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Du et al.

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(54) **CAMERA TO VEHICLE ALIGNMENT WITH MULTIPLE CAMERA ADJUSTMENT**

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G06T 3/12	(2024.01)
G06T 3/60	(2006.01)
G06T 7/33	(2017.01)

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CPC ***G06T 7/337*** (2017.01); ***G06T 3/12*** (2024.01); ***G06T 3/60*** (2013.01); *G06T 2207/30244* (2013.01); *G06T 2207/30252* (2013.01)

(58) **Field of Classification Search**

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USPC 348/148

See application file for complete search history.

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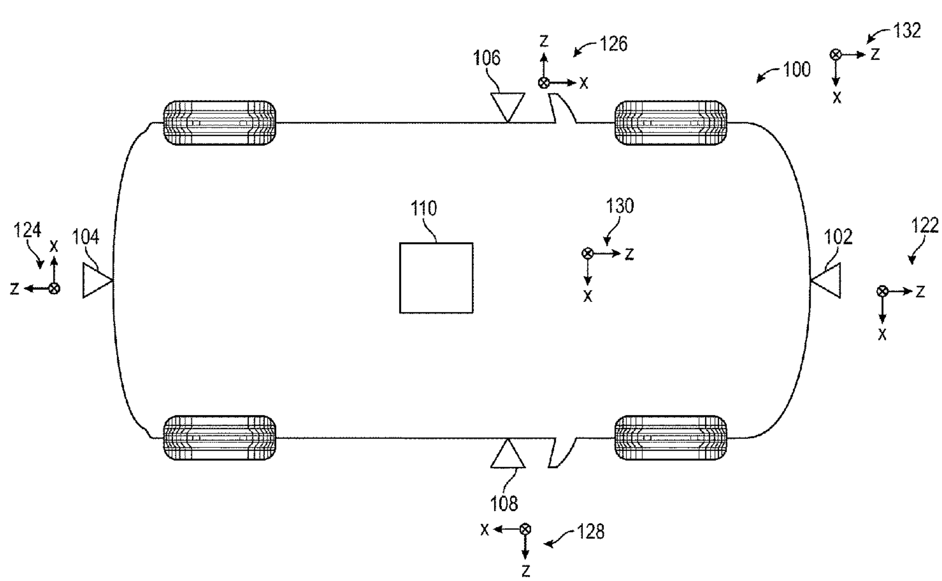
(57) **ABSTRACT**

A vehicle includes a system that performs a method for aligning a first camera and a second camera to a reference frame of the vehicle. The first camera has a first coordinate system, and the second camera has a second coordinate system. The first camera obtains a first image. The processor is configured to obtain a first camera-to-ground transformation matrix for the first camera using the first image, wherein the first camera-to-ground transformation matrix relates the first coordinate system to a ground coordinate system, obtain a camera-to-camera transformation matrix between the first coordinate system of the first camera and the second coordinate system of the second camera, calculate a constructed camera-to-ground transformation matrix for the second camera using the first camera-to-ground transformation matrix and the camera-to-camera transformation matrix, and update the second coordinate system of the second camera using the constructed camera-to-ground transformation.

20 Claims, 9 Drawing Sheets



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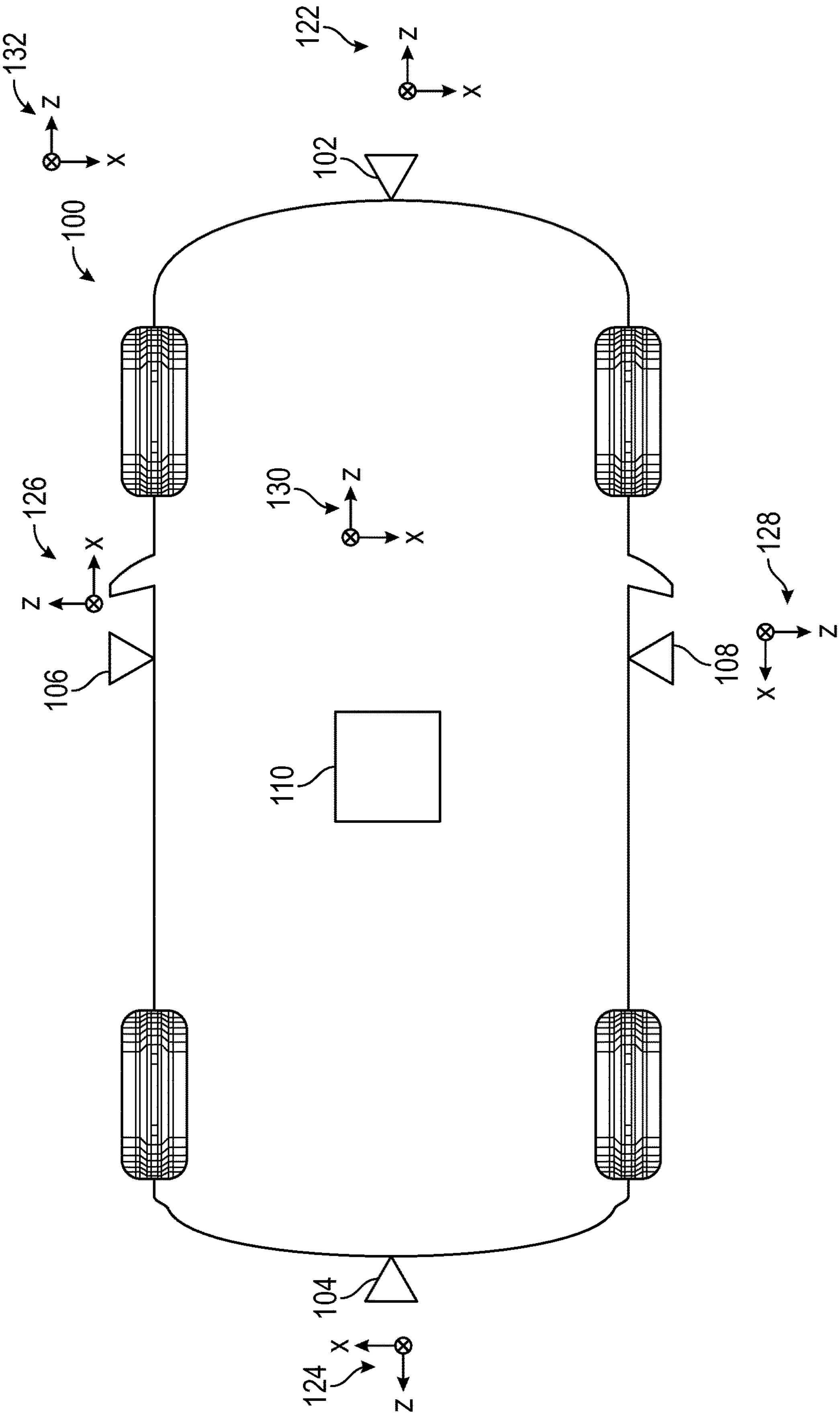

