



US009221396B1

(12) **United States Patent**
Zhu et al.

(10) **Patent No.:** **US 9,221,396 B1**
(45) **Date of Patent:** **Dec. 29, 2015**

(54) **CROSS-VALIDATING SENSORS OF AN AUTONOMOUS VEHICLE**

(71) Applicant: **Google Inc.**, Mountain View, CA (US)

(72) Inventors: **Jiajun Zhu**, Sunnyvale, CA (US);
Dmitri A. Dolgov, Mountain View, CA (US); **Christopher Paul Urmson**,
Mountain View, CA (US)

(73) Assignee: **Google Inc.**, Mountain View, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 547 days.

(21) Appl. No.: **13/628,986**

(22) Filed: **Sep. 27, 2012**

(51) **Int. Cl.**
H04N 7/18 (2006.01)
B60R 1/00 (2006.01)

(52) **U.S. Cl.**
CPC . **B60R 1/00** (2013.01); **H04N 7/181** (2013.01)

(58) **Field of Classification Search**
USPC 348/148
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,214,408	A *	5/1993	Asayama	340/435
8,521,352	B1 *	8/2013	Ferguson et al.	701/25
2006/0208169	A1 *	9/2006	Breed et al.	250/221
2008/0012938	A1 *	1/2008	Kubota et al.	348/118
2009/0115610	A1 *	5/2009	Steinhage et al.	340/572.1
2009/0177347	A1 *	7/2009	Breuer et al.	701/29

2010/0169013	A1	7/2010	Nakamura et al.	
2010/0312461	A1	12/2010	Haynie et al.	
2011/0035123	A1	2/2011	Katrak et al.	
2011/0075518	A1 *	3/2011	Huhta et al.	367/90
2011/0166746	A1 *	7/2011	Breuer et al.	701/34
2012/0136510	A1 *	5/2012	Min et al.	701/2
2012/0269387	A1 *	10/2012	Becker et al.	382/103
2013/0058527	A1 *	3/2013	Peynot	382/103
2013/0245877	A1 *	9/2013	Ferguson et al.	701/23
2013/0300872	A1 *	11/2013	Park	348/148
2013/0321629	A1 *	12/2013	Zhang et al.	348/148

FOREIGN PATENT DOCUMENTS

JP 6-195121 7/1994

* cited by examiner

Primary Examiner — Geepy Pe

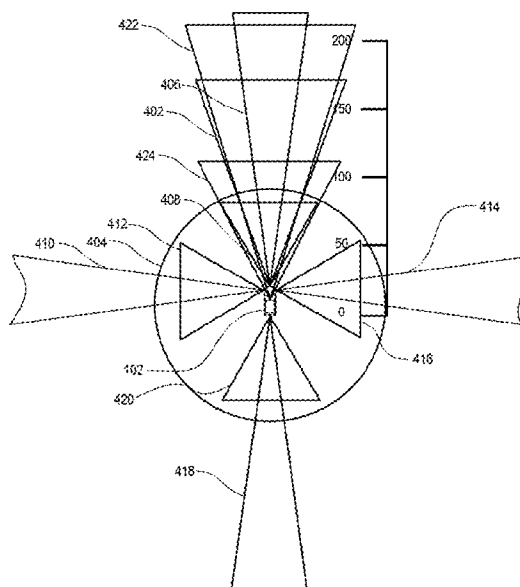
Assistant Examiner — Asmamaw G Tarko

(74) *Attorney, Agent, or Firm* — Lerner, David, Littenberg, Krumholz & Mentlik, LLP

(57) **ABSTRACT**

Methods and systems are disclosed for cross-validating a second sensor with a first sensor. Cross-validating the second sensor may include obtaining sensor readings from the first sensor and comparing the sensor readings from the first sensor with sensor readings obtained from the second sensor. In particular, the comparison of the sensor readings may include comparing state information about a vehicle detected by the first sensor and the second sensor. In addition, comparing the sensor readings may include obtaining a first image from the first sensor, obtaining a second image from the second sensor, and then comparing various characteristics of the images. One characteristic that may be compared are object labels applied to the vehicle detected by the first and second sensor. The first and second sensors may be different types of sensors.

