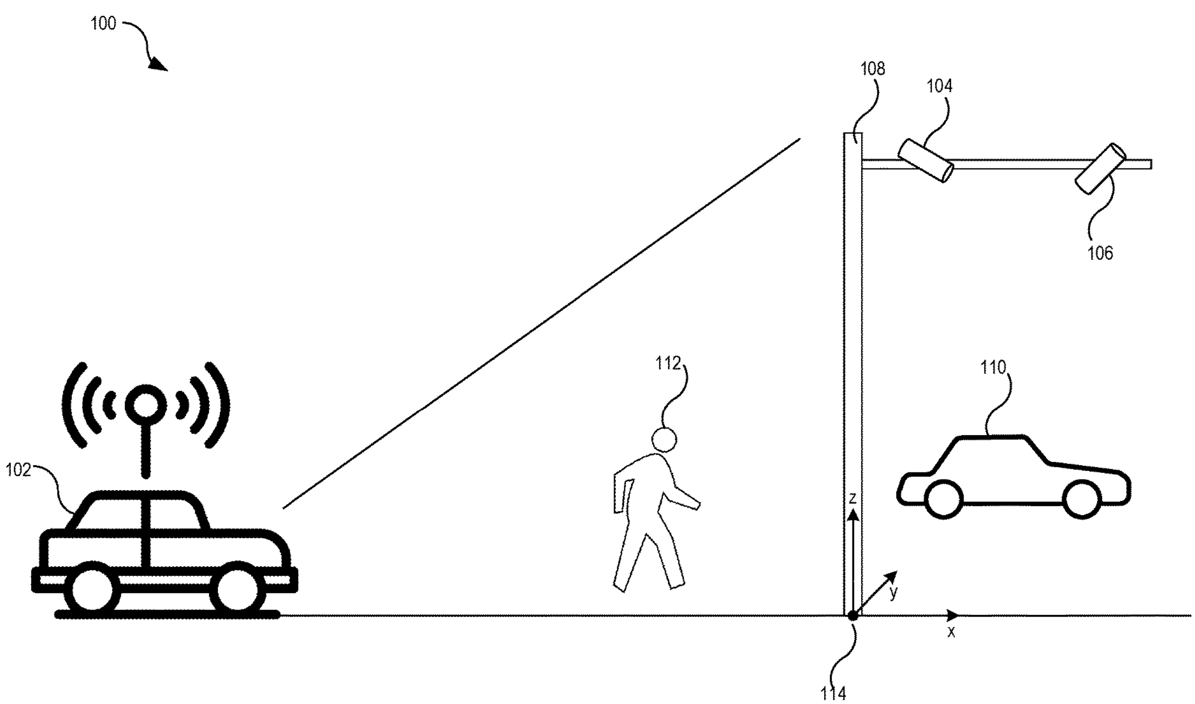
(57) **ABSTRACT**

Embodiments of this disclosure can provide a system and method for calibrating extrinsic parameters of roadside sensors for autonomous driving. During operation, a portable light-detection-and-ranging (lidar) unit can be brought to a sensor-installation site comprising one or more to-be-calibrated roadside sensors, and the portable lidar unit can scan outer surfaces of the to-be-calibrated roadside sensors from different angles to generate a stream of frames. The system can align, spatially, the stream of frames based on a local reference coordinate system, superimpose the aligned frames, and segment a point cloud associated with a to-be-calibrated roadside sensor. The system can determine extrinsic parameters of the to-be-calibrated roadside sensor with respect to the local reference coordinate system based on the segmented point cloud and convert the extrinsic parameters from the local reference coordinate system to a road-based coordinate system.