FIG. 1

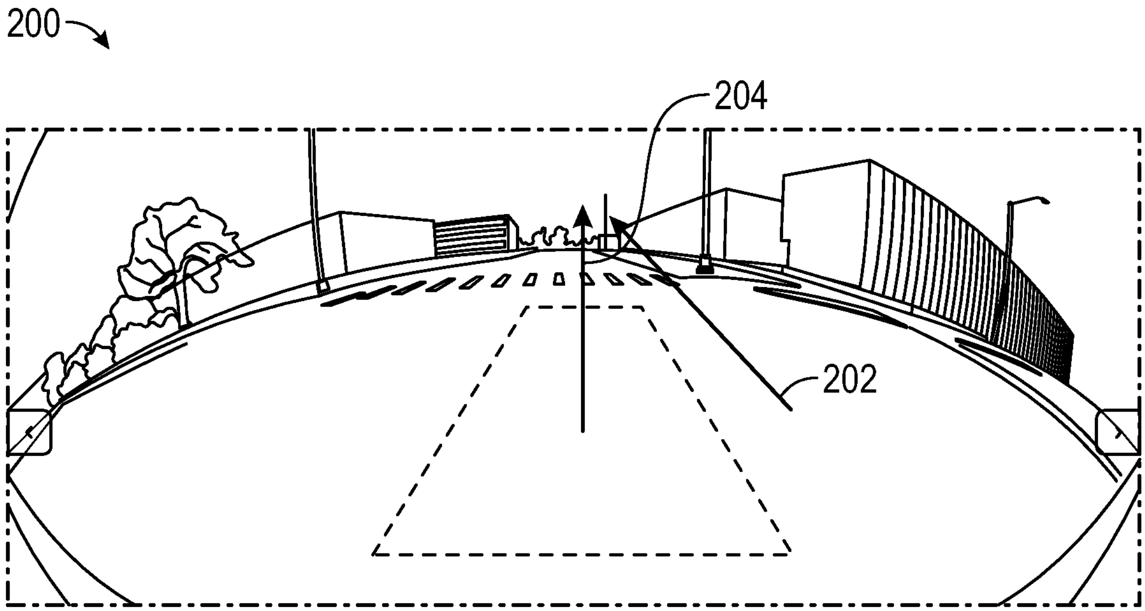
200
204
202

FIG. 2

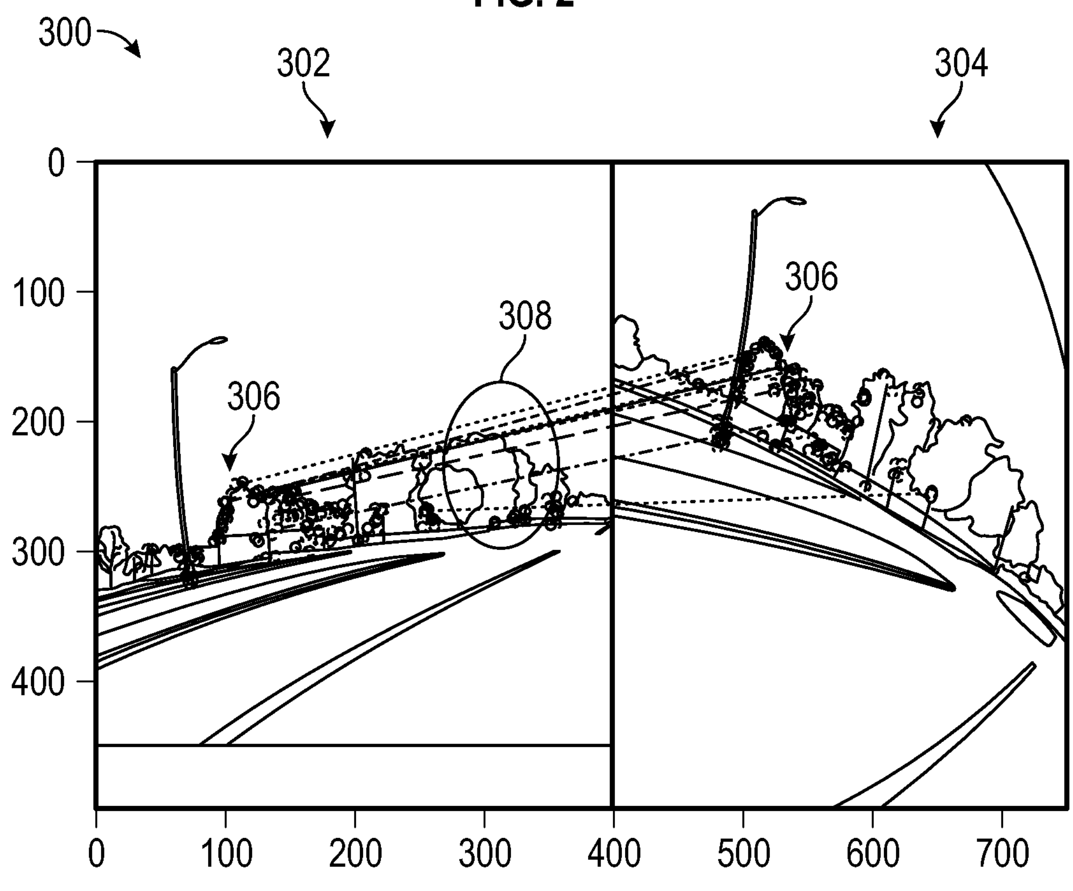
300
302
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FIG. 3