20 Claims, 14 Drawing Sheets



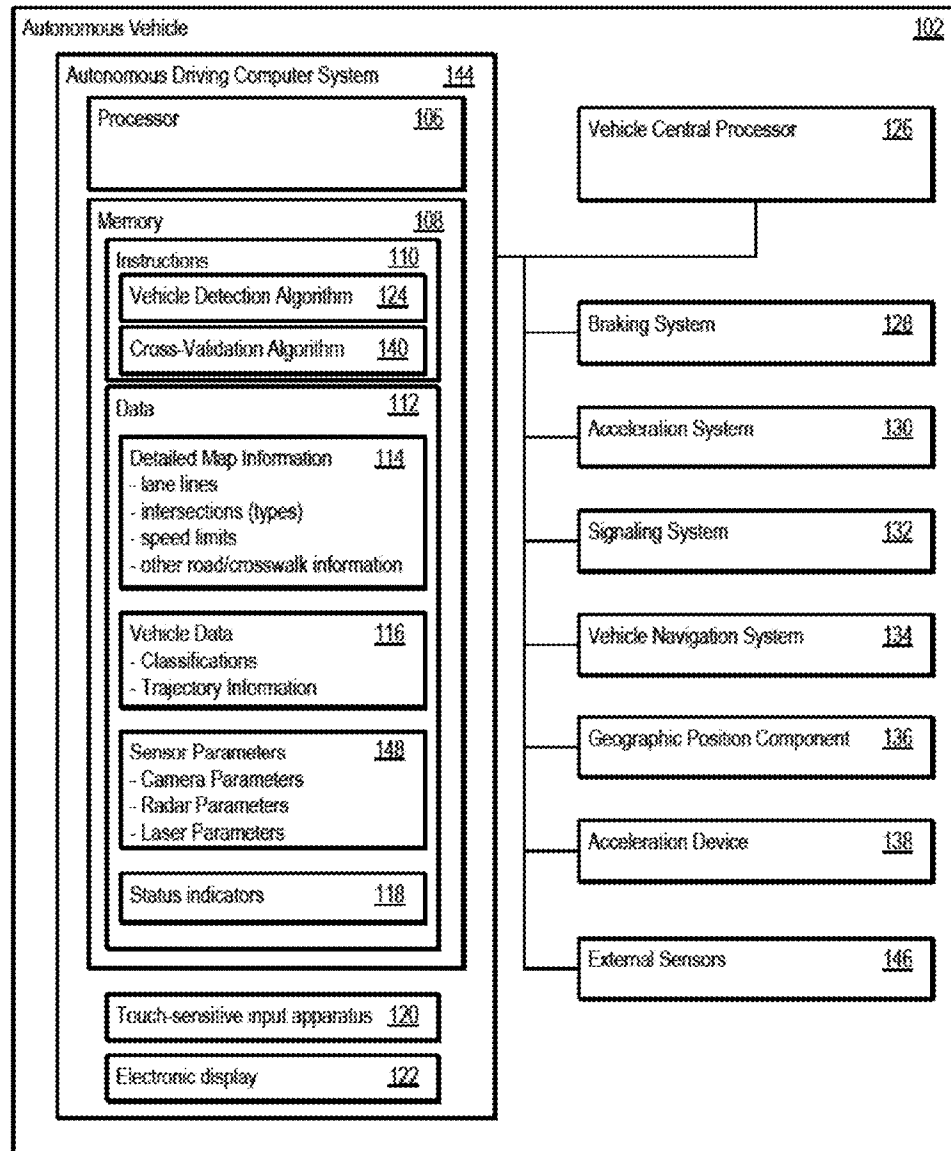


FIG. 1

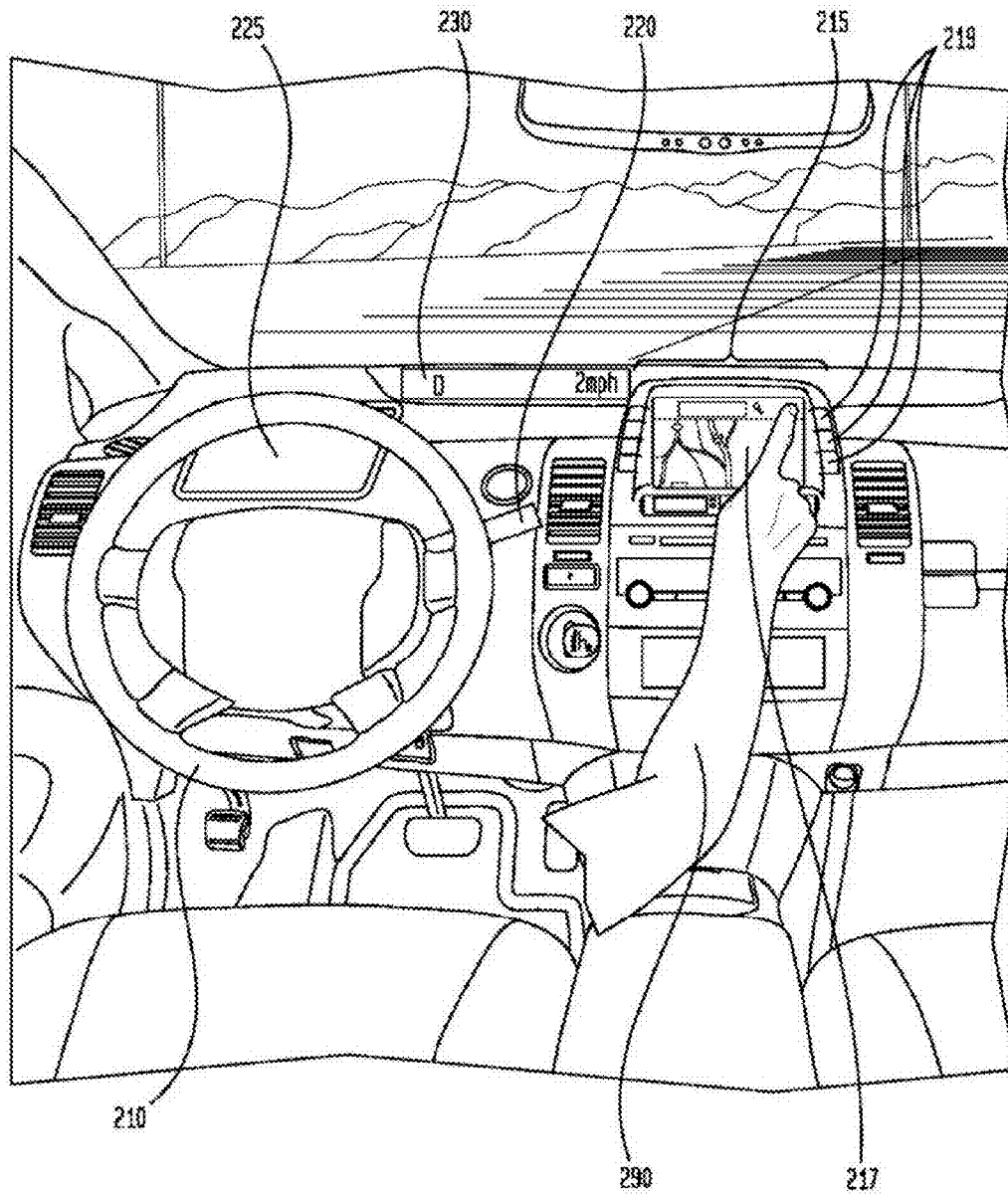


FIG. 2

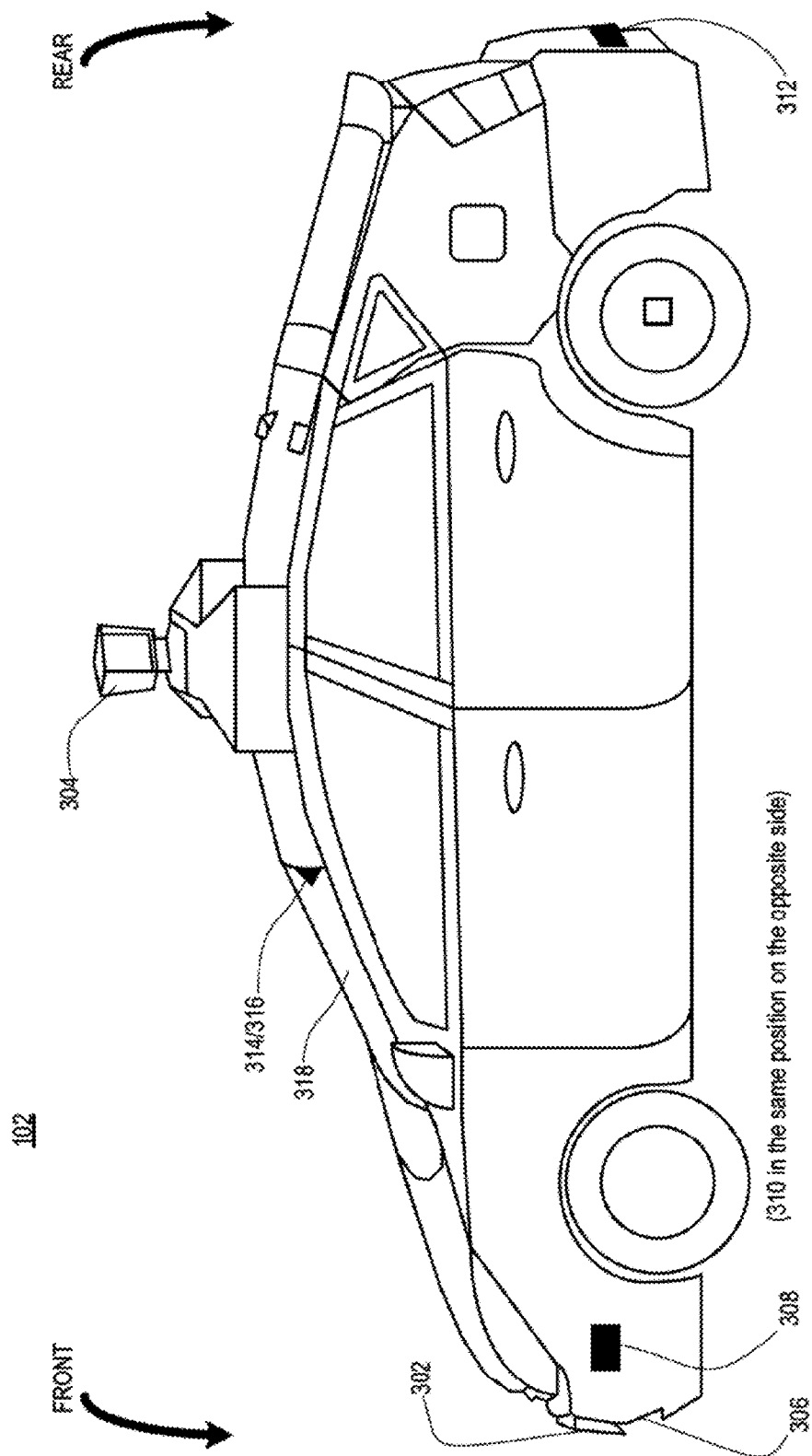


FIG. 3

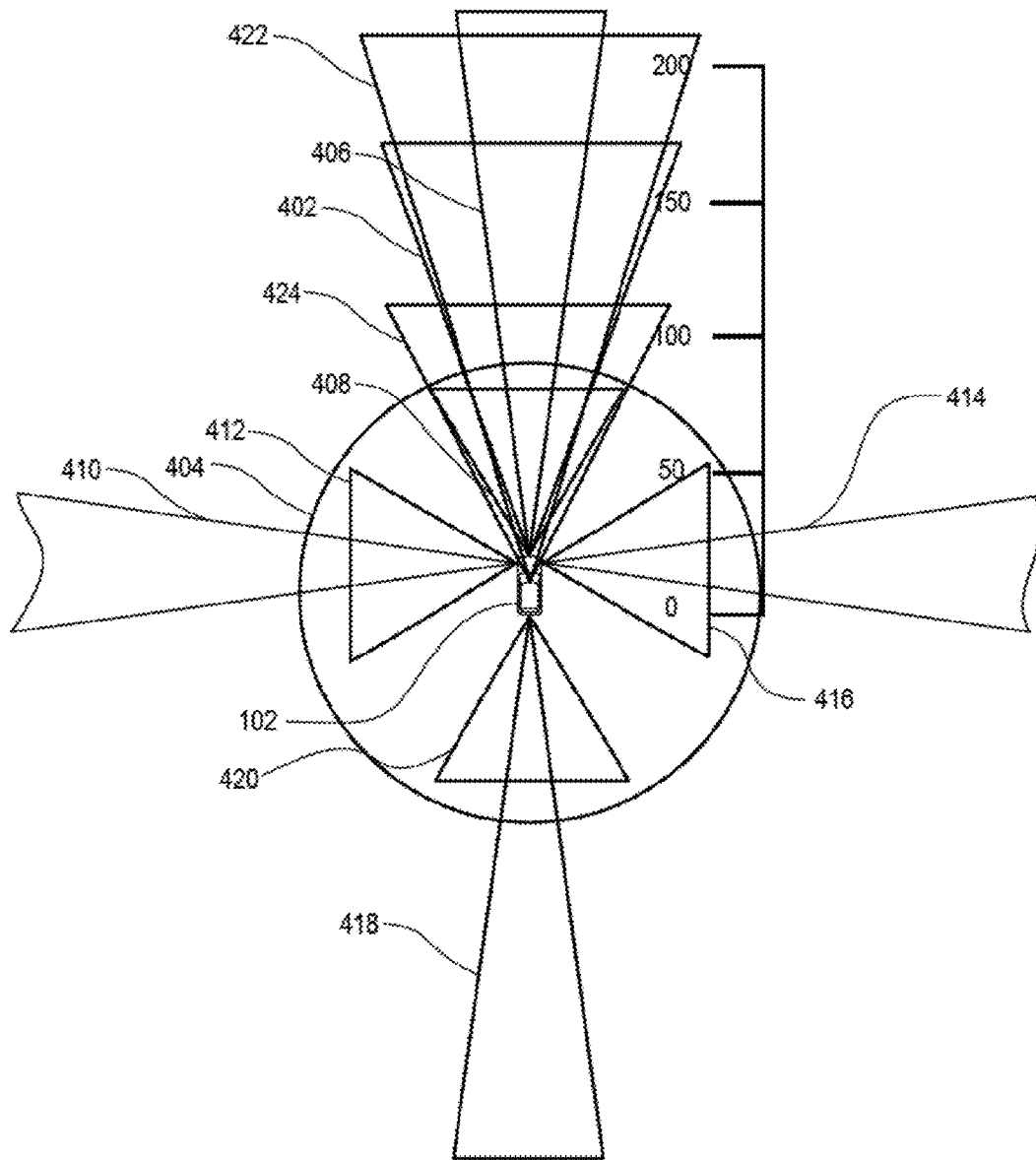


FIG. 4A

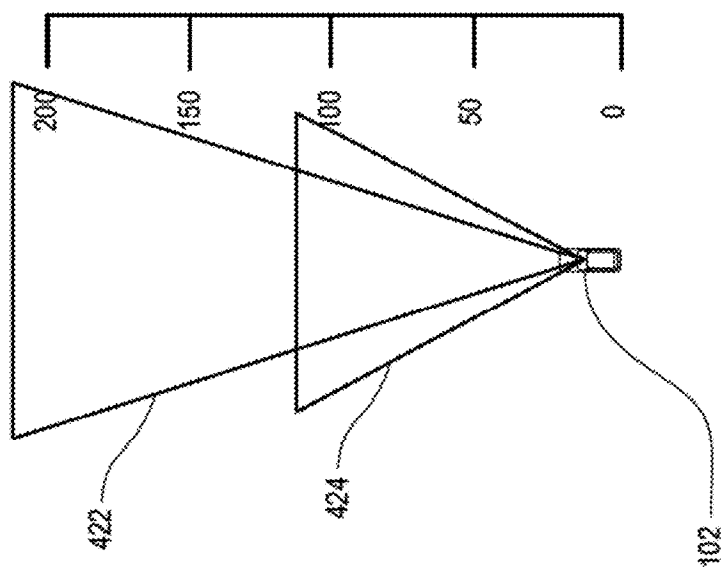


FIG. 4D

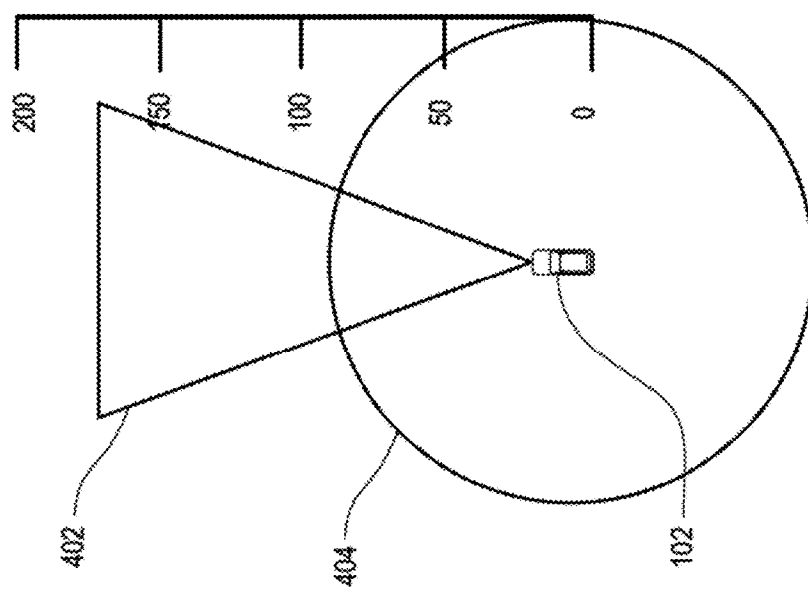


FIG. 4B

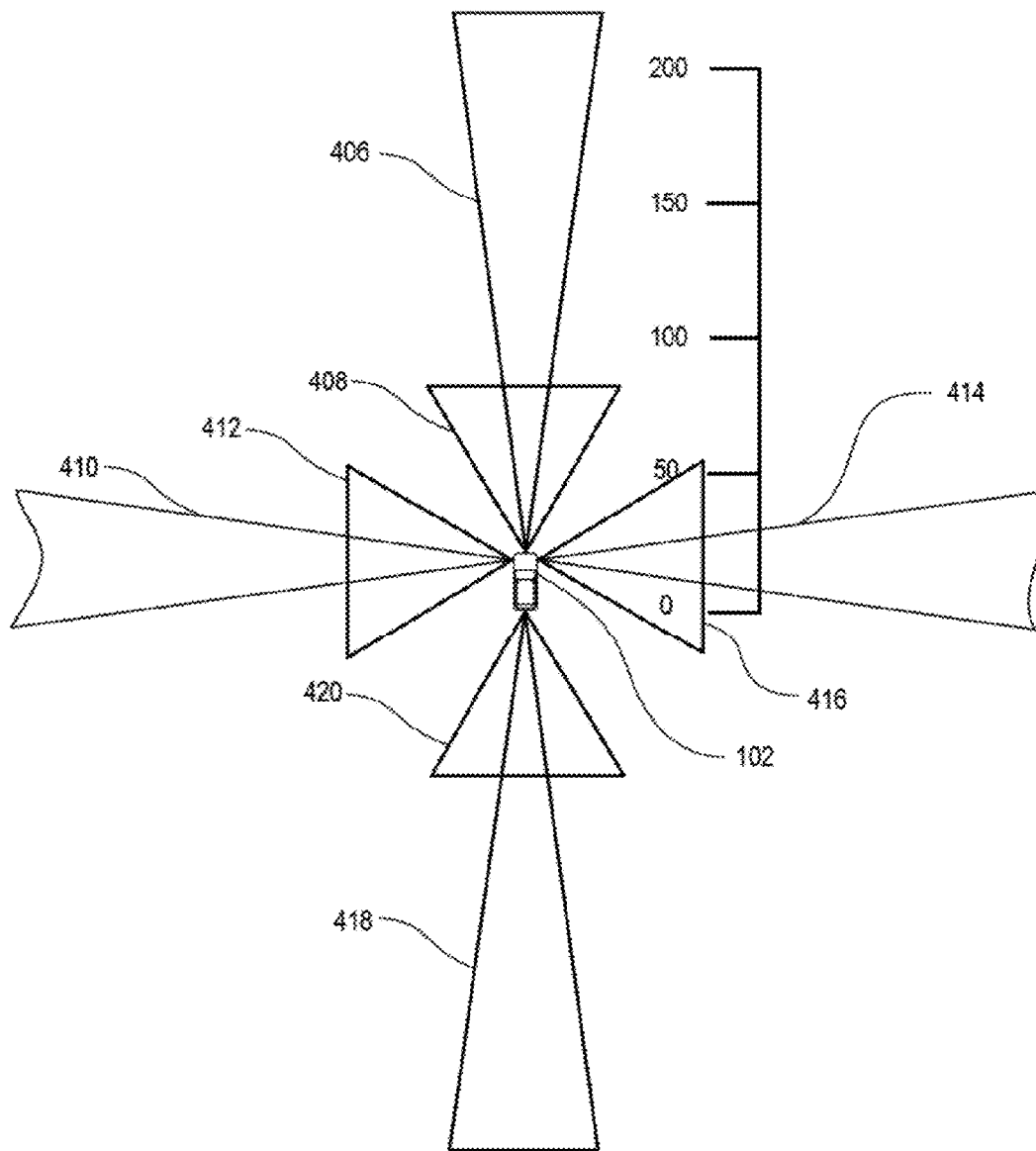


FIG. 4C

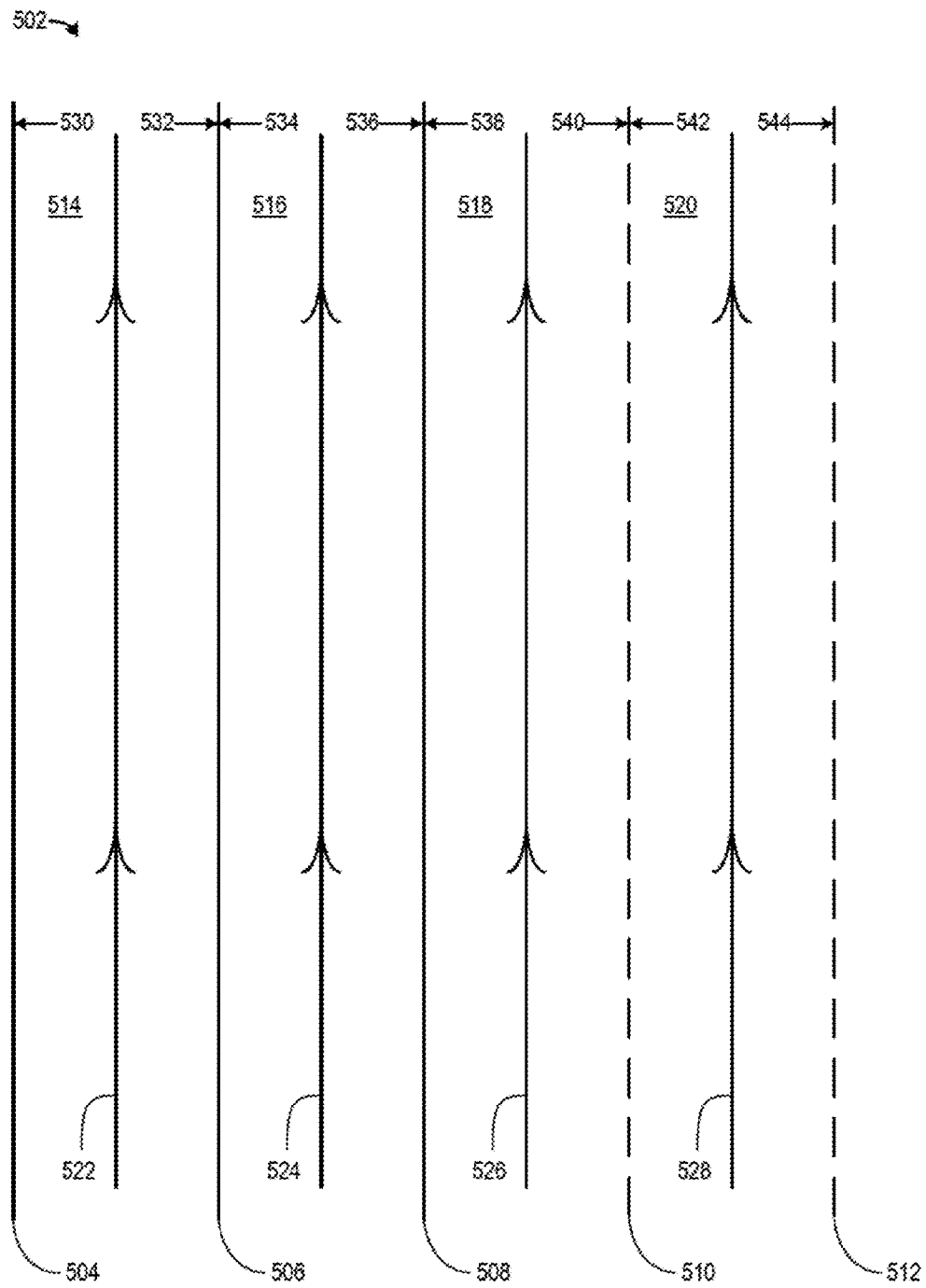


FIG. 5

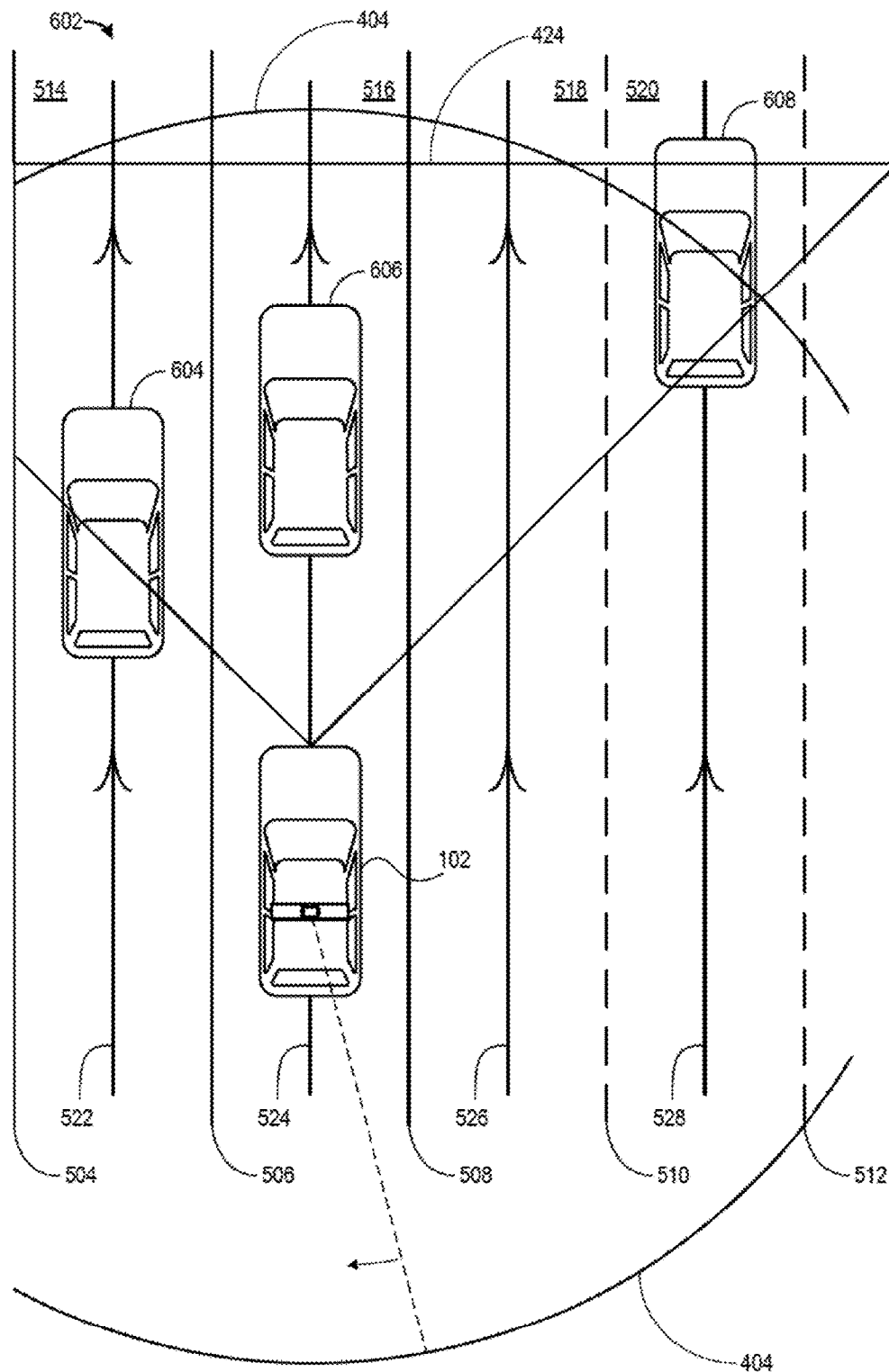


FIG. 6



FIG. 7

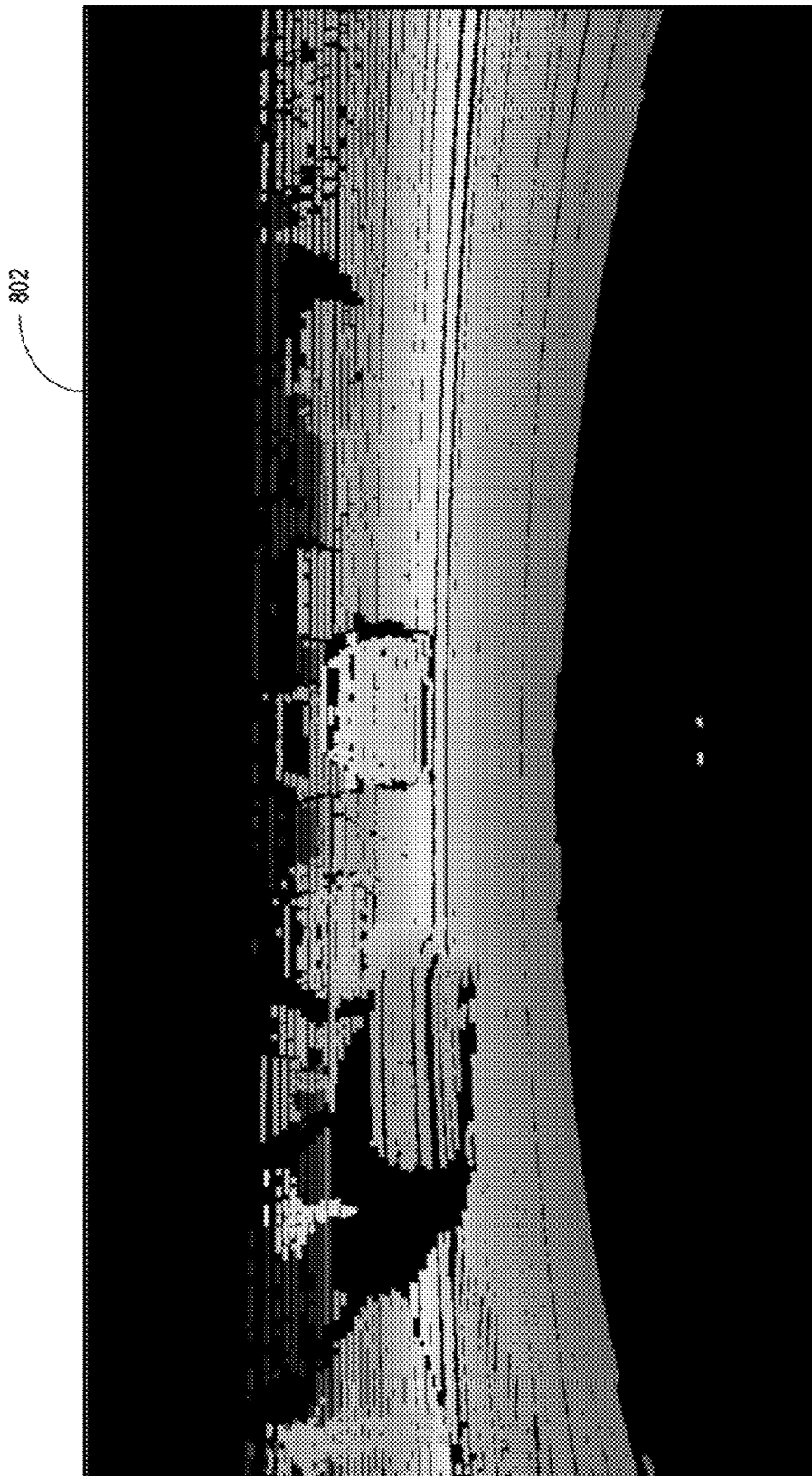


FIG. 8



FIG. 9

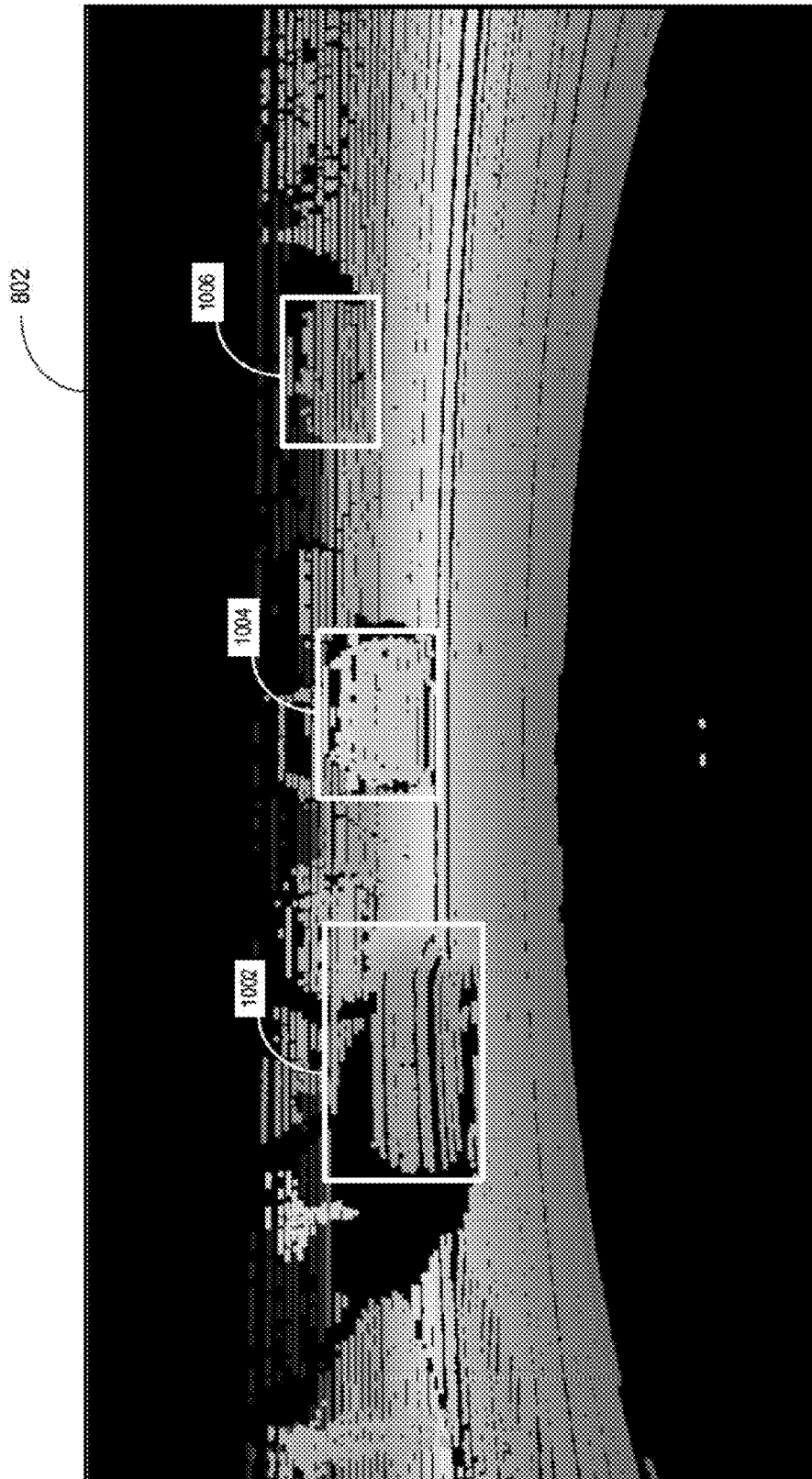


FIG. 10

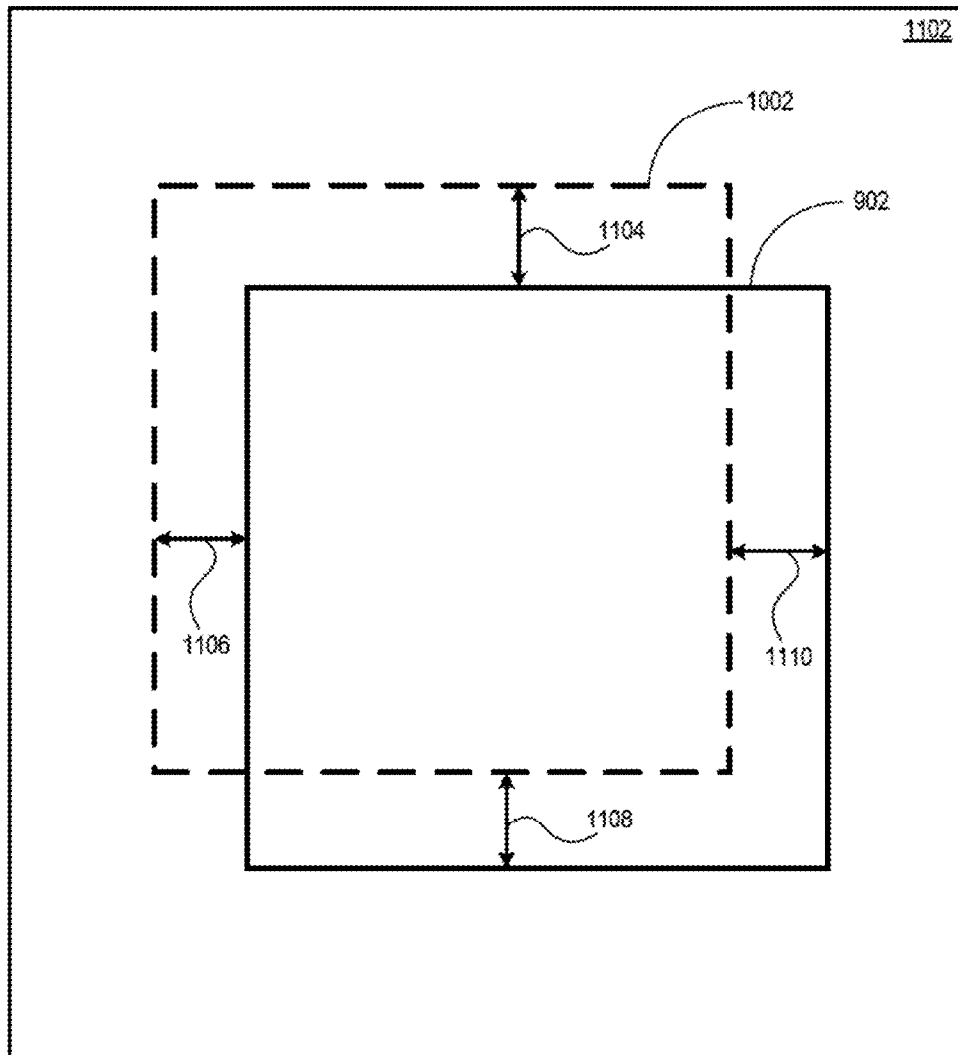


FIG. 11

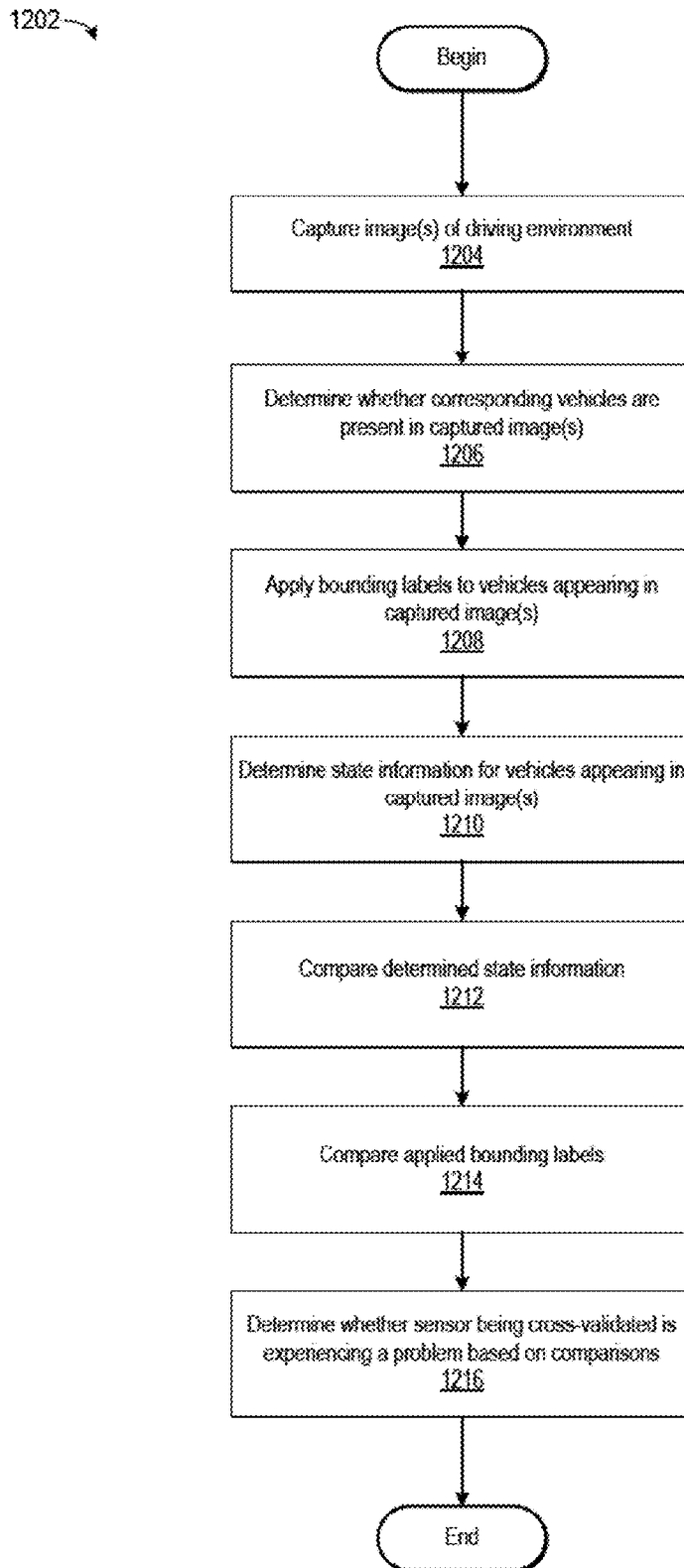


FIG. 12

1

CROSS-VALIDATING SENSORS OF AN AUTONOMOUS VEHICLE

BACKGROUND

An autonomous vehicle may use various computing systems to aid in the transport of passengers from one location to another. In addition, the autonomous vehicle may require an initial input or continuous input from an operator, such as a pilot, driver, or passenger. Other autonomous systems, for example autopilot systems, may be used only when the system has been engaged, which permits the operator to switch from a manual mode (where the operator exercises a high degree of control over the movement of the autonomous vehicle) to an autonomous mode (where the autonomous vehicle essentially drives itself) to modes that lie somewhere in between.

The autonomous vehicle may be equipped with various types of sensors in order to detect objects in its environment. For example, the autonomous vehicles may include such sensors as lasers, sonar, radar, cameras, and other sensors that scan and record data from the autonomous vehicle's environment. Sensor data from one or more of these sensors may be used to detect objects and their respective characteristics (position, shape, heading, speed, etc.). This detection and identification is a critical function for the safe operation of the autonomous vehicle.

To navigate an environment confidently and precisely, the autonomous vehicle may rely on a prior stored electronic representation of the environment (e.g., a roadway, a highway, etc.). The electronic representation of the environment may be considered a "map" that identifies such features as lane markings, lane edges, k-rail concrete barriers, lane dividers, road medians, traffic safety cones, and other such features. The autonomous vehicle may store the map for both complex and simple environments.

However, the sensors on the autonomous vehicle may experience one or more problems, such as failure, inaccurate readings, or other such problems. When the sensor has a problem, the sensor may be unusable for determining whether there are objects, such as other vehicles, proximate to the autonomous vehicle. Having a sensor failure decreases the ability of the autonomous vehicle to navigate its environment confidently and precisely.

BRIEF SUMMARY

An apparatus and method are disclosed. In one embodiment, the apparatus includes a first sensor configured to detect a vehicle in a driving environment, a second sensor configured to detect the vehicle in the driving environment, and a memory that stores detailed map information for the driving environment, first sensor parameters for determining whether the vehicle is present in a first image of the driving environment, and second sensor parameters for determining whether the vehicle is present in a second image of the driving environment. The apparatus may also include a processor in communication with the memory, the first sensor and the second sensor, the processor being configured to receive first sensor information from the first sensor, the first sensor information being used to produce the first image and receive second sensor information from the second sensor, the second sensor information being used to produce the second image. The processor may also be configured to determine whether the vehicle is in both the first image and the second image, determine a deviation value by comparing the first image with the second image when it is determined that the vehicle is present

2

in the first image and the second image, and compare the determined deviation value with a deviation threshold to determine whether the first or second sensor has a problem detecting the vehicle.

In another embodiment of the apparatus, the first sensor is a first type of imaging sensor and the second sensor is a second type of imaging sensor, the first type of imaging sensor being different than the second type of imaging sensor.

In a further embodiment of the apparatus, the processor is further configured to select the first sensor as a reference sensor for determining whether the second sensor has the problem detecting the vehicle.

In yet another embodiment of the apparatus, the processor selects the first sensor based on a predetermined time interval.

In yet a further embodiment of the apparatus, the processor selects the second sensor for cross-validation with the first sensor based on an amount of time that has elapsed since the second sensor was last cross-validated.