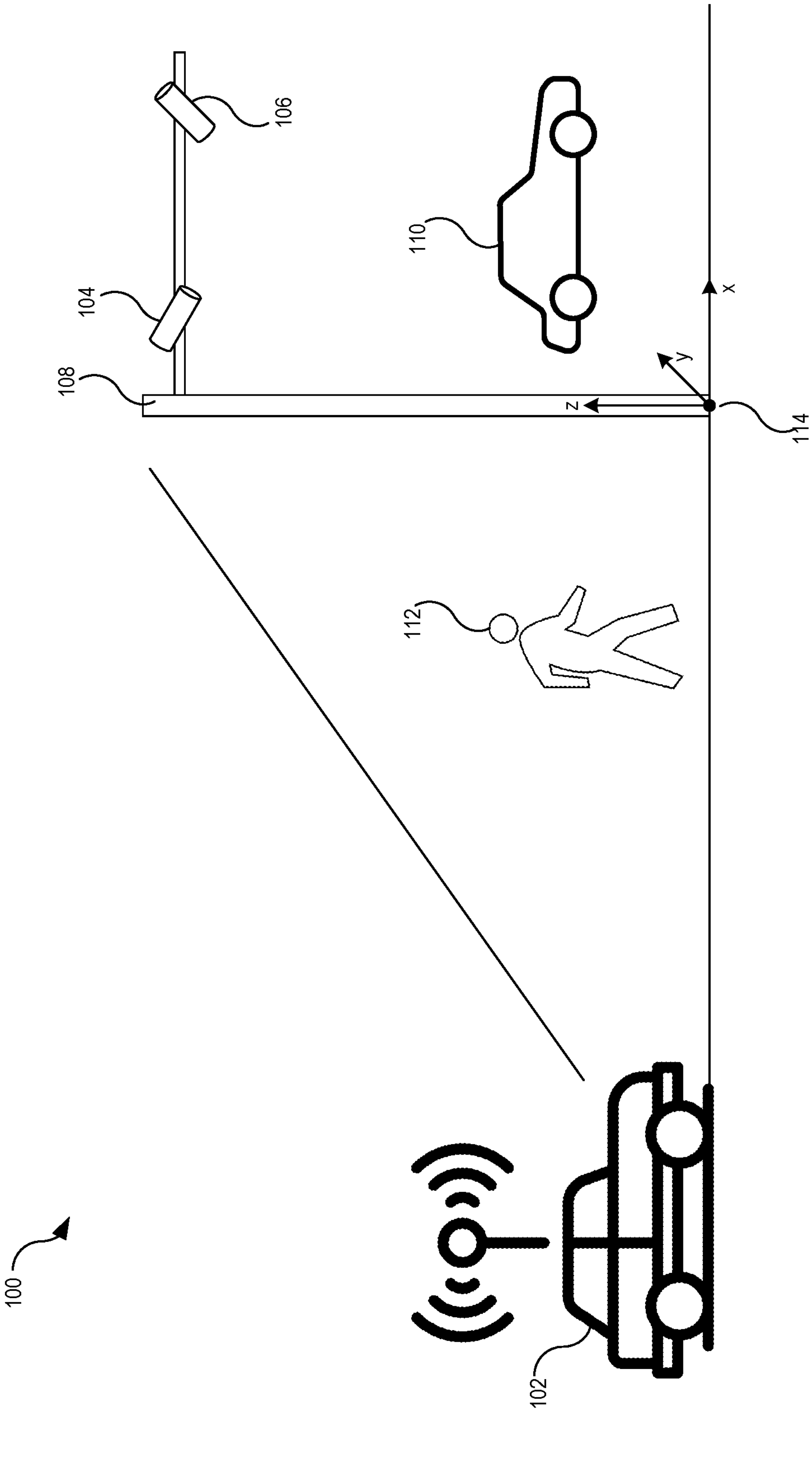


FIG. 1

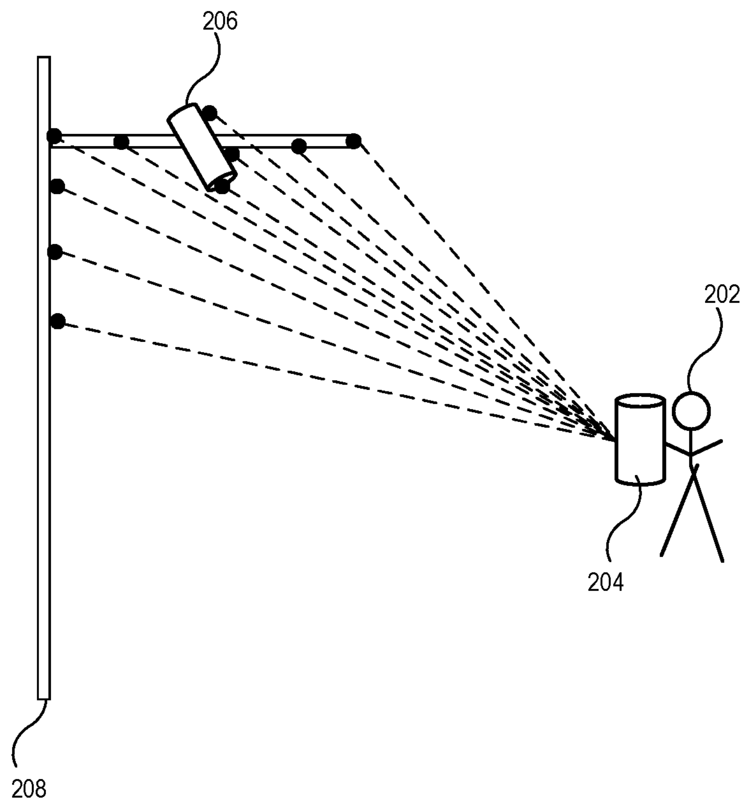


FIG. 2

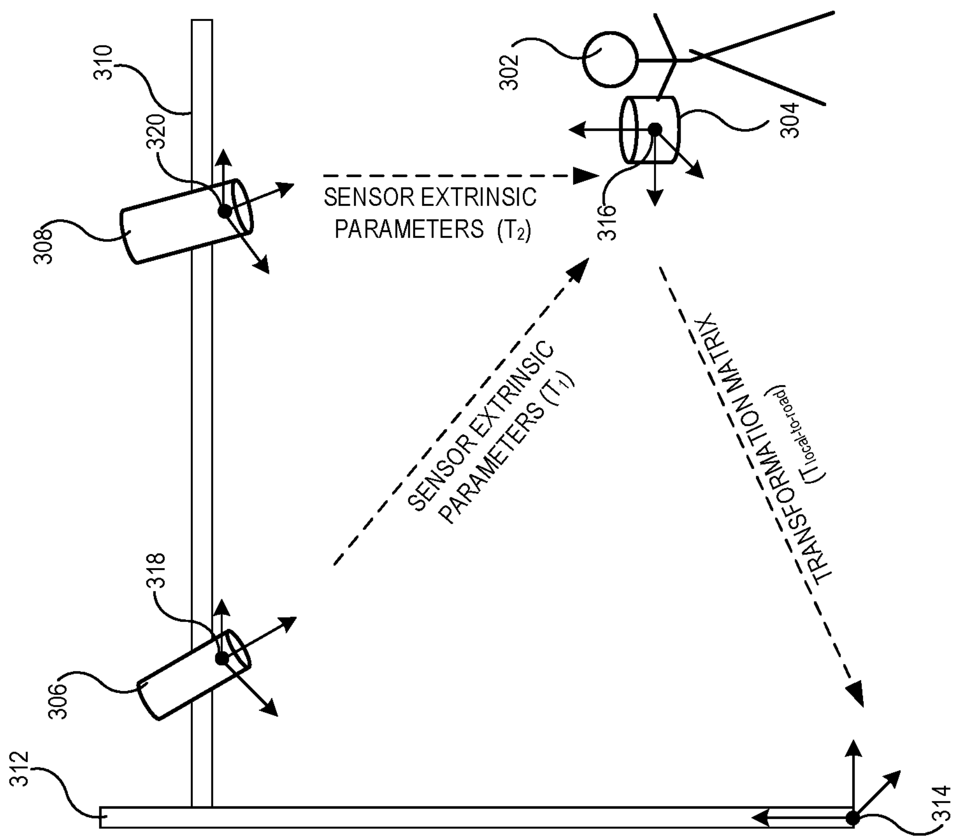

310
320
308
SENSOR EXTRINSIC PARAMETERS (T_2)
302
304
316
SENSOR EXTRINSIC PARAMETERS (T_1)
TRANSFORMATION MATRIX ($T_{local\text{-}to\text{-}road}$)
318
306
312
314

FIG. 3

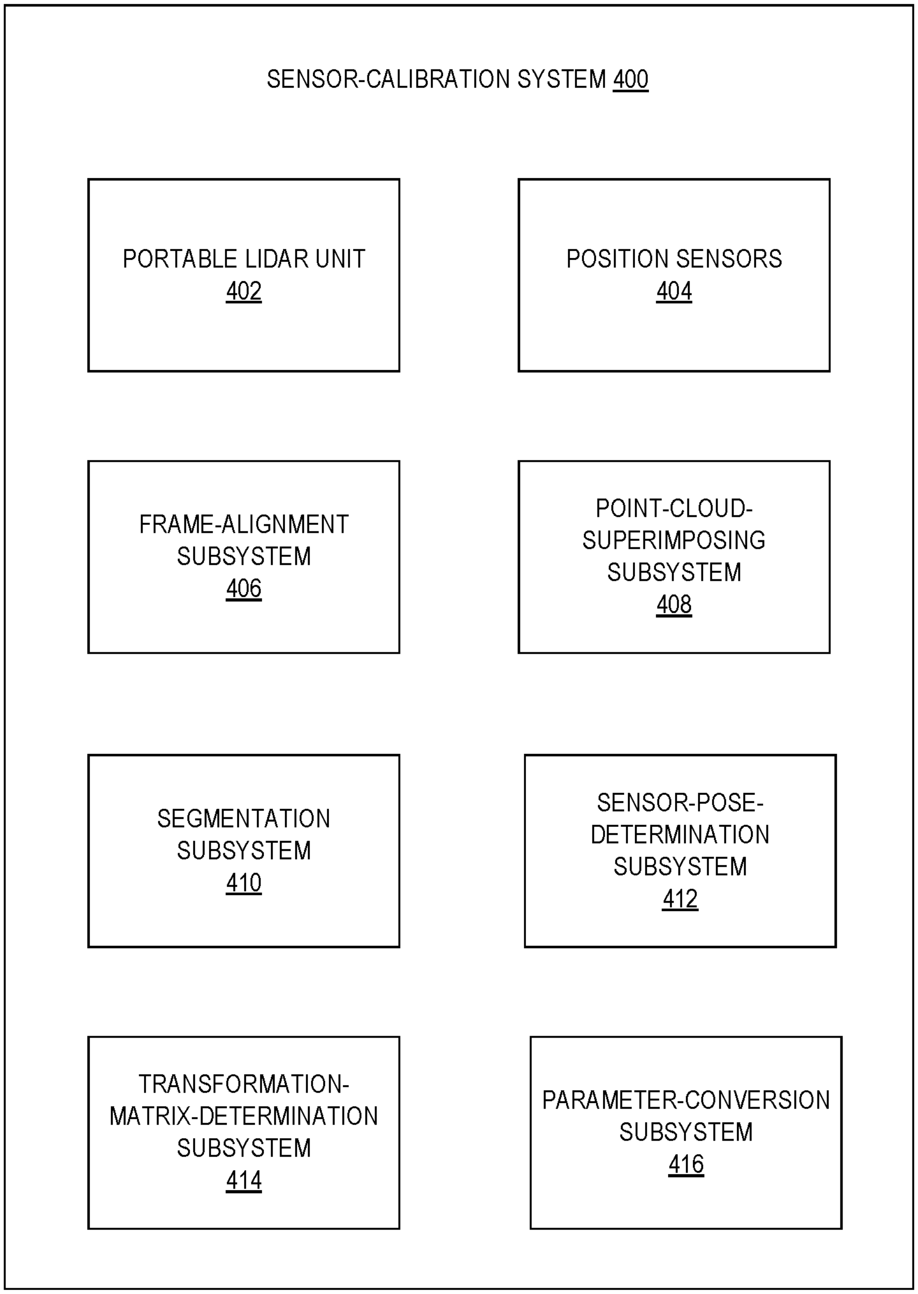

SENSOR-CALIBRATION SYSTEM 400
PORTABLE LIDAR UNIT 402
POSITION SENSORS 404
FRAME-ALIGNMENT SUBSYSTEM 406
POINT-CLOUD-SUPERIMPOSING SUBSYSTEM 408
SEGMENTATION SUBSYSTEM 410
SENSOR-POSE-DETERMINATION SUBSYSTEM 412
TRANSFORMATION-MATRIX-DETERMINATION SUBSYSTEM 414
PARAMETER-CONVERSION SUBSYSTEM 416