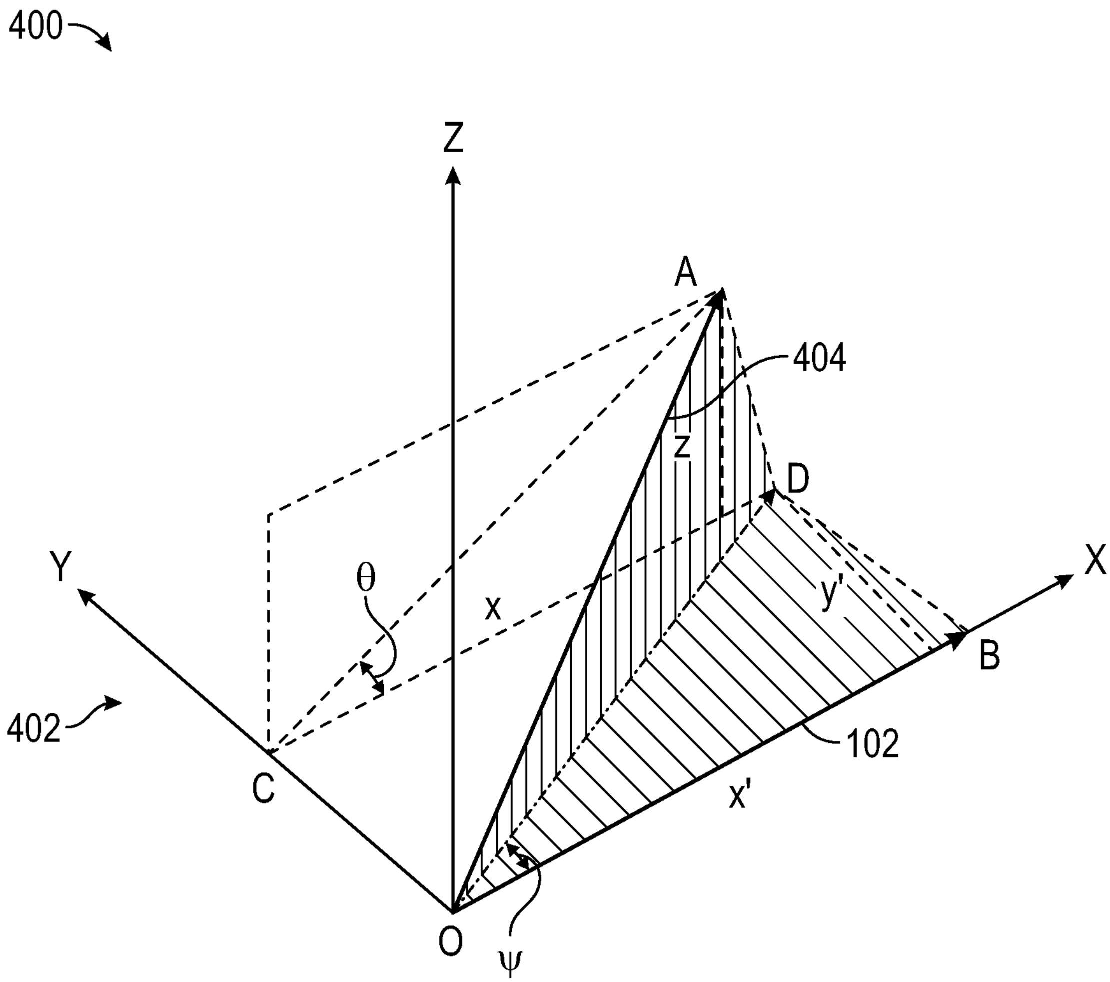

FIG. 4