In another embodiment of the apparatus, the memory further stores a multi-level failure threshold comprising a plurality of levels, wherein each level is associated with an action for the processor to perform, and a level of the plurality of levels is associated with a condition of the deviation value exceeding the deviation threshold. The processor may also perform the action of the level associated with the condition of the deviation value exceeding the deviation threshold when the processor determines that the deviation value exceeds the deviation threshold.

In a further embodiment of the apparatus, the memory stores a failure count threshold that identifies an action to be performed when the failure count threshold is exceeded, the comparison of the determined deviation value with the deviation threshold causes the failure count threshold to be exceeded, and the action identified by the failure count threshold is performed.

In yet another embodiment of the apparatus, the first image comprises a plurality of images determined from the first sensor information, the first sensor information being received during a predetermined time interval, and the second image comprises a plurality of images determined from the second sensor information, the second sensor information being received during the predetermined time interval. The processor may also be configured to determine first state information about the vehicle from the first plurality of images, determine second state information about the vehicle from the second plurality of images, and compare the first state information with the second state information to determine the deviation value.

In yet a further embodiment of the apparatus, the first state information comprises at least one of a first vehicle speed, a first vehicle position, or a first vehicle heading, the second state information comprises at least one of a second vehicle speed, a second vehicle position, or a second vehicle heading, and the processor compares at least one of the first vehicle speed, first vehicle position or first vehicle heading with at least one of the second vehicle speed, second vehicle position, or second vehicle heading.

In another embodiment of the apparatus, the first image comprises a first object label encompassing the vehicle, the first object label comprising a first parameter that defines a characteristic of the first object label, the second image comprises a second object label encompassing the vehicle, the second object label comprising a second parameter that defines a characteristic of the second object label, and the processor compares the first image with the second image to determine the deviation value by comparing the first object label with the second object label.

3

In yet another embodiment of the apparatus, the processor compares the first object label with the second object label by comparing the first parameter with the second parameter.

In one embodiment of the method, the method includes receiving, with a processor in communication with a first sensor, first sensor information, the first sensor information being used to produce a first image of a driving environment, receiving, with the processor in communication with the second sensor, second sensor information, the second sensor information being used to produce the second image of the driving environment, and determining, with the processor, whether a vehicle is present in both the first image and the second image. The method may also include determining, with the processor, a deviation value by comparing the first image with the second image when it is determined that the vehicle is present in the first image and the second image, and comparing, with the processor, the determined deviation value with a deviation threshold to determine whether the first or second sensor has a problem detecting the vehicle.

In another embodiment of the method, the first sensor is a first type of imaging sensor and the second sensor is a second type of imaging sensor, the first type of imaging sensor being different than the second type of imaging sensor.

In a further embodiment of the method, the method includes selecting, with the processor, the first sensor as a reference sensor for determining whether the second sensor has the problem detecting the vehicle.

In yet another embodiment of the method, the method includes selecting, with the processor, the first sensor based on a predetermined time interval.

In yet a further embodiment of the method, the method includes selecting, with the processor, the second sensor for cross-validation with the first sensor based on an amount of time that has elapsed since the second sensor was last cross-validated.

In another embodiment of the method, the method includes determining whether the deviation value exceeds a deviation threshold associated with a level of a multi-level failure threshold, wherein an action for the processor to perform is associated with the level, and performing the action of the level based on the determination that the deviation value exceeds the deviation threshold.