FIG. 4

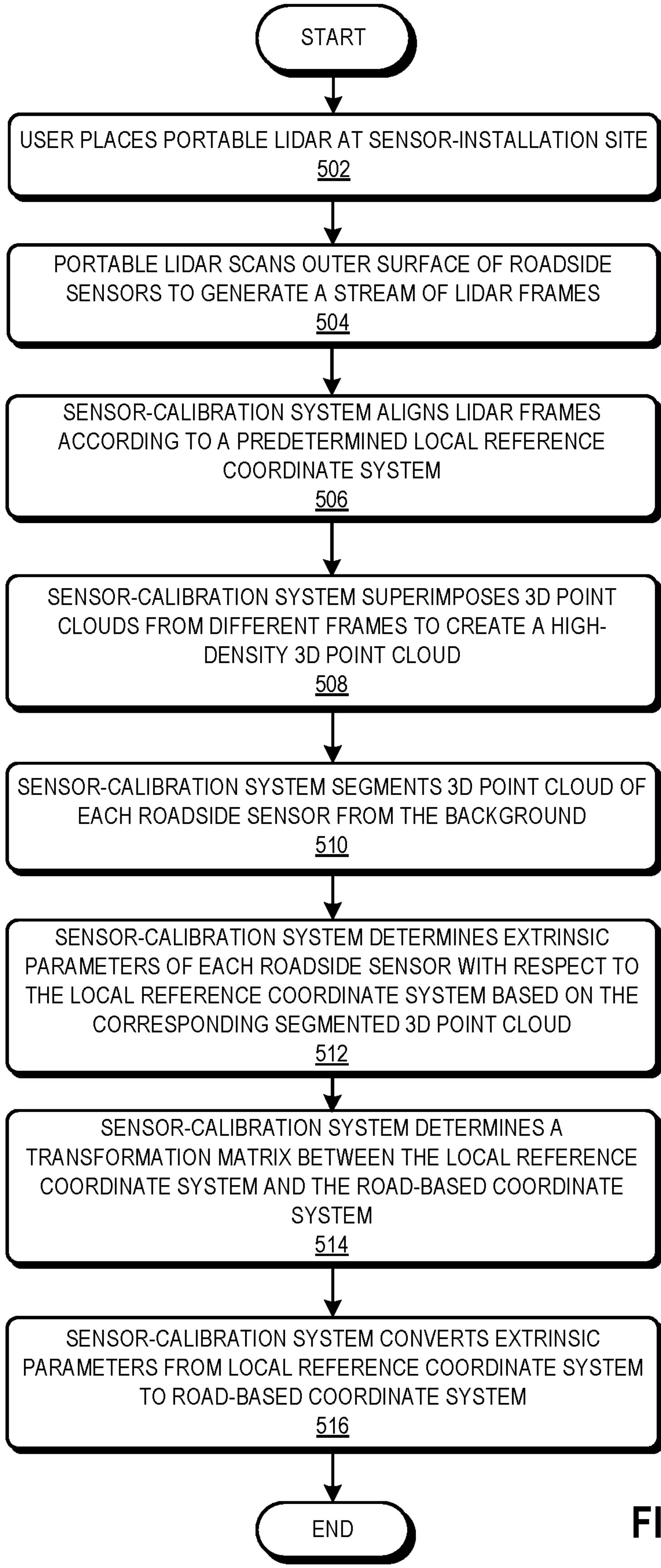

START
USER PLACES PORTABLE LIDAR AT SENSOR-INSTALLATION SITE 502
PORTABLE LIDAR SCANS OUTER SURFACE OF ROADSIDE SENSORS TO GENERATE A STREAM OF LIDAR FRAMES 504
SENSOR-CALIBRATION SYSTEM ALIGNS LIDAR FRAMES ACCORDING TO A PREDETERMINED LOCAL REFERENCE COORDINATE SYSTEM 506
SENSOR-CALIBRATION SYSTEM SUPERIMPOSES 3D POINT CLOUDS FROM DIFFERENT FRAMES TO CREATE A HIGH-DENSITY 3D POINT CLOUD 508
SENSOR-CALIBRATION SYSTEM SEGMENTS 3D POINT CLOUD OF EACH ROADSIDE SENSOR FROM THE BACKGROUND 510
SENSOR-CALIBRATION SYSTEM DETERMINES EXTRINSIC PARAMETERS OF EACH ROADSIDE SENSOR WITH RESPECT TO THE LOCAL REFERENCE COORDINATE SYSTEM BASED ON THE CORRESPONDING SEGMENTED 3D POINT CLOUD 512
SENSOR-CALIBRATION SYSTEM DETERMINES A TRANSFORMATION MATRIX BETWEEN THE LOCAL REFERENCE COORDINATE SYSTEM AND THE ROAD-BASED COORDINATE SYSTEM 514
SENSOR-CALIBRATION SYSTEM CONVERTS EXTRINSIC PARAMETERS FROM LOCAL REFERENCE COORDINATE SYSTEM TO ROAD-BASED COORDINATE SYSTEM 516
END

FIG. 5

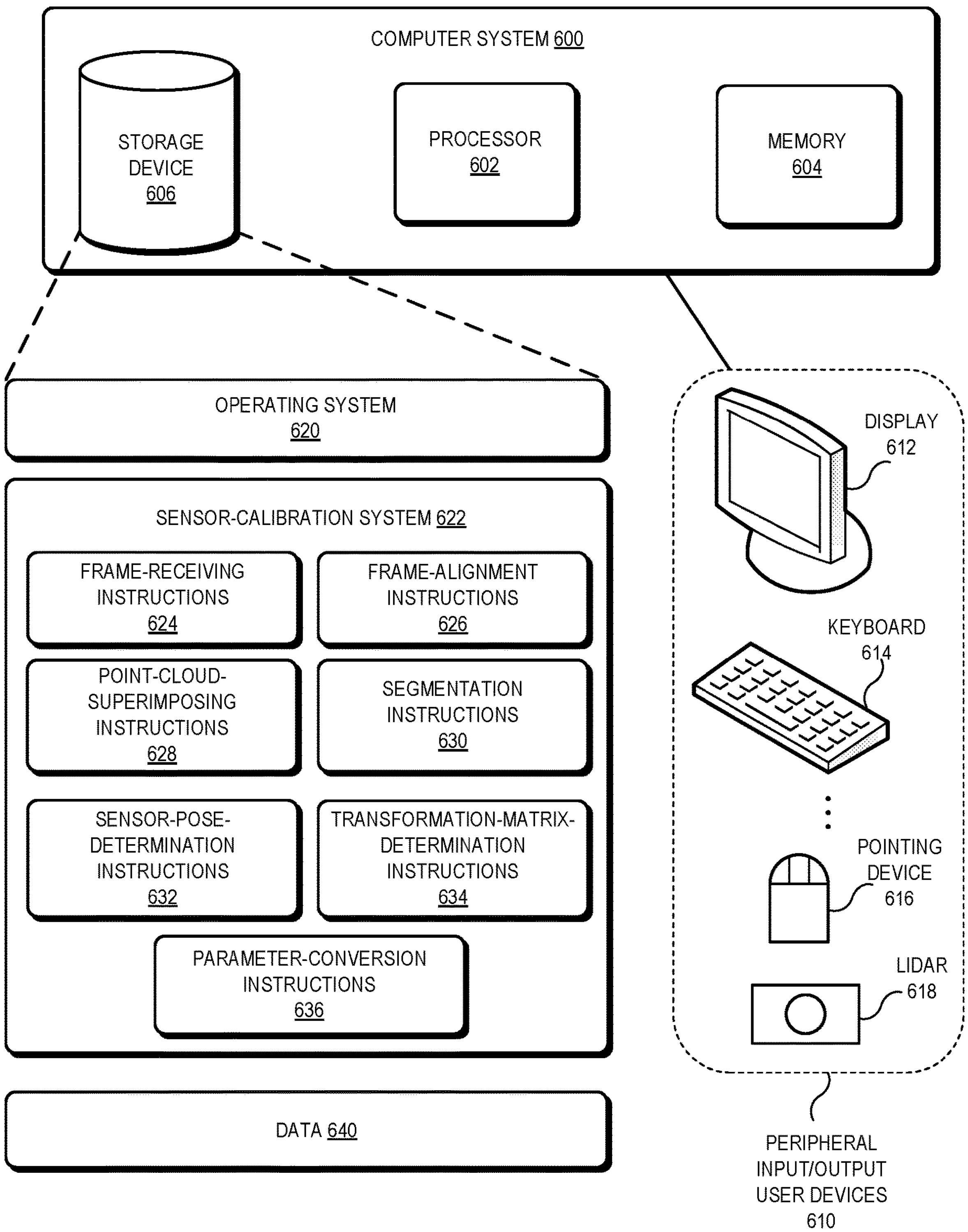

COMPUTER SYSTEM 600
STORAGE DEVICE 606
PROCESSOR 602
MEMORY 604
OPERATING SYSTEM 620
SENSOR-CALIBRATION SYSTEM 622
FRAME-RECEIVING INSTRUCTIONS 624
FRAME-ALIGNMENT INSTRUCTIONS 626
POINT-CLOUD-SUPERIMPOSING INSTRUCTIONS 628
SEGMENTATION INSTRUCTIONS 630
SENSOR-POSE-DETERMINATION INSTRUCTIONS 632
TRANSFORMATION-MATRIX-DETERMINATION INSTRUCTIONS 634
PARAMETER-CONVERSION INSTRUCTIONS 636
DATA 640
DISPLAY 612
KEYBOARD 614
POINTING DEVICE 616
LIDAR 618
PERIPHERAL INPUT/OUTPUT USER DEVICES 610

FIG. 6

SYSTEM AND METHOD FOR REMOTE NON-CONTACT CALIBRATION OF ROADSIDE SENSORS

BACKGROUND

Field

[0001] The disclosed embodiments generally relate to autonomous driving. More specifically, the disclosed embodiments relate to efficient and non-contact calibration of roadside sensors.