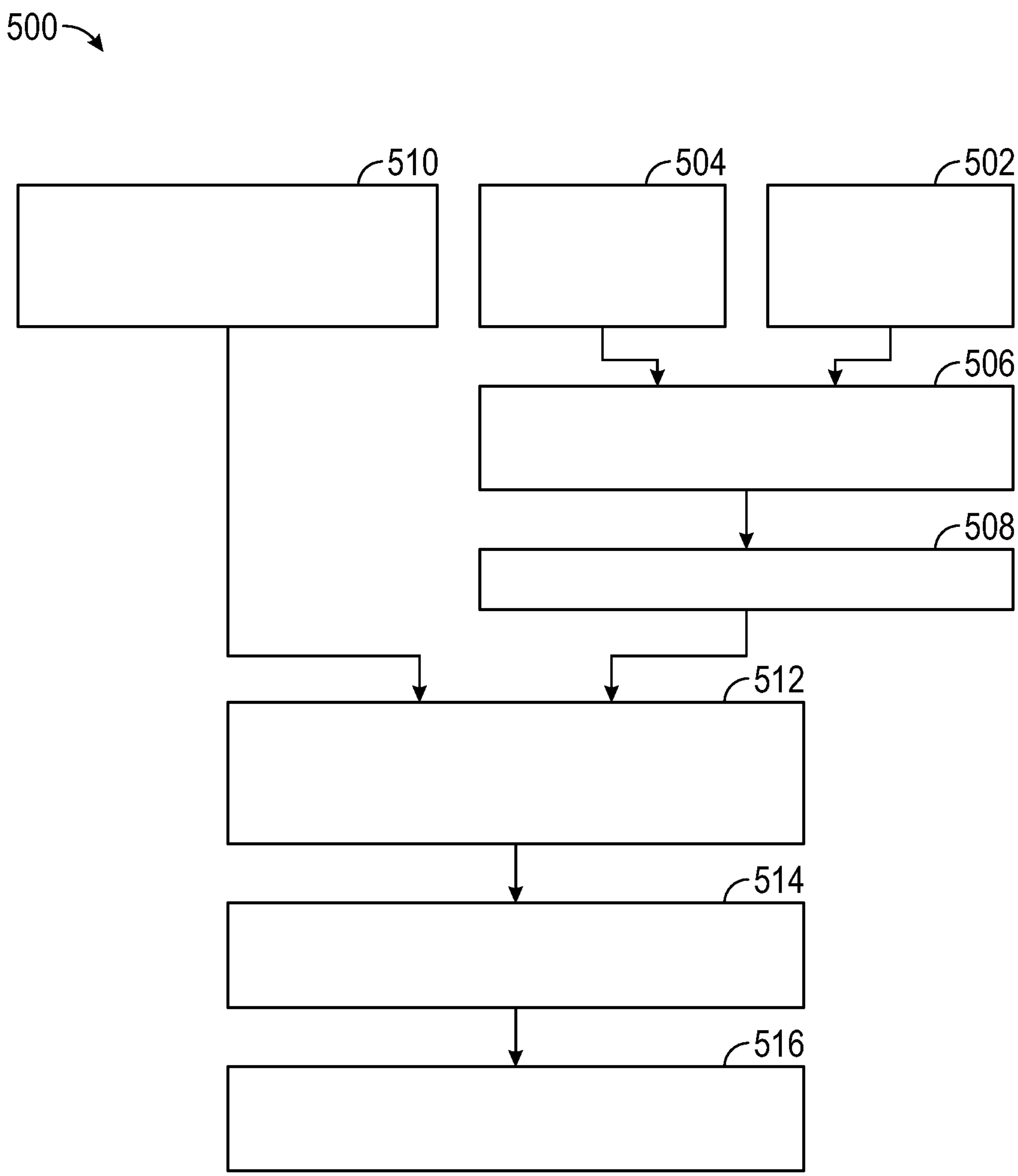

FIG. 5

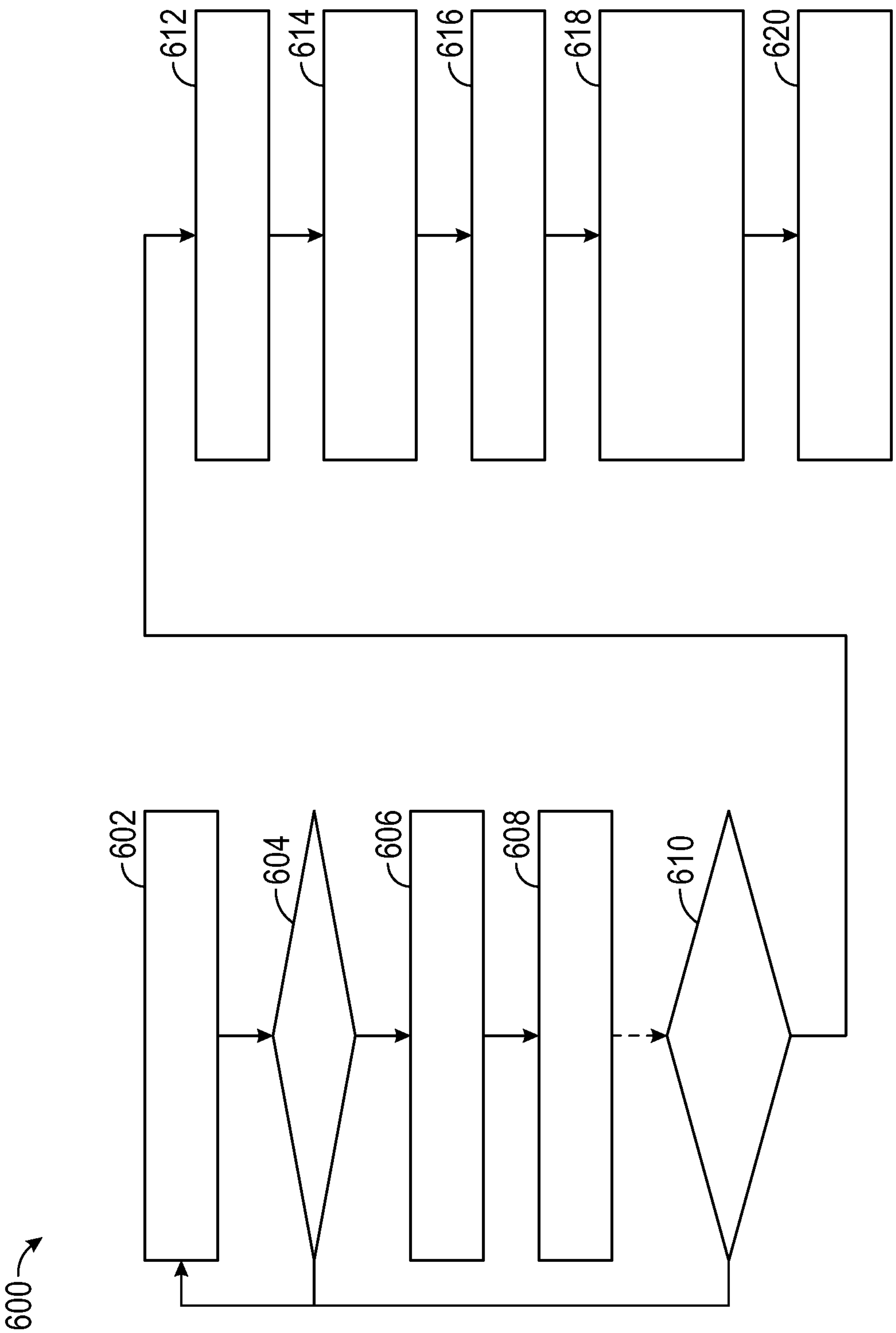