In a further embodiment of the method, the comparison of the determined deviation value with the deviation threshold causes a failure count threshold to be exceeded, the failure count threshold identifying an action to be performed when the failure count threshold is exceeded. The method may also include performing the action identified by the failure count threshold.

In yet another embodiment of the method, the first image comprises a plurality of images determined from the first sensor information, the first sensor information being received during a predetermined time interval, and the second image comprises a plurality of images determined from the second sensor information, the second sensor information being received during the predetermined time interval. The method may also include determining, with the processor, the first state information about the vehicle from the first plurality of images, determining, with the processor, second state information about the vehicle from the second plurality of images, and comparing, with the processor, the first state information with the second state information to determine the deviation value.

In yet a further embodiment of the method, the first state information comprises at least one of a first vehicle speed, a first vehicle position, or a first vehicle heading, and the second state information comprises at least one of a second vehicle

4

speed, a second vehicle position, or a second vehicle heading. The method may also include comparing, with the processor, at least one of the first vehicle speed, first vehicle position or first vehicle heading with at least one of the second vehicle speed, second vehicle position, or second vehicle heading.

In another embodiment of the method, the first image comprises a first object label encompassing the vehicle, the first object label comprising a first parameter that defines a characteristic of the first object label, and the second image comprises a second object label encompassing the vehicle, the second object label comprising a second parameter that defines a characteristic of the second object label. The method may also include comparing, with the processor, the first image with the second image to determine the deviation value by comparing the first object label with the second object label.

In a further embodiment of the method, comparing the first object label with the second object label comprises comparing the first parameter with the second parameter.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

FIG. 1 illustrates an example of an autonomous vehicle configured to cross-validate one or more sensors of the autonomous vehicle according to aspects of the disclosure.

FIG. 2 illustrates an example of an interior of the autonomous vehicle according to aspects of the disclosure.

FIG. 3 illustrates an example of the placement of the one or more sensors of the autonomous vehicle according to aspects of the disclosure.

FIGS. 4A-4D illustrate various views of the approximate sensor fields of the various sensors of the autonomous vehicle according to aspects of the disclosure.

FIG. 5 illustrates an example of detailed map information that may be stored by the autonomous vehicle in accordance with aspects of the disclosure.

FIG. 6 illustrates an example of the autonomous vehicle detecting one or more vehicles in the driving environment according to aspects of the disclosure.

FIG. 7 illustrates an example of a raw camera image captured by a camera sensor of the autonomous vehicle according to aspects of the disclosure.

FIG. 8 illustrates an example of a laser point cloud image captured by the laser sensor of the autonomous vehicle according to aspects of the disclosure.

FIG. 9 illustrates examples object labels being applied to detected vehicles shown in the raw camera image of FIG. 7 according to aspects of the disclosure.

FIG. 10 illustrates object labels being applied to detected vehicles shown in the laser point cloud image of FIG. 8 according to aspects of the disclosure.

FIG. 11 illustrates an example of comparing object labels applied to objects detected by different types of sensors according to aspects of the disclosure.

FIG. 12 illustrates an example of logic flow for cross-validating sensors of the autonomous vehicle according to aspects of the disclosure.

DETAILED DESCRIPTION

This disclosure provides for systems and methods for cross-validating one or more sensors of an autonomous

vehicle. In particular, this disclosure provides for an autonomous vehicle that evaluates whether a sensor is accurately detecting an object (i.e., the sensor being cross-validated) based on the detection of that object by another sensor (i.e., a reference sensor). Using the reference sensor to evaluate whether a second sensor is operating as expected is referred to as “cross-validation.” In this regard, the reference sensor may be a different type of sensor than the second sensor (i.e., the sensor being evaluated).