Related Art

[0002] The success of autonomous driving depends largely on a vehicle's ability to collect and process massive traffic states, including its states (e.g., direction and speed) and the states of other objects surrounding the vehicle. The dynamic nature of the spatial-temporal characteristics of the traffic states and the constrained perception range of the vehicle often hinder the vehicle's ability to collect state information about traffic scenes. Moreover, on-vehicle sensors can have their limitations (e.g., being occluded).

[0003] Roadside sensors have been used to extend the data collection ability of on-vehicle sensors. For example, sensors mounted on roadside traffic structures (e.g., light posts or traffic lights) often have an unobstructed view of the road and can be more effective in collecting traffic states. Various multi-sensor fusion strategies have been proposed to combine data collected by roadside sensors with data collected by on-vehicle sensors. Because raw sensor data are typically based on the coordinate systems respective of the individual sensors, combining or fusing data from different sensors requires a transformation of raw sensor data into a unified coordinate system. Moreover, processing and analyzing the sensor data for autonomous driving purposes are often centered around the road. Therefore, it is important to transform all raw sensor data from their respective sensor-based coordinate systems to the road-based coordinate system. Traditional calibration methods used to establish mappings between sensor-based coordinate systems and the road-based coordinate system are often inadequate for autonomous driving applications that deploy a large number of roadside sensors.

SUMMARY

[0004] Embodiments of this disclosure can provide a system and method for calibrating extrinsic parameters of roadside sensors for autonomous driving. During operation, a portable light-detection-and-ranging (lidar) unit can be brought to a sensor-installation site comprising one or more to-be-calibrated roadside sensors, and the portable lidar unit can scan outer surfaces of the to-be-calibrated roadside sensors from different angles to generate a stream of frames. The system can align, spatially, the stream of frames based on a local reference coordinate system, superimpose the aligned frames, and segment, from the superimposed frames, a point cloud associated with a to-be-calibrated roadside sensor. The system can determine extrinsic parameters of the to-be-calibrated roadside sensor with respect to the local reference coordinate system based on the segmented point cloud and then convert the extrinsic parameters from the local reference coordinate system to a road-based coordinate system.

[0005] In a variation on this embodiment, aligning the stream of frames can include applying an Iterative Closest Point (ICP) algorithm.

[0006] In a variation on this embodiment, the portable lidar unit can further include one or more position sensors. Aligning the stream of frames can include determining an instant pose of the portable lidar unit associated with each frame of the stream of frames based on measurements of the position sensors.

[0007] In a further variation, the local reference coordinate system can be determined based on the instant pose of the portable lidar unit associated with a first frame of the stream of frames.

[0008] In a further variation, the position sensors comprise one or more of: a Global Positioning System (GPS) sensor; an Inertial Measurement Unit (IMU); and a rotary encoder.

[0009] In a variation on this embodiment, the system can determine a transformation matrix between the local reference coordinate system and the road-based coordinate system.

[0010] In a further variation, converting the extrinsic parameters from the local reference coordinate system to the road-based coordinate system comprises multiplying the extrinsic parameters with the transformation matrix.

[0011] In a variation on this embodiment, the portable lidar unit can be configured to scan, in each frame, at least two reference objects with distinctive features, and aligning, spatially, the stream of frames can include aligning the reference objects.

[0012] In a variation on this embodiment, determining the extrinsic parameters of the to-be-calibrated roadside sensor can include comparing the segmented point cloud with a computer-aided design (CAD) model of the roadside sensor or a point cloud of the roadside sensor obtained by scanning the roadside sensor prior to installation.

[0013] In a variation on this embodiment, aligning, spatially, the stream of frames can include removing transitory objects from each frame.

DESCRIPTION OF THE FIGURES

[0014] FIG. **1** illustrates an exemplary multi-sensor data-collection system, according to one embodiment of the instant application.

[0015] FIG. **2** illustrates an exemplary scenario for calibrating a roadside sensor, according to one embodiment of the instant application.

[0016] FIG. **3** illustrates an exemplary scenario for calibrating multiple roadside sensors, according to one embodiment of the instant application.

[0017] FIG. **4** illustrates an exemplary block diagram of a sensor-calibration system, according to one embodiment of the instant application.

[0018] FIG. **5** presents a flowchart illustrating an exemplary sensor-calibration process, according to one embodiment of the instant application.

[0019] FIG. **6** illustrates an exemplary computer system that facilitates the sensor calibration operation, according to one embodiment of the instant application.

[0020] In the figures, like reference numerals refer to the same figure elements.

DETAILED DESCRIPTION

[0021] The following description is presented to enable any person skilled in the art to make and use the disclosed embodiments and is provided in the context of one or more particular applications and their requirements. Various modifications to the disclosed embodiments will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the scope of those that are disclosed. Thus, the present invention or inventions are not intended to be limited to the embodiments shown, but rather are to be accorded the widest scope consistent with the disclosure.

Overview

[0022] Embodiments of this disclosure provide a system and method for determining poses (i.e., the extrinsic parameters) of roadside sensors using a non-contact technique. To facilitate the efficient and accurate calibration of roadside sensors, a sensor-calibration system can include a portable light detection and ranging (lidar) unit (or lidar for short) that can scan the exterior of roadside sensors to obtain multiple lidar frames. The multiple lidar frames can be aligned in the spatial domain and superimposed to obtain a high-precision three-dimensional (3D) point cloud of each to-be-calibrated roadside sensor. The pose (or extrinsic parameters) of a roadside sensor in a lidar-based coordinate system can then be determined based on known dimensions of the roadside sensor. Given that the pose of the lidar in the road-based coordinate system is known, a transformation matrix between the lidar-based coordinate system and the road-based coordinate system can be derived. Accordingly, the previously obtained extrinsic parameters of the roadside sensor can be converted from the lidar-based coordinate system and the road-based coordinate system, thus facilitating the calibration of the roadside sensor. Once the extrinsic parameters of a roadside sensor are calibrated, raw sensor data collected by the roadside sensor can be converted to the road-based coordinate system.

Roadside-Sensor Calibration

[0023] FIG. **1** illustrates an exemplary multi-sensor data-collection system, according to one embodiment of the instant application. In FIG. **1**, a multi-sensor data-collection system **100** can include a vehicle **102** driving on a road and roadside sensors **104** and **106** mounted on a permanent traffic structure **108**.

[0024] Vehicle **102** can be equipped with various types of sensors, such as visible-light cameras, infrared cameras, radars, lidar units, Global Positioning System (GPS) sensors, Inertial Measurement Unit (IMU) modules, sound sensors, etc. Roadside sensors **104** and **106** can include similar types of sensors.

[0025] Each sensor, regardless of an on-vehicle or roadside sensor, can collect data (e.g., traffic states) regarding its surroundings, which can include another vehicle **110** and a pedestrian **112**. The raw sensor data are inherently expressed in the coordinate system centered at the corresponding sensor. For example, data collected by a sensor (e.g., a camera or a lidar unit) on vehicle **102** can be expressed in the vehicle coordinate system, the origin of which can be anchored to a fixed point on vehicle **102**. On the other hand, data collected by roadside sensor **104** or **106** can be represented in a corresponding roadside-sensor-based coordinate system anchored to sensor **104** or **106**, respectively.