FIG. 6

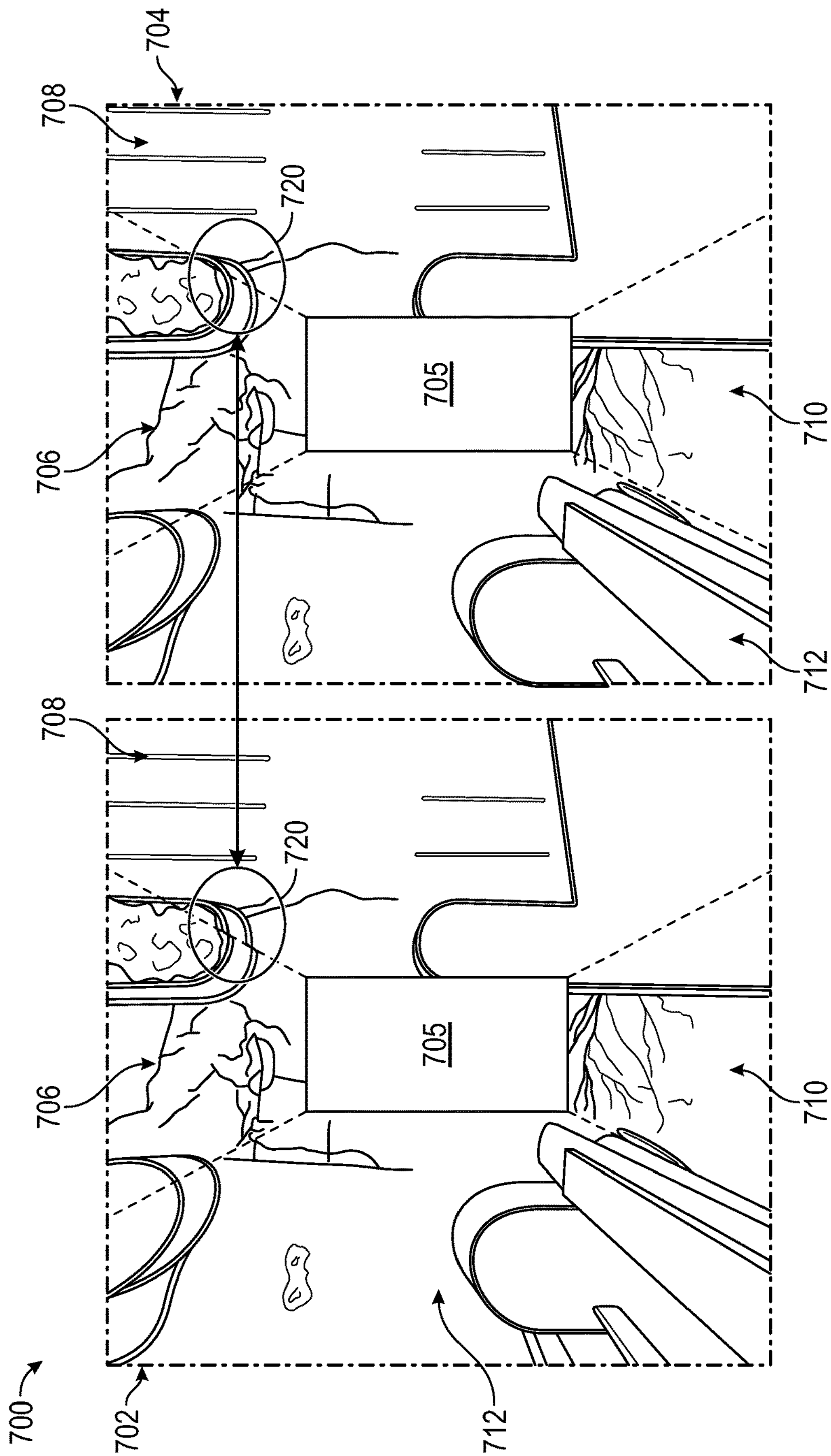

FIG. 7