In evaluating the second sensor, the autonomous vehicle may, in a first embodiment, determine one or more object parameter values from the reference sensor having detected an object, determine one or more expected object parameter values for the second sensor based on the determined object parameter values from the reference sensor, and then compare the expected object parameter values with the object parameter values (if any) determined from the second sensor having detected the object.

In a second embodiment, the autonomous vehicle may compare a first object label applied to the detected object by the autonomous vehicle based on sensor data received from the reference sensor, and then compare the first object label with a second object label applied to the detected object by the autonomous vehicle based on sensor data received from the second sensor. In this regard, either embodiment, or a combination thereof, may facilitate the cross-validation of one or more sensors of the autonomous vehicle.

FIG. 1 illustrates an autonomous vehicle **102** configured to cross-validate one or more of its sensors. The autonomous vehicle **102** may be configured to operate autonomously, e.g., drive without the assistance of a human driver. Moreover, the autonomous vehicle **102** may be configured to detect various objects and determine whether the detected object is a vehicle.

While certain aspects of the disclosure are particularly useful in connection with specific types of vehicles, the autonomous vehicle **102** may be any type of vehicle including, but not limited to, cars, trucks, motorcycles, busses, boats, airplanes, helicopters, lawnmowers, recreational vehicles, amusement park vehicles, farm equipment, construction equipment, trams, golf carts, trains, and trolleys.

In one embodiment, the autonomous driving computer system **144** may include a processor **106** and a memory **108**. The autonomous driving computer system **144** may also include other components typically present in a general purpose computer.

The memory **108** may store information accessible by the processor **106**, such as instructions **110** and data **112** that may be executed or otherwise used by the processor **106**. The memory **108** may be of any type of memory operative to store information accessible by the processor **106**, including a computer-readable medium, or other medium that stores data that may be read with the aid of an electronic device. Examples of the memory **108** include, but are not limited, a hard-drive, a memory card, read-only memory (“ROM”), random-access memory (“RAM”), digital video disc (“DVD”), or other optical disks, as well as other write-capable and read-only memories. Systems and methods may include different combinations of the foregoing, whereby different portions of the instructions and data are stored on different types of media.

The instructions **110** may be any set of instructions that may be executed directly (such as machine code) or indirectly (such as scripts) by the processor **106**. For example, the instructions **110** may be stored as computer code on the computer-readable medium. In that regard, the terms “instructions” and “programs” may be used interchangeably

herein. The instructions **110** may be stored in object code format for direct processing by the processor **106**, or in any other computer language including scripts or collections of independent source code modules that are interpreted on demand or compiled in advance. Functions, methods and routines of the instructions **110** are explained in more detail below.

The data **112** may be retrieved, stored, or modified by processor **106** in accordance with the instructions **110**. For instance, although the disclosed embodiments not limited by any particular data structure, the data **112** may be stored in computer registers, in a relational database as a table having a plurality of different fields and records, XML documents, flat files, or in any computer-readable format. By way of example only, image data may be stored as bitmaps comprised of grids of pixels that are stored in accordance with formats that are compressed or uncompressed, lossless (e.g., BMP) or lossy (e.g., JPEG), and bitmap or vector-based (e.g., SVG), as well as computer instructions for drawing graphics. The data **112** may comprise any information sufficient to identify the relevant information, such as numbers, descriptive text, proprietary codes, references to data stored in other areas of the same memory or different memories (including other network locations) or information that is used by a function to calculate the relevant data.

The processor **106** may be any conventional processor, including Reduced Instruction Set Computing (“RISC”) processors, Complex Instruction Set Computing (“CISC”) processors, or combinations of the foregoing. Alternatively, the processor may be a dedicated device such as an application-specific integrated circuit (“ASIC”).

Although FIG. 1 functionally illustrates the processor **106**, the memory **108**, and other elements of the autonomous driving computer system **144** as being within the same block, it will be understood by those of ordinary skill in the art that the processor **106** and the memory **108** may actually comprise multiple processors and memories that may or may not be stored within the same physical housing. For example, the memory **108** may be a hard drive or other storage media located in a housing different from that of the autonomous driving computer system **144**.

Accordingly, references to a processor or computer will be understood to include references to a collection of processors or computers or memories that may or may not operate in parallel. Rather than using a single processor to perform the acts described herein, some of the components, such as steering components and deceleration components, may each have their own processor that only performs calculations related to the component’s specific function.

In various embodiments described herein, the processor **106** may be located remotely from the autonomous vehicle **102** and may communicate with the autonomous vehicle wirelessly. In other aspects, some of the processes described herein are executed on a processor disposed within the autonomous vehicle **102** and others by a remote processor, including taking the acts necessary to execute a single maneuver.

The autonomous driving computer system **144** may include all of the components normally used in connection with a computer, such as a central processing unit (CPU), a memory (e.g., RAM and internal hard drives) storing data **112** and instructions such as an Internet browser or other software application, an electronic display **122** (e.g., a monitor having a screen, a small liquid crystal display (“LCD”) touch-screen or any other electrical device that is operable to display information), one or more user input devices (e.g., a mouse, keyboard, touch screen and/or microphone), as well as various

sensors (e.g., a video camera) for gathering the explicit (e.g., a gesture) or implicit (e.g., “the person is asleep”) information about the states and desires of a person.

The autonomous vehicle **102** may also include a geographic position component **136** in communication with the autonomous driving computer system **144** for determining the geographic location of the autonomous vehicle **102**. For example, the geographic position component **136** may include a Global Positioning System (“GPS”) receiver to determine the autonomous vehicle’s **102** latitude, longitude and/or altitude position. Other location systems such as laser-based localization systems, inertial-aided GPS, or camera-based localization may also be used to identify the location of the vehicle. The location of the autonomous vehicle **102** may include an absolute geographical location, such as latitude, longitude, and altitude as well as relative location information, such as location relative to other vehicles immediately around it, which can often be determined with less noise than absolute geographical location.

The geographic position component **136** may also include other devices in communication with the autonomous driving computer system **144**, such as an accelerometer, gyroscope or another direction/speed detection device **138** to determine the direction and speed of the vehicle or changes thereto. By way of example only, the geographic position component **136** may determine its pitch, yaw or roll (or changes thereto) relative to the direction of gravity or a plane perpendicular thereto. The geographic position component **136** may also track increases or decreases in speed and the direction of such changes. The location and orientation data as set forth herein may be provided automatically to the user, the autonomous driving computer **144**, the vehicle central processor **126**, other computers and combinations of the foregoing.

The autonomous driving computer system **144** may control the direction and speed of the autonomous vehicle **102** by controlling various components. By way of example, if the autonomous vehicle **102** is operating in a completely autonomous mode, the autonomous driving computer system **144** may cause the autonomous vehicle **102** to accelerate via the acceleration system **130** (e.g., by increasing fuel or other energy provided to the engine), decelerate via the braking system **128** (e.g., by decreasing the fuel supplied to the engine or by applying brakes) and change direction (e.g., by turning the front two wheels). The autonomous driving computer system **144** may also control one or more systems, such as the signaling system **130**, when controlling the acceleration system **130** and/or the braking system **128**.

The autonomous driving computer system **144** may also control one or more status indicators **118**, which may convey the status of the autonomous vehicle **102** and its components to a passenger. For example, the autonomous vehicle **102** may be equipped with an electronic display **122** for displaying information relating to the overall status of the vehicle, particular sensors, or information about or from the autonomous driving computer system **144**. The electronic display **122** may display computer-generated images of the vehicle’s surroundings including, for example, the status of the autonomous driving computer system **144**, the autonomous vehicle **102** itself, roadways, intersections, as well as other objects and information.

The autonomous driving computer system **144** may use visual or audible cues to indicate whether it is obtaining valid data from one or more sensors, whether a passenger or the autonomous driving computer system **144** is partially or completely controlling the direction or speed of the autonomous vehicle **102** or both, such as whether there are any errors, etc. In addition, the autonomous driving computer system **144**

may also have external indicators which indicate whether, at the moment, a human or an automated system is in control of the vehicle, that are readable by humans, other computers, or both.

The autonomous driving computer system **144** may also communicate with other components of the autonomous vehicle **102**. For example, the autonomous driving computer system **144** may communicate with a vehicle central processor **126**. The autonomous driving computer system **144** may also send and receive information from the various systems of the autonomous vehicle **102**. Communicating with the various systems may include communicating with the braking system **128**, the acceleration system **130**, the signaling system **132**, and the vehicle navigation system **134**. Communications with these systems may facilitate the control of the movement, speed, etc. of the autonomous vehicle **102**. In addition, when engaged, autonomous driving computer system **144** may control some or all of these functions of the autonomous vehicle **102** and thus be fully or partially autonomous. Although various systems and the autonomous driving computer system **144** are shown within the autonomous vehicle **102**, these systems and components may be external to the autonomous vehicle **102** or physically separated by large distances.

The autonomous vehicle **102** may also include one or more sensors **146** for detecting objects external to it, such as other vehicles, obstacles in the roadway, traffic signals, signs, trees, etc. The sensors **146** may include lasers, sonar, radar, cameras or any other detection devices. For example, where the autonomous vehicle **102** is a small passenger car, the small passenger car may include a laser mounted on the roof or other convenient location. In one aspect, the laser may measure the distance between the autonomous vehicle **102** and the object surfaces facing the autonomous vehicle **102** by spinning on its axis and changing its pitch. The autonomous vehicle **102** may also include various radar detection units, such as those used for adaptive cruise control systems. The radar detection units may be located on the front and back of the car as well as on either side of the front bumper. In another example, a variety of cameras may be mounted on the autonomous vehicle **102** at known distances from one another. In this manner, the parallax from the different images may be used to compute the distance to various objects captured by the one or more cameras. These sensors may assist the vehicle in responding to its environment to maximize safety for passengers as well as objects or people in the environment.

FIG. 3 illustrates one example of the autonomous vehicle **102** and the placement of its one or more sensors. The autonomous vehicle **102** may include lasers **302** and **304**, for example, mounted on the front and top of the autonomous vehicle **102**, respectively. The laser **302** may have a range of approximately 150 meters, a thirty degree vertical field of view, and approximately a thirty degree horizontal field of view. The laser **304** may have a range of approximately 50-80 meters, a thirty degree vertical field of view, and a 360 degree horizontal field of view. The lasers **302-304** may provide the autonomous vehicle **102** with range and intensity information that the processor **106** may use to identify the location and distance of various objects. In one aspect, the lasers **302-304** may measure the distance between the vehicle and object surfaces facing the vehicle by spinning on its axes and changing their pitch. Other lasers with different ranges and fields of view may also be used.

The autonomous vehicle **102** may also include various radar detection units, such as those used for adaptive cruise control systems. The radar detection units may be located on the front and back of the car as well as on either side of the

front bumper. As shown in the example of FIG. 3, the autonomous vehicle **102** includes radar detection units **306-312** located on the side (only one side being shown), front and rear of the vehicle. Each of these radar detection units **306-312** may have a range of approximately 200 meters for an approximately 18 degree field of view as well as a range of approximately 60 meters for an approximately 56 degree field of view. Again, other radar detection units with different ranges and fields of view may also be used.

In another example, a variety of cameras may be mounted on the autonomous vehicle **102**. The cameras may be mounted at predetermined distances so that the parallax from the images of two or more cameras may be used to compute the distance to various objects. As shown in FIG. 3, the autonomous vehicle **102** may include two cameras **314-316** mounted under a windshield **318** near the rear view mirror (not shown). The camera **314** may include a range of approximately 200 meters and an approximately 30 degree horizontal field of view, while the camera **316** may include a range of approximately 100 meters and an approximately 60 degree horizontal field of view. Other cameras with different ranges and fields of view may also be used.

Each sensor may be associated with a particular sensor field defined by the ranges and fields of view for which the sensor may be used to detect objects. FIG. 4A is a top-down view of the approximate sensor fields of the various sensors. FIG. 4B depicts the approximate sensor fields **402** and **404** for the lasers **302** and **304**, respectively based on the fields of view for these sensors. In this example, the sensor field **402** includes an approximately 30 degree horizontal field of view for approximately 150 meters, and the sensor field **404** includes a 360-degree horizontal field of view for approximately 80 meters.

FIG. 4C depicts the approximate sensor fields **406-420** and for radar detection units **306-312**, respectively, based on the fields of view for these sensors. For example, the radar detection unit **306** includes sensor fields **406** and **408**. The sensor field **406** includes an approximately 18 degree horizontal field of view for approximately 200 meters, and the sensor field **408** includes an approximately 56 degree horizontal field of view for approximately 80 meters.

Similarly, the radar detection units **308-312** include the sensor fields **410/414/418** and sensor fields **412/416/420**. The sensor fields **410/414/418** include an approximately 18 degree horizontal field of view for approximately 200 meters, and the sensor fields **412/416/420** include an approximately 56 degree horizontal field of view for approximately 80 meters. The sensor fields **410** and **414** extend passed the edge of FIGS. 4A and 4C.

FIG. 4D depicts the approximate sensor fields **422-424** of cameras **314-316**, respectively, based on the fields of view for these sensors. For example, the sensor field **422** of the camera **314** includes a field of view of approximately 30 degrees for approximately 200 meters, and sensor field **424** of the camera **316** includes a field of view of approximately 60 degrees for approximately 100 meters.

In general, an autonomous vehicle **102** may include sonar devices, stereo cameras, a localization camera, a laser, and a radar detection unit each with different fields of view. The sonar may have a horizontal field of view of approximately 60 degrees for a maximum distance of approximately 6 meters. The stereo cameras may have an overlapping region with a horizontal field of view of approximately 50 degrees, a vertical field of view of approximately 10 degrees, and a maximum distance of approximately 30 meters. The localization camera may have a horizontal field of view of approximately 75 degrees, a vertical field of view of approximately 90

degrees and a maximum distance of approximately 10 meters. The laser may have a horizontal field of view of approximately 360 degrees, a vertical field of view of approximately 30 degrees, and a maximum distance of 100 meters. The radar may have a horizontal field of view of 60 degrees for the near beam, 30 degrees for the far beam, and a maximum distance of 200 meters. Hence, the autonomous vehicle **102** may be configured with any arrangement of sensors having different fields of view, ranges, and sensor fields, and each of these sensors may capture one or more raw images for detecting the various objects near and around the autonomous vehicle **102**.

In addition to the sensors **146** described above, the autonomous driving computer system **144** may also use input from sensors found in non-autonomous vehicles. As examples, these sensors may include tire pressure sensors, engine temperature sensors, brake heat sensors, break pad status, tire tread sensors, fuel sensors, oil level and quality sensors, air quality sensors (for detecting temperature, humidity, or particulates in the air), etc.