[0026] Combining data from the various sensors requires that raw sensor data captured by the different sensors be represented using the same coordinate system. Because various tasks involved in autonomous driving (e.g., path planning, localization, mapping, obstacle detection, etc.) often require analyzing data in the road-based coordinate system (e.g., coordinate system **114** shown in FIG. **1**), it makes sense to convert raw sensor data from different sensors from their respective sensor-based coordinate systems to the road-based coordinate system. In the example shown in FIG. **1**, the origin of road-based coordinate system **114** can be placed at the base of traffic structure **108**, with the x-axis being along the direction of the road, the y-axis being perpendicular to the road, and the z-axis being the vertical axis. There can be other ways to define the road-based coordinate system.

[0027] The conversion of the raw roadside sensor data from the roadside-sensor-based coordinate system to the road-based coordinate system requires the knowledge of the extrinsic parameters of the roadside sensor that define the pose (position and orientation) of the sensor. The process for determining such extrinsic parameters can be referred to as calibration.

[0028] Some existing calibration techniques often rely on using instruments, such as real-time kinematic positioning (RTK) GPS, to measure the installation positions/orientations of roadside sensors (e.g., cameras, lidars, or millimeter-wave radars). Such approaches require expensive survey-grade equipment and can only determine the position/orientation of one sensor at a time. The measurement process can be time-consuming and may sometimes require temporary road closures. Certain calibration approaches also require high-elevation construction lifts, meaning that additional measures must be taken to ensure the safety of the measurement personnel. Some other existing calibration methods may rely on additional data (e.g., high-resolution maps) and auxiliary equipment (e.g., calibration boards, calibration target vehicles with RTK GPS, drones that can capture images, etc.) to perform joint calibration, which cannot be applied to non-camera sensors (e.g., thermal cameras, radars, lidars, etc.) and cameras with nonpublic data. Moreover, existing approaches are generally not suitable for calibrating a large number of sensors.

[0029] To overcome the shortcomings of existing calibration approaches, some embodiments of the instant application provide a system and method that can calibrate roadside sensors in an efficient and non-contact manner, making it an ideal candidate for autonomous driving applications.

[0030] FIG. **2** illustrates an exemplary scenario for calibrating a roadside sensor, according to one embodiment of the instant application. In FIG. **2**, a user **202** carrying a portable lidar unit **204** is approaching a roadside sensor **206** mounted on a permanent traffic structure (e.g., a light post) **208**. User **202** can use portable lidar unit **204** to perform a continuous scan of the scene that comprises roadside sensor **206** and its surroundings. For example, user **202** can aim portable lidar unit **204** at roadside sensor **206** and manipulate it in a way such that the laser beam of portable lidar unit **204** can repeatedly sweep over the exterior (e.g., the outer shell) of road sensor **206** (e.g., from left to right or from top to bottom). To increase the calibration accuracy, one should make sure that the laser beam can scan as much surface as possible to achieve a high-density 3D point cloud. In one example, portable lidar unit **204** can generate a stream of lidar frames comprising at least ten lidar frames, with each frame containing a point cloud corresponding to roadside sensor **206**.

[0031] In some embodiments, to achieve a high-density point cloud for roadside sensor **206**, one can superimpose multiple lidar frames, with each frame comprising a point cloud of roadside sensor **206**. However, the pose of portable lidar unit **204** changes as it scans the surface of roadside sensor **206**, meaning that the lidar frames are generated based on different coordinate systems, and the point clouds in different lidar frames are misaligned spatially. More specifically, each lidar frame can be generated based on the instant lidar-based coordinate system (i.e., the distance vectors are defined with respect to the instant lidar-based coordinate system). Before the lidar frames can be superimposed, they should be aligned in the spatial domain. In some embodiments, aligning the lidar frames in the spatial domain can include converting all lidar frames to the same coordinate system.

[0032] Various techniques can be used to align the lidar frames defined under different coordinate systems. In some embodiments, lidar frames, including the point clouds in the lidar frames, can be aligned using an iterative closest point (ICP) algorithm. To ensure the alignment accuracy, in some embodiments, each lidar frame captured by portable lidar unit **204** should include multiple reference objects. Each reference object can have a distinct easy-to-recognize feature. Large cylindrical objects (e.g., utility poles or light posts) are good examples of reference objects. Moreover, each lidar frame can also include the ground as a reference plane. For example, two lidar frames can be aligned by aligning the reference objects and ground in one frame with the corresponding reference objects and ground in another frame.

[0033] In alternative embodiments, a local reference coordinate system can be determined, and all lidar frames captured by portable lidar unit **204** can be converted to the local reference coordinate system. The local reference coordinate system can be determined arbitrarily. In one example, the local reference coordinate system can be chosen as the lidar-based coordinate system corresponding to the first frame in the stream of frames. In other words, the local reference coordinate system can be determined based on the instant pose of portable lidar unit **204** when it captures the first lidar frame. For example, the origin of the local reference coordinate system can be the location of a predetermined point on portable lidar unit **204** at that time instant, and an axis of the local reference coordinate system can be in the direction the optical axis of portable lidar unit **204** at that time instant. In some embodiments, portable lidar unit **204** can include a number of built-in location sensors, including but not limited to an RTK GPS, an IMU, a rotary encoder, etc. In such a scenario, the lidar frames can be aligned based on sensor data from the various location sensors. For example, the instant pose of portable lidar unit **204** at a given time instant with respect to the local reference coordinate system can be determined based on the location sensor data, and the corresponding frame captured at the given time instant can then be converted to the local reference coordinate system based on the instant pose.

[0034] After the lidar frames or point clouds have been converted to the local reference coordinate system, they can be superimposed onto each other to create a high-density point cloud of the scene. The number of data points on a particular surface of roadside sensor **206** can increase when lidar frames captured from different angles are superimposed.

[0035] A segmentation operation can be performed on the aligned and superimposed lidar frames to distinguish a point cloud of roadside sensor **206** from its surroundings. Ideally, the outer shell of roadside sensor **206** can be made of a high-reflective material such as metal or glass. More specifically, the reflective index corresponding to the lidar wavelength of the outer shell of roadside sensor **206** can be higher than its surrounding objects (e.g., light post **208**). This way, the segmentation of the point cloud for roadside sensor **206** from its surroundings can be relatively easy. Various techniques can be used for the segmentation task. In some embodiments, a deep-learning neural network can be trained to perform the segmentation task.

[0036] In most cases, the dimensions and shape of roadside sensor **206** are known. Therefore, one can determine the pose of roadside sensor **206** in the local reference coordinate system by comparing the segmented 3D point cloud of roadside sensor **206** with its known dimensions and shape. For example, the accurate pose of roadside sensor **206** in the local reference coordinate system can be determined by matching points in the 3D point cloud to surface points of a known computer-aided design (CAD) model of roadside sensor **206**. In another example, a 3D scan of roadside sensor **206** can be performed before it is installed to generate a known 3D model (e.g., a point cloud) of roadside sensor **206**.

[0037] As discussed previously, the local reference coordinate system can be the lidar-based coordinate system that corresponds to the pose of portable lidar unit **204** at the time instance it captures a certain frame (e.g., the first frame). In some embodiments, portable lidar unit **204** can be associated with a number of position sensors, including but not limited to an RTK GPS, an IMU, a rotary encoder, etc. For example, one or more position sensors can be integrated into portable lidar unit **204**, or they can be included in the same enclosure with their relative positions/orientations predetermined. The pose of portable lidar unit **204** in the road-based coordinate system at a particular time instant can be determined based on data from the various position sensors at that time instant. For example, given a particular time instant (e.g., the instant it captures the first frame), the RTK GPS in portable lidar unit **204** can provide precise geographic location information, and the IMU or rotary encoder can provide information regarding the orientation of portable lidar unit **204**.

[0038] Once the pose of portable lidar unit **204** is determined, a transformation matrix between the lidar-based coordinate system and the road-based coordinate system can be computed to transform the pose of roadside sensor **206** from the local reference coordinate system to the road-based coordinate system. Therefore, the extrinsic parameters of roadside sensor **206** with respect to the road-based coordinate system can be obtained, and the calibration of roadside sensor **206** is completed.

[0039] In the example shown in FIG. **2**, portable lidar unit **204** is held by user **202**. User **202** can walk around an intersection where one or more roadside sensors are located and use portable lidar unit **204** to scan the roadside sensors and their surroundings. In practice, it is also possible to mount a lidar unit on a vehicle (e.g., a specially designed data-collection vehicle). As the vehicle drives through the intersection, the lidar unit can scan the roadside sensors and their surroundings. When there are multiple to-be-calibrated roadside sensors in an intersection, it is preferable that the lidar scan (which can generate a continuous stream of lidar frames) cover the outer surface of all sensors. In addition, at any given time instant, the lidar frame should include at least two reference objects (e.g., a post and a cantilever attached to the post) along with the ground, thus allowing efficient and accurate alignment and stitching of point clouds from different lidar frames. The pose of each individual roadside sensor can then be determined based on the corresponding point cloud. For example, after the alignment of all lidar frames in a stream, the point cloud of each roadside sensor can be segmented to distinguish it from the background. The point cloud of a particular sensor can then be compared with its known shape and dimensions (or a known CAD or pre-scanned model) to obtain the pose of the particular sensor with respect to the local reference coordinate system.