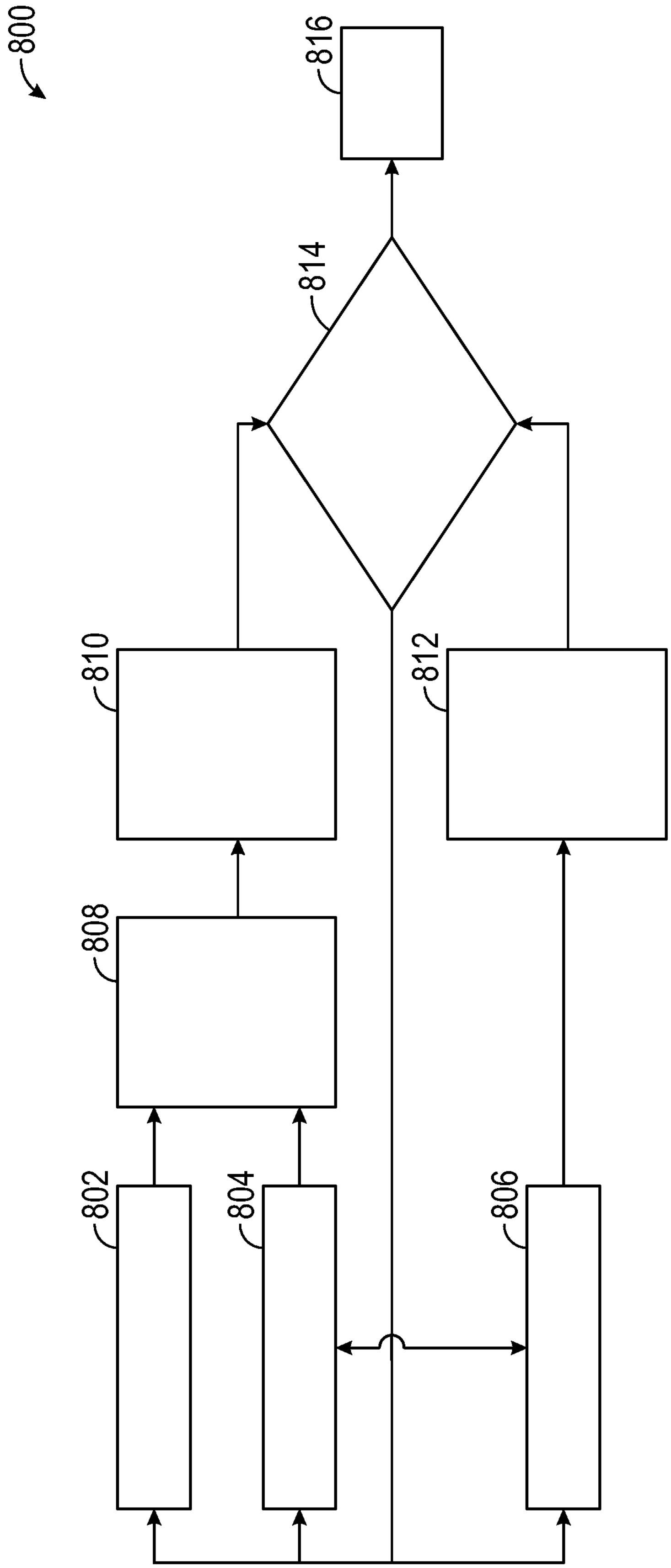

FIG. 8

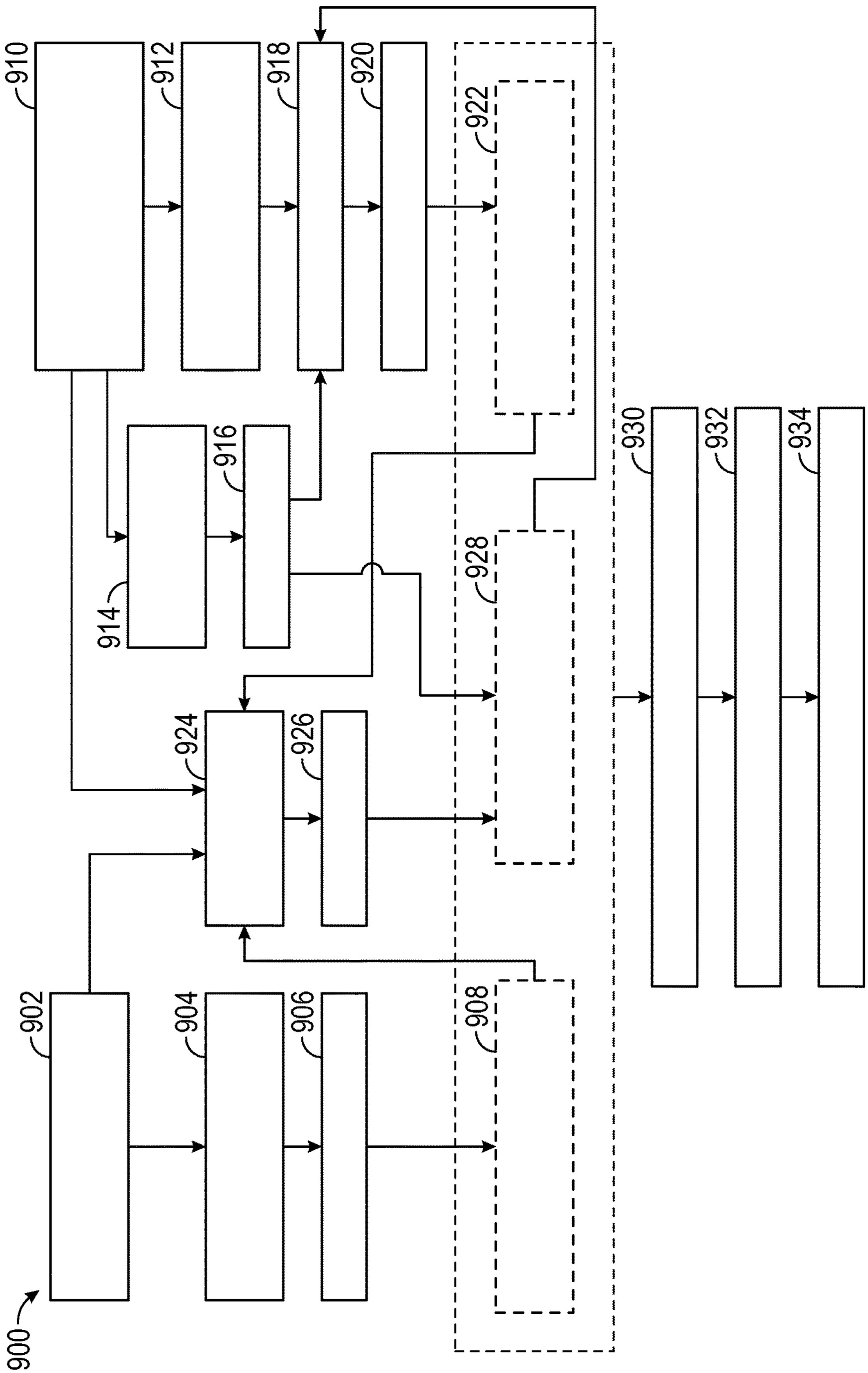
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FIG. 9