The data provided by the sensors **146** may be processed by the autonomous driving computer system **144** in real-time. In this context, the sensors **146** may continuously update their output to reflect the environment being sensed at or over a range of time, and continuously or as demanded. The sensors **146** may provide the updated output to the autonomous driving computer system **144** so that it can determine whether the autonomous vehicle's **102** then-current direction or speed should be modified in response to the sensed environment.

Referring back to FIG. 1, the autonomous vehicle **102** may also include an electronic representation of a driving environment for maneuvering in the driving environment, and for determining whether there are one or more objects proximate to the autonomous vehicle **102** in the driving environment. For example, autonomous driving computer system **144** may include detailed map information **114** that defines one or more driving environments. The detailed map information **114** may include various maps that identify the shape and elevation of roadways, lane lines, intersections, crosswalks, speed limits, traffic signals, buildings, signs, real time traffic information, or other such objects and information. The detailed map information **114** may further include explicit speed limit information associated with various roadway segments. The speed limit data may be entered manually or scanned from previously taken images of a speed limit sign using, for example, optical-character recognition. In addition, the detailed map information **114** may include three-dimensional terrain maps incorporating one or more of the objects (e.g., crosswalks, intersections, lane lines, etc.) listed above.

The detailed map information **114** may also include lane marker information identifying the location, elevation, and shape of lane markers. The lane markers may include features such as solid or broken double or single lane lines, solid or broken lane lines, reflectors, etc. A given lane may be associated with left and right lane lines or other lane markers that define the boundary of the lane. Thus, most lanes may be bounded by a left edge of one lane line and a right edge of another lane line.

The autonomous vehicle **102** may also include persistent data for detecting objects and cross-validating one or more of the sensors **146** based on the detected objects. For example, the data **112** may include one or more sensor parameters **148** used by the processor **106** to determine when a sensor has detected an object, and the type of object detected by the sensor. More particularly, the sensor parameters **148** may define an arrangement of pixels, laser points, intensity maps, etc., should be considered an object. The sensor parameters **148** may also define how an object is classified.

11

Each of the sensors **146** of the autonomous vehicle **102** may be associated with a corresponding set of sensor parameters **148**. Thus, the one or more camera(s) may be associated with camera parameters, the one or more laser(s) may be associated with laser parameters, and the one or more radar detection unit(s) may be associated with radar parameters. Examples of camera parameters may include the minimal brightness of a pedestrian, the minimum pixel size of a car object, the minimum width of a car object, and other such parameters. Examples of laser parameters may include the height of a pedestrian, the length of a car object, an obstacle detection threshold, and other such parameters. Examples of radar parameters may include minimum distance to an object, a delay threshold for detecting an object, the height of a pedestrian, and other such parameters.

In detecting vehicles in various driving environments, the data **112** may include vehicle data **116** that defines one or more parameters for classifying a vehicle. Classifications of vehicle may include such classifications as “passenger car,” “bicycle,” “motorcycle,” and other such classifications. The parameters defined by the vehicle data **116** may inform the autonomous driving computer system **144** as to the type of vehicle detected by a given sensor. For example, the vehicle data **116** may include parameters that define the type of vehicle when the vehicle is detected by one or more of the camera sensors, one or more of the laser sensors, and so forth.

Vehicles may be identified through a vehicle detection algorithm **124**, which the processor **106** may use to classify vehicles based on various characteristics, such as the size of the vehicle (bicycles are larger than a breadbox and smaller than a car), the speed of the vehicle (bicycles do not tend to go faster than 40 miles per hour or slower than 0.1 miles per hour), and other such characteristics. In addition, the vehicle may be classified based on specific attributes of the vehicle, such as information contained on a license plate, bumper sticker, or logos that appear on the vehicle.

The vehicle data **116** may also include state, positional, and/or trajectory information collected by the autonomous driving computer system **144** when a vehicle is detected. The autonomous driving computer system **144** may collect the state and/or positional information about a detected object such as a vehicle to assist in the determination of the detected vehicle’s trajectory. The vehicle trajectory for the detected vehicle may define the direction and speed that a vehicle has when in a given driving environment. The vehicle trajectory may also define the past positions, directions, and speed that the detected vehicle had while in the driving environment.

The autonomous vehicle **102** may generate state information about detected objects, such as other vehicles, regardless of whether the autonomous vehicle **102** is operating in an autonomous mode or a non-autonomous mode. Thus, whether the autonomous vehicle **102** is operating by itself or has a driver, the autonomous vehicle **102** may collect state and object information, for example, in order to determine the aforementioned vehicle trajectories.

The instructions **110** may also include a cross-validation algorithm for cross-validating one or more of the sensors **146**. As previously discussed, cross-validating a second sensor (i.e., the sensor being validated) may be performed by detecting an object with a first sensor, and then determining whether the second sensor also detects the object and/or the accuracy of the second sensor in detecting the object.

The autonomous driving computer system **144** may take various actions defined by the cross-validation algorithm **140** in response to the cross-validation operations previously described. For example, the autonomous driving computer system **144** may display a warning to a passenger of the

12

autonomous vehicle **102** when the autonomous driving computer system **144** determines that the sensor being cross-validated is experiencing a problem (e.g., not accurately reporting a detected object). The warning may inform the passenger which sensor is not operating within operational parameters. As another example, the autonomous driving computer system **144** may request that a passenger take control of the autonomous vehicle **102**. Moreover, the autonomous driving computer system **144** may perform a combination of actions, such as displaying the warning and requesting that a passenger take control of the autonomous vehicle **102**.

FIG. 2 illustrates an example of an interior of the autonomous vehicle **102** according to aspects of the disclosure. The autonomous vehicle **102** may include all of the features of a non-autonomous vehicle, for example: a steering apparatus, such as steering wheel **210**; a navigation display apparatus, such as navigation display **215**; and a gear selector apparatus, such as gear shifter **220**. The vehicle **102** may also have various user input devices, such as gear shifter **220**, touch screen **217**, or button inputs **219**, for activating or deactivating one or more autonomous driving modes and for enabling a driver or passenger **290** to provide information, such as a navigation destination, to the autonomous driving computer **106**.

The autonomous vehicle **102** may also include one or more additional displays. For example, the autonomous vehicle **102** may include a display **225** for displaying information regarding the status of the autonomous vehicle **102** or its computer. In another example, the autonomous vehicle **102** may include a status indicating apparatus such as status bar **230**, to indicate the current status of vehicle **102**. In the example of FIG. 2, the status bar **230** displays “D” and “2 mph” indicating that the autonomous vehicle **102** is presently in drive mode and is moving at 2 miles per hour. In that regard, the autonomous vehicle **102** may display text on an electronic display, illuminate portions of the autonomous vehicle **102**, such as the steering wheel **210**, or provide various other types of indications.

FIG. 5 illustrates an example of a portion of a detailed map **502** that may represent the driving environment of the autonomous vehicle **102**. The detailed map **502** may be retrieved or referenced by the autonomous vehicle **102** based on a detected position of the autonomous vehicle **102**. The detailed map **502** may be stored as part of the detailed map information **114**.

The detailed map **502** may further represent a section of a road, such as highway, parkway, etc., and may include lane information such as information about solid lane lines **504-508** and broken lane lines **510-512**. These lane lines may define lanes **514-520**. Each of the lanes **514-520** may be associated with a respective centerline rail **522-528** which may indicate the direction in which a vehicle should generally travel in the respective lane. For example, a vehicle may follow centerline rail **522** when driving in lane **514**. In this example, the lane **514** may be bounded by a left lane line **504** and the right lane line **506**. Similarly, the lane **516** may be bounded by the left lane line **506** and the right lane line **508**, the lane **518** may be bounded by the left lane line **508** and the right lane line **510**, and the lane **520** may be bounded by the left lane line **510** and the right lane line **512**.

Each of the lanes **514-520** may be bounded by corresponding lane edges. Thus, lane **514** may be bounded by edges **530,532**, lane **516** may be bounded by edges **534,536**, lane **518** may be bounded by edges **538,540** and lane **520** may be bounded by edges **542,544**.

In the example shown in FIG. 5, the detailed map information **114** may be depicted as an image-based map. However,

13

the detailed map information **114** need not be entirely or completely image-based (e.g., raster-based). For example, the detailed map information **114** may include one or more roadgraphs or graph networks of information such as roads, lanes, intersections, and the connections between these features. Each feature may be stored as graph data and may be associated with information such as a geographic location and whether or not it is linked to other related features, for example, a stop sign may be linked to a road and an intersection, etc. In some examples, the associated data may include grid-based indices of a roadgraph to allow for efficient lookup of certain roadgraph features.

The detailed map information **114** may be loaded into the memory **108** of the autonomous vehicle **102** at a predetermined time. In one embodiment, the detailed map information **114** may be loaded into the memory **108** of the autonomous vehicle **102** on a daily basis. Alternatively, or in addition, the detailed map information **114** may be loaded into the memory **108** at other predetermined times, such as on a monthly or weekly basis.

As previously discussed, the autonomous driving computer system **144** may include instructions **110** having various algorithms for detecting objects in a driving environment and for cross-validating one or more of the sensors **126** based on the detected objects.

The vehicle detection algorithm **124** may facilitate the detection of vehicles by the autonomous driving computer system **144**. FIG. 6 illustrates an example **602** of the autonomous vehicle **102** in a driving environment. The detailed map **502** may correspond to the driving environment of FIG. 6. In the example **602**, the autonomous vehicle **102** may detect one or more vehicles, such as vehicles **604-608**, using the vehicle detection algorithm **124**. The vehicles **604-608** may be within range of one or more of the sensor fields projected by the autonomous vehicle **102**, such as the laser sensor field **404** and the camera sensor field **424**. The vehicles **604-608** may be within range of other sensor fields, but these other sensor fields have been omitted for simplicity and clarity.

In the example of FIG. 6, the vehicles **604-608** and the autonomous vehicle **102** may be in various lanes of the driving environment. In particular, the vehicle **604** may be in the lane **514**, the vehicle **606** may be in the lane **516**, and the vehicle **608** may be in the lane **520**. The autonomous vehicle **102** may be in the lane **516**.

The autonomous driving computer system **144** may receive data from sensors regarding various objects in the autonomous vehicle's surroundings. For example, the autonomous driving computer system **144** may receive data regarding the vehicles **604-608** from the laser **304** (corresponding to the laser sensor field **404**) and from the one or more of the cameras **314/316** (corresponding to the camera sensor field **404**). FIG. 7 illustrates a camera image **702** captured using one or more of the cameras **314/316**. FIG. 8 illustrates an example of a laser point cloud image **802** generated using data from the laser **304**. The view shown in the laser point cloud image **802** may approximate the view shown in the camera image **702**.

In one embodiment of the cross-validation algorithm **140**, the autonomous driving computer system **144** may determine which of the sensors to cross-validate, i.e., which of the sensors to evaluate. In one example, the autonomous driving computer system **144** may determine that the laser **304** is to be cross-validated. As noted above the autonomous driving computer system **144** may determine to cross-validate the laser **304** based on such factors as time (e.g., when the laser **304** was last cross-validated), distance (e.g., how far the autonomous vehicle **104** travelled since last cross-validating the

14

laser **304**), manual request (e.g., a passenger requests cross-validation of the laser **304**), or any other such factors or combination of factors.

The autonomous driving computer system **144** may then select a first sensor by which to cross-validate the sensor determined for validation above. For example, the autonomous driving computer system **144** may select one or more of the cameras **314/316** to perform the cross-validation of the laser **304**. Selection of the cameras **314/316** may be based on one or more selection criterion, such as when the cameras **314/316** were used in a cross-validation or cross-validated themselves, whether the cameras **314/316** are operating within expected parameters, time between cross-validations, and other such criterion.

In cross-validating a sensor, the autonomous driving computer system **144** may be configured to cross-validate the sensor based on one or more parameters. For example, the autonomous vehicle computer system **144** may be configured to cross-validate one or more of the sensors **126** at predetermined time intervals, such as every thirty seconds, every minute, every ten minutes, and so forth. As another example, the autonomous vehicle computer system **144** may be configured to cross-validate one or more of the sensors **126** based on distance travelled by the autonomous vehicle **102**, such as every ten meters, every one hundred meters, and so forth. Moreover, different sensors **126** may be cross-validated at different intervals [you have time and distance in the example], e.g., a camera sensor may be cross-validated every ten minutes and a laser sensor may be cross-validated every ten meters.

In cross-validating the sensors of the autonomous vehicle **102**, the autonomous driving computer system **144** may use the objects detected in the images produced from the various sensor **14**. For example, the autonomous driving computer system **144** may perform vehicle detection on the captured camera image **702** according to the vehicle detection algorithm **124**. In this regard, the autonomous driving computer system **144** may refer to one or more of the sensor parameters **148**, such as the camera parameters previously discussed, to determine whether there are objects present in the captured camera image **702**, and which of the objects are vehicles.

When the autonomous driving computer system **144** detects an object, the autonomous driving computer system **144** may apply an object label to the detected object based on one or more of the sensor parameters **148** previously discussed. The object label may be defined by a bounding box encompassing the object. In alternative embodiments, the object label may be defined by a bounding oval or other bounding shape. FIGS. 9-10 illustrate examples of object labels being applied to various objects (i.e., vehicles) detected in the camera image **702** and the laser point cloud image **802**.

An object label may have one or more object label parameters that define the shape of the object label. The object label parameters may be defined by one or more of the instructions **110**, such as the vehicle detection algorithm **124**. Moreover, the object label parameters may vary depending on the sensor type of the sensor that captured the image. For example, where the shape of the object label is a bounding box, and the sensor that captured the image is a one or more of the cameras, the object label parameters may include a height parameter that defines the height of the bounding box (e.g., in pixels), a width parameter that defines the width of the bounding box (e.g., in pixels), a first pixel coordinate that defines the latitudinal placement of the bounding box (e.g., an X-coordinate), and a second pixel coordinate that defines the longitudinal placement of the bounding box (e.g., a Y-coordinate).

15

Where the sensor that captured the image is one or more of the lasers, the object label parameters may also include a third pixel coordinate that defines the physical height of the object or a particular laser point depicted in the captured image (e.g., a Z-coordinate). This third pixel coordinate should not be confused with the height parameter of the object label, because this third pixel coordinate may indicate the elevation of the detected object or of a given laser point (e.g., 3 meters above sea level, 2 meters above sea level, etc.) This third pixel coordinate may further indicate the height of the detected object or laser point relative to the autonomous vehicle **102**.