[0040] FIG. **3** illustrates an exemplary scenario for calibrating multiple roadside sensors, according to one embodiment of the instant application. In FIG. **3**, a user **302** carrying a portable lidar unit **304** is approaching a sensor installation site (e.g., an intersection) with roadside sensors **306** and **308** mounted on a cantilever **310** attached to a light post **312**. Roadside sensors **306** and **308** can be any type of sensor that can collect traffic data, including but not limited to visible-light cameras, infrared cameras, radars, lidar units, Global Positioning System (GPS) sensors, Inertial Measurement Unit (IMU) modules, sound sensors, etc.

[0041] While at the intersection, user **302** can aim portable lidar unit **304** at roadside sensors **306** and **308** to capture a stream of lidar frames. To calibrate all sensors in the intersection, portable lidar unit **304** should scan the outer surfaces of all sensors to include all sensors in the stream of lidar frames. More specifically, while performing the scan, user **302** should make sure that the laser beam(s) within portable lidar unit **304** can be shone upon as much outer surface of each sensor as possible. Moreover, to facilitate accurate frame alignment, each lidar scan (or frame) should include at least two reference objects and the ground. In the example shown in FIG. **3**, each lidar frame should include both light post **312** and cantilever **310**.

[0042] FIG. **3** also shows the various coordinate systems involved in multi-sensor data collection, including a road-based coordinate system **314**, a lidar-based coordinate system **316**, a first roadside-sensor-based coordinate system **318** (which is based on roadside sensor **306**), and a second roadside-sensor-based coordinate system **320** (which is based on roadside sensor **308**). In this example, the origin of road-based coordinate system **314** can be placed at the base of light post **312**. In one example, the x-y plane of road-based coordinate system **314** can be the road surface with the x-axis along the road direction. The z-axis can point up from the ground. The origin of lidar-based coordinate system **316** can be anchored at a fixed point (e.g., the optical center) on portable lidar unit **304**, and the z-axis can be along the optical axis of portable lidar unit **304**. Similarly, the origin of a roadside-sensor-based coordinate system (e.g., coordinate system **318** or **320**) can be anchored at a fixed point on the corresponding roadside sensor, and the z-axis can be along the optical axis of the corresponding roadside sensor.

[0043] Road-based coordinate system **314** can be an absolute, time-invariant coordinate system, and all sensor data should be converted into road-based coordinate system **314** such that they can be combined or fused. Because the pose of each roadside sensor remains unchanged with respect to road-based coordinate system **314**, the roadside-sensor-based coordinate systems are also considered as time-invariant coordinate systems. Data collected by each roadside sensor (e.g., distance vectors) are represented according to the corresponding coordinate system. For example, data collected by roadside sensor **306** can be represented using values within coordinate system **318**, and data collected by roadside sensor **308** can be represented using values within coordinate system **320**.

[0044] On the other hand, lidar-based coordinate system **316** can be dynamic with respect to road-based coordinate system **314**, as the pose of portable lidar unit **304** changes when it scans roadside sensors **306** and **308** from different angles. In some embodiments, a local reference coordinate system can be defined based on lidar-based coordinate system **316**. In one example, the local reference coordinate system can be defined based on an initial pose (or the pose when it captures the first frame) of portable lidar unit **304** with respect to road-based coordinate system **314**. Because the local reference coordinate system is defined based on the pose of portable lidar unit **304** at a particular time instant, it is also time-invariant with respect to road-based coordinate system **314**. For simplicity of illustration, lidar-based coordinate system **316** in FIG. **3** can also represent the local reference coordinate system.

[0045] Converting data collected by a roadside sensor to road-based coordinate system **314** often requires the knowledge of the extrinsic parameters (or pose) of the roadside sensor with respect to road-based coordinate system **314**. However, such knowledge is not readily available. In some embodiments, one can first determine the extrinsic parameters of a roadside sensor with respect to local reference coordinate system **316**. To do so, lidar frames that contain the roadside sensor and are captured by portable lidar unit **304** can be aligned according to local reference coordinate system **316** to obtain a high-density point cloud of the scene. Subsequently, the point cloud corresponding to the particular roadside sensor can be segmented, and the local pose (i.e., the pose with respect to local reference coordinate system **316**) of the roadside sensor can be determined based on the segmented point cloud. The extrinsic parameters of the roadside sensor with respect to the local reference coordinate system (or the local extrinsic parameters) can be denoted $T_{sensor\text{-}to\text{-}local}$. In the example shown in FIG. **3**, the local extrinsic parameters of roadside sensor **306** are denoted T_1, and the local extrinsic parameters of roadside sensor **308** are denoted T_2.

[0046] A transformation matrix between local reference coordinate system **316** and road-based coordinate system **314** can be derived based on the spatial relationship between portable lidar **304** and the road. Note that portable lidar unit **304** can be equipped with a number of position sensors, such as an RTK GPS, an IMU, a rotary encoder, etc. The pose of portable lidar unit **304** with respect to road-based coordinate system **314** can be determined based on the outputs of those position sensors. In one example, local reference coordinate system **316** corresponds to the initial pose of portable lidar unit **304**, which can be determined based on the output of the position sensors at the corresponding time instant. For example, those position sensors can provide the exact location of a predetermined point on portable lidar unit **394**, which can be the origin of local reference coordinate system **316**. Given the initial pose of portable lidar unit **304**, the transformation matrix (denoted $T_{local\text{-}to\text{-}road}$) between local reference coordinate system **316** and road-based coordinate system **314** can be computed. Given the transformation matrix, a vector in the local reference coordinate system (denoted $\vec{V}_{local}$) can be converted to a vector in the road-based coordinate system (denoted $\vec{V}_{road}$) according to $\vec{V}_{road}=T_{local\text{-}to\text{-}road}\vec{V}_{local}$.

[0047] The pose (or the extrinsic parameters) of a roadside sensor with respect to road-based coordinate system **314** can then be computed based on the transformation matrix $T_{local\text{-}to\text{-}road}$ More specifically, the extrinsic parameters of a roadside sensor can be computed as $T_{sensor}=T_{sensor\text{-}to\text{-}local}\times T_{local\text{-}to\text{-}road}$. In the example shown in FIG. **3**, the sensor-to-local extrinsic parameters of roadside sensor **306** can be computed as $T_1\times T_{local\text{-}to\text{-}sensor}$, and the extrinsic parameters of roadside sensor **306** can be computed as $T_2\times T_{local\text{-}to\text{-}sensor}$.

[0048] FIG. **4** illustrates an exemplary block diagram of a sensor-calibration system, according to one embodiment of the instant application. Sensor-calibration system **400** can include a portable lidar unit **402**, a number of position sensors **404**, a frame-alignment subsystem **406**, a point-cloud-superimposing subsystem **408**, a segmentation subsystem **410**, a sensor-pose-determination subsystem **412**, a transformation-matrix-determination subsystem **414**, and a parameter-conversion subsystem **416**.

[0049] Portable lidar unit **402** can be carried by a human user or a data-collection vehicle. Portable lidar unit **402** can be configured to scan a scene (e.g., an intersection) comprising one or more roadside sensors. More specifically, portable lidar unit **402** can be configured to scan the scene from different angles to ensure that the outer surface of each roadside sensor can be sufficiently covered by the scans. For higher-up sensors (e.g., sensors mounted on top of a light post), portable lidar unit **402** may not be able to scan the entire outer surface of a sensor but should scan as much surface area as possible.

[0050] Position sensors **404** can include but are not limited to an RTK GPS, an IMU, a rotary encoder, etc. Position sensors **404** can provide precise pose information (e.g., location and orientation) about portable lidar unit **402**. For example, the RTK GPS can provide location information, and the IMU can provide orientation information. In some embodiments, position sensors **404** can be integrated within portable lidar unit **402**. In some embodiments, position sensors **404** can be standalone sensors placed within the same physical enclosure with portable lidar unit **402**.