Where the sensor that provides data about the object is one or more of the radar detection units, the object label parameters may include a height parameter that defines the height of the height of the bounding box (e.g., in pixels), a width parameter that defines the width of the bounding box (e.g., in pixels), a first pixel coordinate that defines the latitudinal placement of the bounding box (e.g., an X-coordinate), and a second pixel coordinate that defines the longitudinal placement of the bounding box (e.g., a Y-coordinate).

FIG. 9 illustrates an example of object labels **902-906** having been applied to vehicles detected in the camera image **702** based on the vehicle detection algorithm **124**. As previously discussed, the object labels **902-906** may take the form of a rectangular bounding box that encompasses a detected object. In FIG. 9, the object label **902** may be applied to the vehicle **604**, the object label **904** may be applied to the vehicle **606**, and the object label **906** may be applied to the vehicle **608**.

The autonomous driving computer system **144** may store various parameters about the object labels **902-906**. These parameters may include two-dimensional coordinates for each of the vertices of the object labels **902-906**, the width of each of the object labels **902-906**, the height of each of the object labels **902-906**, and other such parameters.

Having detected the vehicles **604-608**, the autonomous driving computer system **144** may also determine state information for each of the vehicles **604-608**. State information may include characteristics about the detected vehicles **604-608**. Examples of state information include, but are not limited to, the detected vehicle's speed, the path traveled by the vehicle, the driving environment in which the vehicle is traveling, any directional or orientation changes by the vehicle, or other such state information. The state information may also be associated with one or more segments of the detailed map information **114** to further refine the state of the detected vehicle. For example, where the detected vehicle is detected as being on a highway (as defined by the detailed map information **114**), the collected state information may identify that the detected vehicle was traveling in a highway, and may further identify the direction of the detected vehicle, various positional information or changes about the detected vehicle (e.g., the original starting lane of the detected vehicle, the ending lane of the detected vehicle), and other such state information.

In determining state information for one or more of the vehicles **604-608**, the autonomous driving computer system **144** may determine the state information based on one or more state information parameters. Determining state information for a vehicle may be based on a number of state information parameters associated with the sensor data including predetermined time intervals, distance traveled by the autonomous vehicle **102**, number of images produced by the sensor data, clarity and/or accuracy of the images, and other such factors.

For example, with regard to time, the autonomous driving computer system **144** may determine the state information for

16

a vehicle based on one or more camera images, laser point cloud images, radar intensity images, and so forth, produced over a period of two seconds, five seconds, one minute, or other measurement of time.

With regard to distance, the autonomous driving computer system **144** may determine the state information for a vehicle based on one or more images produced over a distance of five meters, ten meters, one kilometer, or other measurement of distance.

Similarly, with regard to the number of images, the autonomous driving computer system **144** may determine the state information for a vehicle based on two images, three images, fifteen images, or any other number of images. Combinations of the state information parameters being used in the determination of the state information for a vehicle are also possible.

State information for one or more of the detected vehicles **604-608** may be used to cross-validate the laser **304**. To determine state information for one or more of the vehicles **604-608**, the autonomous driving computer system **144** may track and/or monitor the vehicles **604-608** as they travel in the driving environment. In this regard, the state information determined about each of the detected vehicles **604-608** may include the vehicle's position, the vehicle's speed, the vehicle's direction of travel, and other such information. In one embodiment, the autonomous driving computer system **144** may determine this state information from additional camera images (not shown) captured by the one or more cameras **314/316** (e.g., through one or more extrapolation techniques).

The autonomous driving computer system **144** may also determine whether any of the vehicles **604-608** are expected in the field of view of the sensor being cross-validated (i.e., the laser **304**). The autonomous driving computer system **144** may perform this determination by determining the position of the vehicles **604-608** relative to the detailed map information **114**, and then extrapolating whether the field of view of the laser **304** (i.e., within the sensor field **404**) would encompass the vehicles' positions. The vehicles that the autonomous driving computer system **144** determines would be within the field of view of the laser **304** may be used to cross-validate the laser **304**.

For example, the autonomous driving computer system **144** may determine that each of the vehicles **604-608** are within the field of view of the laser **304**. More generally, the autonomous driving computer system **144** may exclude objects having been detected by the sensor being used in the cross-validation (i.e., the reference sensor), but not within the field of view of the sensor being cross-validated (i.e., the sensor being evaluated). In this regard, the autonomous driving computer system **144** may ensure that only objects appearing in the field of view for both the reference sensor and the sensor being evaluated are used in the cross-validation.

In one embodiment, cross-validation of a sensor may be performed by leveraging the state information determined from the sensor readings of the reference sensor. In general, the autonomous driving computer system **144** may determine vehicle state information based on sensor readings from the reference sensor, and then compare the vehicle state information determined from sensor readings of the reference sensor with vehicle state information determined from the sensor readings of the sensor being evaluated. With reference to the cameras **314/316** (i.e., the reference sensor(s)) and the laser **304** (i.e., the sensor to be evaluated), the autonomous driving computer system **144** may determine vehicle state information based on the sensor readings from one or more of the cameras **314/316**, determine vehicle state information based on the sensor readings from the laser **304**, and then compare

17

the state information determined from the one or more cameras **314/316** with the state information determined from the laser **304**. Based on this comparison, the autonomous driving computer system **144** may determine whether the laser sensor **304** is operating within operational parameters. Similar comparisons may be performed between other sensors used by the computer system **144** to detect and respond to objects external to the autonomous vehicle **102**.

In another embodiment, the autonomous driving computer system **144** may apply a first object label to a detected object for a first sensor, apply a second object label to the detected object for a second sensor, and then compare the applied first and second object labels. This may include one or more comparisons of various parameters associated with each object label, such as height and/or width comparisons, positional placement comparisons, vertex coordinate comparisons, object classification comparisons, and other such comparisons. Based on these one or more comparisons, the autonomous driving computer system **144** may determine whether the second sensor detected the object, and whether an accurate object label was applied to the detected object.

FIG. **10** illustrates an example of object labels **1002-1006** having been applied to the vehicles **604-608** detected by the laser **304**. The autonomous driving computer system **144** has applied an object label **1002** to the vehicle **604**, an object label **1004** to the vehicle **606**, and an object label to the vehicle **1006**.

The autonomous driving computer system **144** may determine which objects should receive object labels based on the laser sensor parameters previously discussed with reference to FIG. **1**. In addition, the autonomous driving computer system **144** may identify disturbances and/or differences in the captured laser point cloud image **802** by comparing the captured laser point cloud image **802** with an expected laser point cloud image based on the detailed map information **114**. Areas of the captured laser point cloud image **802** that are different from the expected laser point cloud image based on the detailed map information **114** may indicate an object present in the captured laser point cloud image **802**. Those areas may then be analyzed by the autonomous driving computer system **144** to determine whether an object is present in that area. The autonomous driving computer system **144** may then classify the object based on the stored vehicle data **116**.

As with determining state information for the vehicles **604-606** based on one or more captured camera images, the autonomous driving computer system may determine state information for the vehicles **604-606** based on one or more laser point cloud images by comparing consecutive captured laser point cloud images. The autonomous driving computer system **144** may then store the state information determined from the laser point cloud images as part of the vehicle data **116**.

Determining state information from the sensor data of two different sensors may be based on the same or different state information parameters. For example, the state information parameters used in determining the state information based on the laser point cloud images may be the same, or different from, the state information parameters used in determining state information for the vehicles based on the captured camera images. In this regard, determining state information based on the laser point cloud images may be based on laser point cloud images captured over a distance of two meters, whereas determining state information based on the camera images may be based on camera images captured over a period of two minutes. The values of the state information parameters may also vary (e.g., a time period state informa-

18

tion parameter for the camera may be thirty seconds and a time period state information parameter for the laser sensor may be every minute).

The autonomous driving computer system **144** may then compare the state information determined from the determined sensor data with the state information determined from the sensor data from the first sensor selected to cross-validate the determined sensor. Moreover, the cross-validation algorithm **140** may contain instructions such that the autonomous driving computer system **144** compares state information for only objects that appear both in the field of view of the one or more cameras **314/316** and in the field of view of the laser **304**.

Comparing state information for one or more vehicles may include comparing any number of vehicle characteristics. For example, comparing state information may include a comparing vehicle's position, a vehicle's speed, a vehicle's heading (i.e., direction of travel), the size of a vehicle, the type of vehicle, or any other combination of characteristics. Furthermore, the autonomous driving computer system **144** may compare the state information relative to the detailed map information **114** (e.g., the detailed map **502**) and/or relative to the autonomous vehicle **102**. For example, the autonomous driving computer system **144** may compare the position of the vehicle **604** determined from one or more camera images with the position of the vehicle **604** determined from one or more laser point cloud images, relative to the autonomous vehicle **102** or relative to the detailed map **502**. Similarly, the autonomous driving computer system **144** may compare the speed of the vehicle **604** determined from one or more camera images with the speed of the vehicle **604** determined from one or more laser point cloud images, relative to the autonomous vehicle **102** or relative to the detailed map **502**. Comparing the state information may also be in terms absolute values.

In one embodiment, the results of comparing the state information from the various sensors should indicate that the state information obtained from the sensors is substantially, or nearly, identical. Otherwise, deviations (i.e., differences) in the state information may indicate that a sensor (i.e., the laser **304**) is experiencing a problem. To determine whether there are differences, and the extent of those differences, the autonomous driving computer system **144** may employ one or more state information thresholds. For example, there may be a positional threshold (e.g., one meter), a speed threshold (e.g., 0.5 km/hr), a size threshold (e.g., height and/or width), a classification threshold (e.g., one size classification above or below), and other such state information thresholds.

In addition to the state information thresholds, the autonomous driving computer system **144** may establish a multi-level failure threshold based on the compared state information. The multi-level failure threshold may include escalating levels of failure that indicate the extent to which a sensor being cross-validated (i.e., laser **304**) is experiencing a problem. For example, the multi-level failure threshold may have a first level of one threshold difference, a second level of two threshold differences, a third level of three threshold differences, and so forth. Thus, where the compared state information indicates that the state information position threshold has been exceeded, the autonomous driving computer system **144** may record that the first level of the multi-level failure threshold was reached. Similarly, where the compared state information indicates that the state information position threshold and the state information speed threshold have been exceeded, the autonomous driving computer system **144** may record that the second level of the multi-level failure threshold was reached.

Based upon the level of failure reached in the multi-level failure threshold, the autonomous driving computer system **144** may take a variety of actions. For example, at the first level of the multi-level failure threshold, the autonomous driving computer system **144** may record in an electronic log that the first level was reached. At the second level of the multi-level failure threshold, the autonomous driving computer system **144** may display an error message. At the third level, the autonomous driving computer system **144** may request that a passenger take control of the autonomous vehicle **102**. In this manner, the multi-level failure threshold serves as a safety mechanism to alert a passenger when there is a problem with a sensor being cross-validated.

The autonomous driving computer system **144** may also maintain a total failure count threshold. The total failure count threshold may be in addition to the multi-level failure threshold. The total failure count threshold may be a threshold based on the number of times a state information threshold has been exceeded, either during the cross-validation of a sensor, the lifetime of a sensor, or at any other time. There may be a global total failure count threshold (i.e., a failure count threshold for all the sensors **146** of the autonomous vehicle **102**), total failure count thresholds for each sensor of the autonomous vehicle **102**, or combinations thereof. Furthermore, each of the state information characteristics (e.g., position, speed, heading, etc.) may each have their own failure count threshold. The failure count threshold may be as low as five (or lower) or as high as ten (or higher).

Similar to the multi-level failure threshold, the autonomous driving computer system **144** may take a variety of actions based on the value of the total failure count threshold (global or individual sensor), based on the values of the individual failure count thresholds for the state information, or a combination thereof. For example, each time the individual sensor total failure count is increased, the autonomous driving computer system **144** may record this fact in an electronic log. However, when the individual sensor total failure count is equal to or greater than a first predetermined value (e.g., fifty), the autonomous driving computer system **144** may display an error message regarding the failure (e.g., the fact that a sensor failed to cross-validate, that a specific state information characteristic was different, etc.). Moreover, when the individual sensor total failure count is equal to or greater than a second predetermined value (e.g., two hundred), the autonomous driving computer system **144** may request that a passenger take control of the autonomous vehicle **102**.

Each of the failure thresholds (e.g., the multi-level failure threshold and/or the failure count threshold(s)), may be used to quickly identify different problems in the sensors of the autonomous vehicle **102**. For example, the multi-level failure threshold may be used to identify a single, catastrophic failure in a sensor (e.g., the failure count may be low, but all of the state information thresholds may have been exceeded). As another example, a failure count threshold may be used to identify an intermittent problem, such as where a failure count threshold is increased at time t_0 , not increased at time t_1 (e.g., one minute from time t_0), but then increased again at time t_2 (e.g., two minutes from time t_2). In this regard, the various failure thresholds for the compared state information serve as safety mechanisms to readily identify potential failures or problems in sensors being cross-validated.

As mentioned above, comparing determined state information may encompass one embodiment of the cross-validation algorithm **140**. In another embodiment of the cross-validation algorithm **140**, the autonomous driving computer system **144** may be configured to compare the object labels applied to the

objects detected in the captured images (e.g., the camera image **702** and the laser point cloud image **802**).

FIG. **11** illustrates an example **1102** of comparing a first object label (e.g., object label **902**) and a second object label (e.g., object label **1002**). The autonomous driving computer system **144** may compare various characteristics of the object labels **902,1002**. For example, the autonomous driving computer system **144** may compare the height and/or width of the object labels **902,1002**, the placement of the object labels **902,1002** in the camera image **702** and the laser point cloud image **802**, the individual locations of the vertices of the object labels **902,1002** relative to their respective images **702,802**, and other such characteristics.

FIG. **11** illustrates comparing the height and width of the object labels **902,1002**. When corrected for perspective (e.g., the laser point cloud image **802** may be slightly skewed compared to the camera image **702**), a comparison of the height and width of the object labels **902,1002** may serve as a proxy for determining whether the laser **304** is operating within expected parameters.

In comparing the object labels **902,1002**, the autonomous driving computer system **144** may determine a number of object label deviations. The number of object label deviations may be dependent on the number of sides of the object label. For example, where the object label is a polygon, such as a rectangular bounding box, the object label deviations may include four deviations: a first height deviation **1104**, a second height deviation **1108**, a first width deviation **1106**, and a second width deviation **1110**. The number of deviations may be more where there are more sides to the object labels, such as in the case of pentagons, hexagons, or other multi-sided polygons, or the number of deviations may be less, such as in the case of triangles, circles, ovals, or other similar shapes.