[0051] Frame-alignment subsystem **406** can be responsible for aligning the frames in the stream of frames captured by portable lidar unit **402** to allow the superimposition of point clouds in the frames. In some embodiments, frame-alignment subsystem **406** can apply the ICP algorithm to align the frames. In one example, one can use the ICP algorithm to align two adjacent claims. More specifically, starting from the last frame, the frames in the stream can be aligned one by one until all frames are aligned according to the first frame. Including reference objects with distinctive features (e.g., post **312** and cantilever **310** shown in FIG. **3**) and the ground can increase the accuracy in frame alignment. In alternative embodiments, frame-alignment subsystem **406** can align the frames according to a local reference coordinate system. The local reference coordinate system can be determined based on the pose of portable lidar unit **402** at a predetermined time instant (e.g., the time instant it captures the first frame). To improve the alignment efficiency, in some embodiments, before aligning the frames, frame-alignment subsystem **406** can remove transitory objects (e.g., vehicles or pedestrians) from each frame.

[0052] Point-cloud-superimposing subsystem **408** can be responsible for superimposing the point clouds from the aligned frames to obtain a large high-density point cloud. For a large installation site with many roadside sensors at different locations, superimposing the frames can also include stitching the frames into a wide-view frame. Segmentation subsystem **410** can be responsible for segmenting the point cloud of each roadside sensor in the large frame. In some embodiments, segmentation subsystem **410** can apply a machine learning technique (e.g., by training a deep learning neural network) to perform the segmentation task. To ensure segmentation accuracy, the outer surface or cover of the roadside sensors can be made of a high-reflective material (e.g., metal or glass).

[0053] Sensor-pose-determination subsystem **412** can be responsible for determining the pose of each roadside sensor based on a corresponding segmented point cloud. In some embodiments, determining the pose of a roadside sensor can also include comparing the 3D point cloud of the roadside sensor with its known 3D CAD model or 3D point cloud obtained by scanning the sensor prior to its installation (referred to as a pre-scanned point cloud). For example, the pose of the CAD model can be manipulated to find a match between surface points on the CAD model and the segmented 3D point cloud. Similarly, the pose of the pre-scanned point cloud can be manipulated to match the pose of the segmented point cloud. The determined pose of the roadside sensor is with respect to the local reference coordinate system.

[0054] Transformation-matrix-determination subsystem **414** can be responsible for determining the transformation matrix between two coordinate systems. In some embodiments, transformation-matrix-determination subsystem **414** can compute a transformation matrix between the road-based coordinate system and the local reference coordinate system (i.e., $T_{local\text{-}to\text{-}road}$) based on the corresponding instant pose of the portable lidar in the road-based coordinate system. Note that the instant pose of the portable lidar can be determined based on the output from one or more position sensors associated with the portable lidar. Parameter-conversion subsystem **416** can be responsible for converting the extrinsic parameters (i.e., pose) of each roadside sensor from the local reference coordinate system to the roadside reference system based on a corresponding transformation matrix $T_{local\text{-}to\text{-}road}$. In some embodiments, the extrinsic parameters of a roadside sensor can be converted to the road-based coordinate system according to: $T_{sensor}=T_{sensor\text{-}to\text{-}local}\times T_{local\text{-}to\text{-}road}$.

[0055] The various subsystems included in FIG. **4** (e.g., subsystems **406**-**416**) can include any combination of hardware and software modules. In addition, the various subsystems can be integrated within the same computing entity (e.g., a standalone computer or a server) or can be distributed among multiple computing entities (e.g., multiple servers). In one example, the lidar frames can be sent to one computer for frame alignment and superimposing, and the point cloud segmentation can be performed by a different computer. When the portable lidar unit is carried by a data-collection vehicle, a computer installed on the data-collection vehicle can include all subsystems (e.g., subsystems **406**-**416**) needed for the sensor calibration.

[0056] FIG. **5** presents a flowchart illustrating an exemplary sensor-calibration process, according to one embodiment of the instant application. In one or more embodiments, one or more of the steps in FIG. **5** may be repeated and/or performed in a different order. Accordingly, the specific arrangement of steps shown in FIG. **5** should not be construed as limiting the scope of the technique.

[0057] During operation, a user can place a portable lidar at a sensor installation site (operation **502**). One or more roadside sensors can be installed at the sensor installation site. In some examples, roadside sensors can be installed at an intersection. In different examples, roadside sensors can be installed along a stretch of a road. The portable lidar unit can be handheld and carried by a human user who is on foot, or it can be an on-vehicle unit mounted on a data-collection vehicle parked or driven near the roadside sensors.

[0058] The portable lidar can scan the outer surface of the roadside sensors to generate a stream of lidar frames (operation **504**). To calibrate all roadside sensors in a particular installation site (e.g., an intersection or a stretch of a road), the portable lidar unit should scan all sensors and their surroundings. To ensure that a point cloud representing a roadside sensor can have a sufficient number of points, the portable lidar unit can scan the outer surface of the roadside sensor multiple times from different angles. Moreover, to facilitate subsequent frame alignment, in each scan or lidar frame, the portable lidar unit should capture at least two reference objects with large easy-to-recognize features. Examples of reference objects can include light posts, utility posts, cantilevers, etc.

[0059] The sensor-calibration system can align the lidar frames according to a predetermined local reference coordinate system (operation **506**). Various techniques can be applied. In one embodiment, the system can apply an ICP algorithm to align frames in different coordinate systems. In an alternative embodiment, the spatial relationship between different coordinate systems can be determined based on the output of position sensors associated with the portable lidar unit, and frames in the different coordinate systems can be aligned based on the determined spatial relationship. In some embodiments, transitory objects (e.g., vehicles or pedestrians) can be removed from the lidar frames to improve the alignment efficiency.

[0060] Subsequent to aligning the frames according to the local reference coordinate system, the sensor-calibration system can superimpose the 3D point clouds from the different frames to create a high-density 3D point cloud (operation **508**). The high-density 3D point cloud can represent the sensor installation site comprising the multiple roadside sensors. Data for the high-density point cloud is represented with respect to the local reference coordinate system. The sensor-calibration system can segment the 3D point cloud of each roadside sensor from the background (operation **510**). In some embodiments, multiple roadside sensors can be segmented simultaneously. A machine learning based approach (e.g., a deep-learning neural network) can be used to perform point-cloud segmentation.

[0061] The sensor-calibration system can then determine the extrinsic parameters (or pose) of each roadside sensor with respect to the local reference coordinate system based on the corresponding segmented 3D point cloud (operation **512**). In some embodiments, the 3D point cloud of a roadside sensor can be compared to its known shape and dimensions or known 3D models. In one example, the pose of a 3D CAD model of the roadside sensor can be manipulated to find a match between the surface points of the CAD model and points within the 3D point cloud. In another example, the pose of a pre-scanned point cloud of the roadside sensor can be manipulated to match the pose of the segmented 3D point cloud. The pose information includes both the position and orientation of the roadside sensor. Accordingly, the extrinsic parameters associated with each roadside sensor can be determined. Note that the extrinsic parameters can include a rotation vector $\vec{R}$ and a translation vector $\vec{t}$, and both rotation and translation vectors are with respect to the local reference coordinate system.

[0062] The sensor-calibration system can also determine a transformation matrix between the local reference coordinate system and the road-based coordinate system (operation **514**). In some embodiments, the transformation matrix can be determined based on the measured pose of the portable lidar unit. The sensor-calibration system converts the extrinsic parameters (e.g., rotation and translation vectors) from the local reference system to the road-based coordinate system (operation **516**). More specifically, the extrinsic parameters of each roadside sensor with respect to the local reference coordinate system can be converted to parameters with respect to the road-based coordinate system, thus completing the calibration process of the roadside sensors. The extrinsic parameters of each roadside sensor with respect to the road-based coordinate system can be output as the calibration result. The portable lidar unit can also be transported to the next sensor installation site to calibrate sensors there.

[0063] Compared with existing approaches to calibrating roadside sensors, the proposed solution does not require prior knowledge (e.g., location or orientation) of the roadside sensors and specialized equipment. Moreover, the calibration process will not cause interruption to traffic and can be performed by human operators in a relatively safe manner. To calibrate roadside sensors mounted high above, there is no need for a worker to stand on a high-elevation construction lift to perform manual calibration. Moreover, when there are multiple roadside sensors installed near each other, the multiple sensors can be calibrated simultaneously.

[0064] FIG. **6** illustrates an exemplary computer system that facilitates the sensor calibration operation, according to one embodiment of the instant application. Computer system **600** includes a processor **602**, a memory **604**, and a storage device **606**. Furthermore, computer system **600** can be coupled to peripheral input/output (I/O) user devices **610**, e.g., a display device **612**, a keyboard **614**, a pointing device **616**, and a portable lidar **618**. Storage device **606** can store an operating system **620**, a sensor-calibration system **622**, and data **640**. In some embodiments, computer system **600** can be implemented as part of the data-collection system for autonomous driving.

[0065] Sensor-calibration system **622** can include instructions, which when executed by computer system **600**, can cause computer system **600** or processor **602** to perform methods and/or processes described in this disclosure. Specifically, sensor-calibration system **622** can include instructions for receiving a stream of frames collected by a portable lidar unit (frame-receiving instructions **624**), instructions for aligning the lidar frames (frame-alignment instructions **626**), instructions for superimposing point clouds in the aligned frames (point-cloud-superimposing instructions **628**), instructions for segmenting point clouds corresponding to road-side sensors (segmentation instructions **630**), instructions for determining the pose (or extrinsic parameters) of each roadside sensor with respect to a local reference coordination system (sensor-pose-determination instructions **632**), instructions for determining a transformation matrix between the local reference coordinate system and the road-based coordinate system (transformation-matrix-determination instructions **634**), and instructions for converting the extrinsic parameters of each roadside sensor from the local reference coordinate system to the road-based coordinate system (parameter-conversion instructions **636**). Data **640** can include shape and dimension information about the roadside sensors.

[0066] This disclosure presents a solution to the problem associated with calibrating a large number of roadside sensors. The solution allows simultaneous calibration of multiple roadside sensors installed in the same site (e.g., a traffic intersection or a stretch of a road). To calibrate the sensors, a portable lidar unit can be brought to the sensor installation site to scan the multiple roadside sensors and generate a stream of frames. The frames can be aligned in the spatial domain according to a local reference coordinate system, and the aligned frames can be superimposed to generate a large high-density 3D point cloud. The 3D point cloud of each roadside sensor can be segmented from the large high-density 3D point cloud. The pose (or extrinsic parameters) of a to-be-calibrated roadside sensor with respect to a local reference coordinate system can be determined based on the corresponding segmented 3D point cloud. A transformation matrix between the local reference coordinate system and a road-based coordinate system can be computed, and the extrinsic parameters of the to-be-calibrated roadside sensor can be converted into the road-based coordinate system and outputted as the calibration result.

[0067] Data structures and program code described in this detailed description are typically stored on a non-transitory computer-readable storage medium, which may be any device or medium that can store code and/or data for use by a computer system. Non-transitory computer-readable storage media include, but are not limited to, volatile memory; non-volatile memory; electrical, magnetic, and optical storage devices, solid-state drives, and/or other non-transitory computer-readable media now known or later developed.

[0068] Methods and processes described in the detailed description can be embodied as code and/or data, which may be stored in a non-transitory computer-readable storage medium as described above. When a processor or computer system reads and executes the code and manipulates the data stored on the medium, the processor or computer system performs the methods and processes embodied as code and data structures and stored within the medium.

[0069] Furthermore, the optimized parameters from the methods and processes may be programmed into hardware modules such as, but not limited to, application-specific integrated circuit (ASIC) chips, field-programmable gate arrays (FPGAs), and other programmable-logic devices now known or hereafter developed. When such a hardware module is activated, it performs the methods and processes included within the module.

[0070] The foregoing embodiments have been presented for purposes of illustration and description only. They are not intended to be exhaustive or to limit this disclosure to the forms disclosed. Accordingly, many modifications and variations will be apparent to practitioners skilled in the art. The scope is defined by the appended claims, not the preceding disclosure.

What is claimed is:

1. A method for calibrating extrinsic parameters of road-side sensors for autonomous driving, the method comprising:

placing a portable light-detection-and-ranging (lidar) unit at a sensor-installation site comprising one or more to-be-calibrated roadside sensors;

scanning, by the portable lidar unit, outer surfaces of the to-be-calibrated roadside sensors from different angles to generate a stream of frames;

aligning, spatially, the stream of frames based on a local reference coordinate system;

superimposing the aligned frames;

segmenting, from the superimposed frames, a point cloud associated with a to-be-calibrated roadside sensor;

determining extrinsic parameters of the to-be-calibrated roadside sensor with respect to the local reference coordinate system based on the segmented point cloud; and

converting the extrinsic parameters from the local reference coordinate system to a road-based coordinate system.

2. The method of claim **1**, wherein aligning the stream of frames comprises applying an Iterative Closest Point (ICP) algorithm.

3. The method of claim **1**,

wherein the portable lidar unit further comprises one or more position sensors; and

wherein aligning the stream of frames comprises determining an instant pose of the portable lidar unit associated with each frame of the stream of frames based on measurements of the position sensors.

4. The method of claim **3**, wherein the local reference coordinate system is determined based on the instant pose of the portable lidar unit associated with a first frame of the stream of frames.

5. The method of claim **3**, wherein the position sensors comprise one or more of:

a Global Positioning System (GPS) sensor;

an Inertial Measurement Unit (IMU); and

a rotary encoder.

6. The method of claim **1**, further comprising determining a transformation matrix between the local reference coordinate system and road-based coordinate system.

7. The method of claim **6**, wherein converting the extrinsic parameters from the local reference coordinate system to the road-based coordinate system comprises multiplying the extrinsic parameters with the transformation matrix.

8. The method of claim **1**,

wherein the portable lidar unit is configured to scan, in each frame, at least two reference objects with distinctive features; and

wherein aligning, spatially, the stream of frames comprises aligning the reference objects.

9. The method of claim **1**, wherein determining the extrinsic parameters of the to-be-calibrated roadside sensor comprises comparing the segmented point cloud with a computer-aided design (CAD) model of the roadside sensor or a point cloud of the roadside sensor obtained by scanning the roadside sensor prior to installation.

10. The method of claim **1**, wherein aligning, spatially, the stream of frames further comprises removing transitory objects from each frame.

11. A system for calibrating extrinsic parameters of roadside sensors for autonomous driving, comprising:

a portable light-detection-and-ranging (lidar) unit to be brought to a sensor-installation site comprising one or more to-be-calibrated roadside sensors, wherein the portable lidar is configured to scan outer surfaces of the to-be-calibrated roadside sensors from different angles to generate a stream of frames;

a frame-alignment subsystem configured to align, spatially, the stream of frames based on a local reference coordinate system;

a frame-superimposing subsystem configured to superimpose the aligned frames;

a segmentation subsystem configured to segment, from the superimposed frames, a point cloud associated with a to-be-calibrated roadside sensor;

a sensor-pose determination subsystem to determine extrinsic parameters of the to-be-calibrated roadside sensor with respect to the local reference coordinate system based on the segmented point cloud; and

a parameter-conversion subsystem to convert the extrinsic parameters from the local reference coordinate system to a road-based coordinate system.

12. The system of claim **11**, wherein the frame-alignment subsystem is to apply an Iterative Closest Point (ICP) algorithm to align the stream of frames.

13. The system of claim **11**,

wherein the portable lidar unit further comprises one or more position sensors; and

wherein the frame-alignment subsystem is to determine an instant pose of the portable lidar unit associated with each frame of the stream of frames based on measurements of the position sensors.

14. The system of claim **13**, wherein the local reference coordinate system is determined based on the instant pose of the portable lidar unit associated with a first **2** frame of the stream of frames.

15. The system of claim **13**, wherein the position sensors comprise one or more of:

a Global Positioning System (GPS) sensor;

an Inertial Measurement Unit (IMU); and

a rotary encoder.

16. The system of claim **11**, further comprising a transformation-matrix-determination subsystem to determine a transformation matrix between the local reference coordinate system and road-based coordinate system.

17. The system of claim **16**, wherein the parameter-conversion subsystem is to convert the extrinsic parameters from the local reference coordinate system to the road-based coordinate system by multiplying the extrinsic parameters with the transformation matrix.

18. The system of claim **11**,

wherein the portable lidar unit is configured to scan, in each frame, at least two reference objects with distinctive features; and

wherein the frame-alignment subsystem is to align the reference objects while aligning the stream of frames comprises aligning.

19. The system of claim **11**, wherein the sensor-pose determination subsystem is to determine the extrinsic parameters of the to-be-calibrated roadside sensor by comparing the segmented point cloud with a computer-aided design (CAD) model of the roadside sensor or a point cloud of the roadside sensor obtained by scanning the roadside sensor prior to installation.

20. The system of claim **11**, wherein, while aligning the stream of frames, the frame-alignment subsystem is to remove transitory objects from each frame.

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