The object label deviations may be measured in physical units (e.g., centimeters, meters, etc.) or in electronic units (e.g., pixels). In this regard, the deviations may be assigned values based on the physical characteristics of the object encompassed by the object label (e.g., vehicle **604**) or the deviations may be assigned values based on the characteristics of the captured image in which the object appears.

In addition to determining object label deviations based on individual comparisons (e.g., the comparison of object label **902** with the object label **1002**), the autonomous driving computer system **144** may also determine deviations based on an aggregation of comparisons, such as ten, twenty, or more comparisons. In this regard, the comparisons may include a first comparison of a first object label applied to the vehicle **604** in a first image captured by the one or more cameras **314/316** with a first object label applied to the vehicle **604** in a first image captured by the laser **304**, a second comparison of a second object label applied to the vehicle **604** in a second image captured by the one or more cameras **314/316** with a second object label applied to the vehicle **604** in a second image captured by the laser **304**, and so forth.

The object label deviations determined from the aggregation of comparisons may include one or more maximum deviations, one or more average deviations, and one or more average signed deviations. For example, there may be four maximum deviations, four average deviations, and four average signed deviations (i.e., a total of twelve deviations), where each deviation corresponds to a side of a rectangular bounding box, such as the object labels **902, 1002**. There may be more or less maximum, average, and signed average deviations depending on the number of sides of the object labels being compared.

The values of the maximum deviation(s), average deviation(s), and/or average signed deviation(s) may vary. In par-

ticular, the value of the maximum deviation may equal the value of the maximum difference for a compared set of deviations (e.g., thirty pixels, twenty pixels, fifty meters, etc.). The value of the average deviation may equal the average value of the differences for a compared set of deviations (e.g., two pixels, one meter, etc.). The value of the average signed deviation may equal the average value of the differences for a compared set of deviations and may also indicate whether a side of a object label is shifted to the left/down (where the average signed deviation is negative) or shifted to the right/up (where the average signed deviation is positive). Examples of values for the average signed deviation may include -10 pixels, +10 pixels, -2 meters, +2 meters, and other such values. The maximum, average, and average signed deviations may be based on all sides being compared, for a single side being compared, or combinations thereof.

In one embodiment, the autonomous driving computer system 144 may establish one or more deviation thresholds by which to compare the aforementioned deviations, including the object label deviations 1104-1110. In this regard, the autonomous driving computer system 144 may establish one or more deviation thresholds for a singular object label (e.g., a first height object label deviation threshold) and/or one or more deviation thresholds for the determined maximum deviation, the determined average deviation, and the determined average signed deviation.

Comparisons of the deviations with their corresponding deviation thresholds may indicate whether the sensor being cross-validated is experiencing a problem and the extent of that problem. For example, a comparison of the maximum deviation with the maximum deviation threshold may indicate the magnitude of the problem being experienced by the sensor. Similarly, a comparison of the average signed deviation with the average signed deviation threshold may, not only indicate the magnitude of the problem being experienced by the sensor, but also the extent to which the sensor may be improperly calibrated (e.g., are the sensor readings too far to the left, too far to the right, too high up, too far down, etc.).

The values of the one or more deviation thresholds may be different, or the same as, each other. For example, a first width deviation threshold may have the same value as a second width deviation threshold. However, the values may also be different. Similarly, a first height deviation threshold may have the same or different value as a second height deviation threshold.

Combinations of the foregoing embodiments are also possible. For example, in comparing state information determined from the one or more cameras 314/316 with the state information determined from the laser 304, the autonomous driving computer system 144 may establish a maximum deviation and maximum deviation threshold, an average deviation and an average deviation threshold, and an average signed deviation and an average signed deviation threshold. Similarly, in comparing object labels (e.g., object labels 902, 1002), the autonomous driving computer system 144 may establish a multi-level failure threshold for monitoring when one or more of the height and/or width deviation thresholds have been exceeded, and the autonomous driving computer system 144 may establish a failure count threshold for monitoring the number of times one or more of the deviation thresholds for the object labels 902, 1002 have been exceeded.

FIG. 12 illustrates an example of logic flow 1202 for cross-validating a sensor of the autonomous vehicle 102. Initially, one or more sensors 146 of the autonomous vehicle may capture one or more images of the driving environment

(Block 1204). As discussed with reference to FIG. 7 and FIG. 8, these images may include camera images and/or laser point cloud images.

The autonomous driving computer system 144 may then select which sensor to use a reference sensor (e.g., one or more of the cameras 314/316) and which sensor to cross-validate (e.g., the laser 304). The autonomous driving computer system 144 may then determine whether, and which, objects appearing in one or more images captured by the reference sensor are in one or more images captured by the sensor to be cross-validated (Block 1206). The autonomous driving computer system 144 may then apply object labels to the objects appearing in both sets of images (Block 1208). Alternatively, the object labels may be applied to objects in the first and second set of images, and then the autonomous driving computer system 144 may determine which objects the first and second set of images have in common.

The autonomous driving computer system 144 may then determine state information from the one or more common objects appearing in the one or more images captured by the reference sensor and determine state information for the same objects appearing in the one or more images captured by the sensor being cross-validated (Block 1210). As previously discussed, the state information may include position (relative to the autonomous vehicle 102 and/or driving environment), changes in position, speed (also relative to the autonomous vehicle 102 and/or driving environment), changes in speed, heading, and other such state information.

The autonomous driving computer system 144 may then compare the state information for the common objects to determine one or more deviation values (Block 1212). As previously discussed, the deviation values may include deviation values specific to individual state characteristics (e.g., a positional deviation value, a speed deviation value, etc.) but may also include deviation values determined in the aggregate (e.g., a maximum deviation value, an average deviation value, and an average signed deviation value).

Alternatively, or in addition, the autonomous driving computer system 144 may compare the object labels applied to the common objects (Block 1214). Comparing the object labels may include comparing the object labels from images captured at approximately the same time and/or comparing the object labels from one or more images captured during a predetermined time interval. As with the comparison of the state information, the autonomous driving computer system 144 may determine various deviation values based on the comparison of the object labels.

The autonomous driving computer system 144 may then determine whether the sensor being cross-validated is having a problem (Block 1216). As discussed previously, the autonomous driving computer system 144 may perform this determination by comparing one or more of the determined deviation values with one or more deviation thresholds. The autonomous driving computer system 144 may also establish one or more failure thresholds (e.g., the multi-level failure threshold, the failure count threshold, etc.) that may be exceeded when one or more of the deviation values exceed their corresponding deviation thresholds. The autonomous driving computer system 144 may be configured to perform a variety of actions (e.g., record in an electronic log, display a warning message, request a passenger to take control of the autonomous vehicle, etc.) based on whether one or more of the failure thresholds are exceeded.

In this manner, the autonomous driving computer system 144 determines whether a sensor is experiencing a problem based on sensor readings obtained from another sensor (i.e., the reference sensor). The sensors may even be different types

23

of sensors. Moreover, the autonomous driving computer system 144 may be configured to determine whether the sensor being cross-validated has experienced a catastrophic failure (e.g., the sensor readings from the sensor being cross-validated are substantially different than the sensor readings from the reference sensor) or is experiencing an intermittent problem. As the cross-validation methods and system disclosed herein may be used to determine when a sensor is experiencing a problem, the safety and confidence of the autonomous vehicle in navigating a driving environment is enhanced.

Although aspects of this disclosure have been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present disclosure. It is therefore to be understood that numerous modifications may be made to the illustrative embodiments and that other arrangements may be devised without departing from the spirit and scope of this disclosure as defined by the appended claims. Furthermore, while certain operations and functions are shown in a specific order, they may be performed in a different order unless it is expressly stated otherwise.

The invention claimed is:

1. An apparatus comprising:

a first sensor configured to detect a vehicle in a driving environment;

a second sensor configured to detect the vehicle in the driving environment;

memory that stores:

detailed map information for the driving environment;

first sensor parameters for determining whether the vehicle is present in a first image of the driving environment;

second sensor parameters for determining whether the vehicle is present in a second image of the driving environment; and

a failure count threshold identifying an action to be performed when the failure count threshold is exceeded; and

one or more processors in communication with the memory, the first sensor and the second sensor, the one or more processors being configured to:

receive first sensor information from the first sensor, the first sensor information being used to produce the first image;

receive second sensor information from the second sensor, the second sensor information being used to produce the second image;

determine whether the vehicle is in both the first image and the second image;

determine a deviation value by comparing the first image with the second image when it is determined that the vehicle is present in the first image and the second image; and

compare the determined deviation value with a deviation threshold to determine whether the first or second sensor has a problem detecting the vehicle, wherein the comparison of the determined deviation value with the deviation threshold causes the failure count threshold to be exceeded; and

when the failure count threshold is exceeded, perform the action identified by the failure count threshold.

2. The apparatus of claim 1, wherein the first sensor is a first type of imaging sensor and the second sensor is a second type of imaging sensor, the first type of imaging sensor being different than the second type of imaging sensor.

3. The apparatus of claim 1, wherein the one or more processors are further configured to select the first sensor as a

24

reference sensor for determining whether the second sensor has the problem detecting the vehicle.

4. The apparatus of claim 3, wherein the one or more processors are configured to select the first sensor based on a predetermined time interval.

5. The apparatus of claim 3, wherein the one or more processors are configured to select the second sensor for cross-validation with the first sensor based on an amount of time that has elapsed since the second sensor was last cross-validated.

6. The apparatus of claim 1, wherein:

the memory further stores a multi-level failure threshold comprising a plurality of levels, each level of the plurality of levels is associated with an action for the processor to perform, the failure count threshold being a first level of the plurality of levels is associated with a condition of the deviation value exceeding the deviation threshold; and

the one or more processors are further configured to, prior to performing the action, identify the first level and the action associated with the failure count threshold when the condition of the deviation value exceeding the deviation threshold is met.

7. The apparatus of claim 1, wherein:

the first image comprises a plurality of images determined from the first sensor information, the first sensor information being received during a predetermined time interval;

the second image comprises a plurality of images determined from the second sensor information, the second sensor information being received during the predetermined time interval; and

the one or more processors are further configured to: determine first state information about the vehicle from the first plurality of images; determine second state information about the vehicle from the second plurality of images; and compare the first state information with the second state information to determine the deviation value.

8. The apparatus of claim 7, wherein:

the first state information comprises at least one of a first vehicle speed, a first vehicle position, or a first vehicle heading;

the second state information comprises at least one of a second vehicle speed, a second vehicle position, or a second vehicle heading; and

the one or more processors are further configured to compare at least one of the first vehicle speed, first vehicle position or first vehicle heading with at least one of the second vehicle speed, second vehicle position, or second vehicle heading.

9. The apparatus of claim 1, wherein:

the first image comprises a first object label encompassing the vehicle, the first object label comprising a first parameter that defines a characteristic of the first object label;

the second image comprises a second object label encompassing the vehicle, the second object label comprising a second parameter that defines a characteristic of the second object label; and

the one or more processors are configured to compare the first image with the second image to determine the deviation value by comparing the first object label with the second object label.

10. The apparatus of claim 9, wherein the processor compares the first object label with the second object label by comparing the first parameter with the second parameter.

25

11. A method comprising:

receiving, with one or more processors in communication with a first sensor, first sensor information, the first sensor information being used to produce a first image of a driving environment;

receiving, with the one or more processors in communication with the second sensor, second sensor information, the second sensor information being used to produce the second image of the driving environment;

determining, with the one or more processors, whether a vehicle is present in both the first image and the second image;

determining, with the one or more processors, a deviation value by comparing the first image with the second image when it is determined that the vehicle is present in the first image and the second image;

comparing, with the one or more processors, the determined deviation value with a deviation threshold to determine whether the first or second sensor has a problem detecting the vehicle, wherein the comparison of the determined deviation value with the deviation threshold causes a failure count threshold to be exceeded, the failure count threshold identifying an action to be performed when the failure count threshold is exceeded; and

when the failure count threshold is exceeded, perform the action identified by the failure count threshold.

12. The method of claim 11, wherein the first sensor is a first type of imaging sensor and the second sensor is a second type of imaging sensor, the first type of imaging sensor being different than the second type of imaging sensor.

13. The method of claim 11, further comprising:

selecting, with the one or more processors, the first sensor as a reference sensor for determining whether the second sensor has the problem detecting the vehicle.

14. The method of claim 13, further comprising:

selecting, with the one or more processors, the first sensor based on a predetermined time interval.

15. The method of claim 13, further comprising:

selecting, with the one or more processors, the second sensor for cross-validation with the first sensor based on an amount of time that has elapsed since the second sensor was last cross-validated.

16. The method of claim 11, further comprising:

determining whether the deviation value exceeds a deviation threshold associated with a first level of a multi-level failure threshold, each level of the plurality of levels is associated with an action for the processor to perform, the failure count threshold being the first level of the plurality of levels associated with a condition of the deviation value exceeding the deviation threshold; and

26

prior to performing the action, identifying the first level and the action associated with the failure count threshold when the condition of the deviation value exceeding the deviation threshold is met.

17. The method of claim 11, wherein:

the first image comprises a plurality of images determined from the first sensor information, the first sensor information being received during a predetermined time interval;

the second image comprises a plurality of images determined from the second sensor information, the second sensor information being received during the predetermined time interval; and

the method further comprises:

determining, with the one or more processors, the first state information about the vehicle from the first plurality of images;

determining, with the one or more processors, second state information about the vehicle from the second plurality of images; and

comparing, with the one or more processors, the first state information with the second state information to determine the deviation value.

18. The method of claim 17, wherein:

the first state information comprises at least one of a first vehicle speed, a first vehicle position, or a first vehicle heading;

the second state information comprises at least one of a second vehicle speed, a second vehicle position, or a second vehicle heading; and

the method further comprises:

comparing, with the one or more processors, at least one of the first vehicle speed, first vehicle position or first vehicle heading with at least one of the second vehicle speed, second vehicle position, or second vehicle heading.

19. The method of claim 11, wherein:

the first image comprises a first object label encompassing the vehicle, the first object label comprising a first parameter that defines a characteristic of the first object label;

the second image comprises a second object label encompassing the vehicle, the second object label comprising a second parameter that defines a characteristic of the second object label; and

the method further comprises:

comparing, with the one or more processors, the first image with the second image to determine the deviation value by comparing the first object label with the second object label.

20. The method of claim 19, wherein comparing the first object label with the second object label comprises comparing the first parameter with the second parameter.

* * * * *