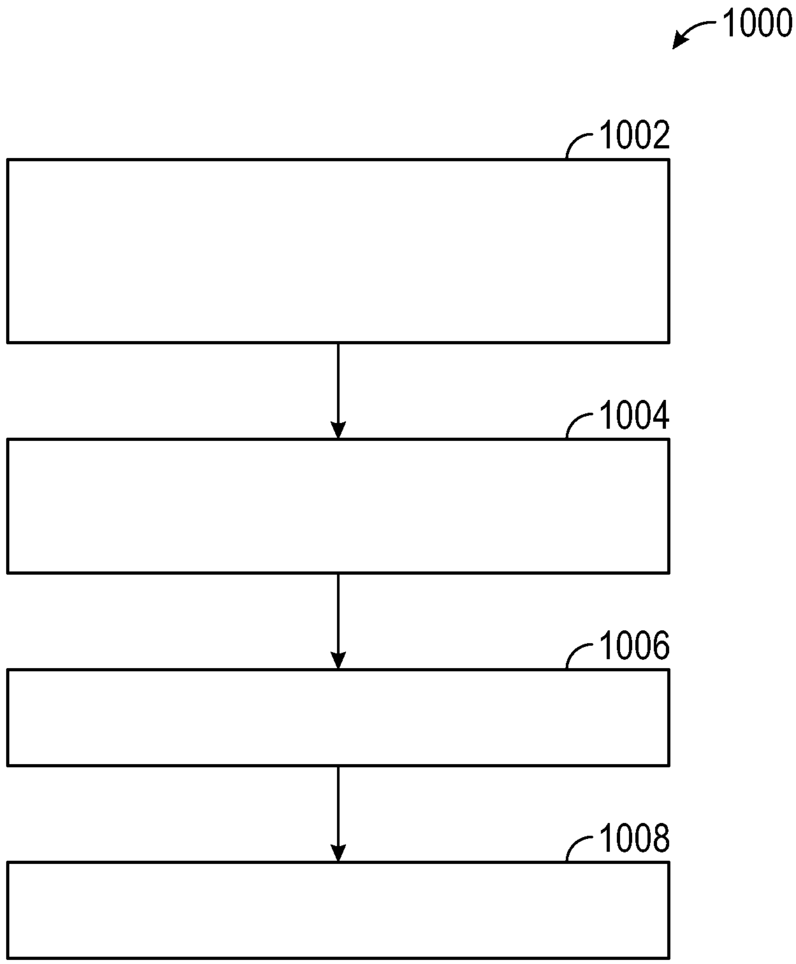

FIG. 10

CAMERA TO VEHICLE ALIGNMENT WITH MULTIPLE CAMERA ADJUSTMENT

INTRODUCTION

The subject disclosure relates to camera alignment of cameras in vehicles and, in particular, to a system and method for aligning reference frames of multiple cameras to a reference frame of a vehicle using images from the multiple cameras.

Camera-to-vehicle alignment is useful for perception and motion planning in vehicles. A camera-to-ground alignment process is used to align a camera reference frame to a ground reference frame. The results of the camera to ground alignment process can be used to align the camera to a vehicle reference frame. However, environment noise, driving maneuvers, or differences in road bank angle can affect the results of camera-to-ground alignment. Accordingly, it is desirable to provide a method of camera to vehicle alignment that overcomes these environmental effects.

SUMMARY

In one exemplary embodiment, a method of aligning a first camera of a vehicle and a second camera of the vehicle to a reference frame of the vehicle is disclosed. A first camera-to-ground transformation matrix is obtained for the first camera using a first image obtained using the first camera, wherein the first camera-to-ground transformation matrix relates a first coordinate system of the first camera to a ground coordinate system. A camera-to-camera transformation matrix is obtained between the first coordinate system of the first camera and a second coordinate system for the second camera. A constructed camera-to-ground transformation matrix is calculated for the second camera using the first camera-to-ground transformation matrix and the camera-to-camera transformation matrix. The second coordinate system is updated using the constructed camera-to-ground transformation matrix for the second camera.

In addition to one or more of the features described herein, updating the second coordinate system further includes extracting a roll angle from the constructed camera-to-ground transformation matrix, obtaining a motion vector and a normal vector from a second image obtained using the second camera, and rotating the motion vector and the normal vector using the roll angle to generate a rotated motion vector. The method further includes generating a pitch angle and a yaw angle using the rotated motion vector and a rotated normal vector. The method further includes determining a first bird's eye view image for the first image and a second bird's eye view image for a second image from the second camera and aligning the first bird's eye view image to the second bird's eye view image. Aligning the first bird's eye view image to the second bird's eye image view further includes running an optimization program on overlapping regions of the first bird's eye view image and the second bird's eye view image. The method further includes running the optimization program to determine a transformation matrix between the first bird's eye view image and the second bird's eye view image that minimizes a difference between a first intensity of a first pixel in the first bird's eye view image and a second intensity of a second pixel in the second bird's eye view image. The method further includes maturating the first camera-to-ground transformation matrix to generate a camera-to-vehicle transformation matrix for the first camera.

In another exemplary embodiment, a system for aligning a first camera of a vehicle and a second camera of the vehicle to a reference frame of the vehicle is disclosed. The system includes a processor configured to obtain a first camera-to-ground transformation matrix for the first camera using a first image obtained using the first camera, wherein the first camera-to-ground transformation matrix relates a first coordinate system of the first camera to a ground coordinate system, obtain a camera-to-camera transformation matrix between the first coordinate system of the first camera and a second coordinate system of the second camera, calculate a constructed camera-to-ground transformation matrix for the second camera using the first camera-to-ground transformation matrix and the camera-to-camera transformation matrix, and update the second coordinate system of the second camera using the constructed camera-to-ground transformation matrix for the second camera.

In addition to one or more of the features described herein, the processor is further configured to extract a roll angle from the constructed camera-to-ground transformation matrix, obtain a motion vector and a normal vector from a second image obtained using the second camera, and rotate the motion vector and the normal vector using the roll angle to generate a rotated motion vector. The processor is further configured to generate a pitch angle and a yaw angle using the rotated motion vector and a rotated normal vector. The processor is further configured to determine a first bird's eye view image for the first image and a second bird's eye view image for a second image from the second camera and align the first bird's eye view image to the second bird's eye view image. The processor is further configured to run an optimization program on overlapping regions of the first bird's eye view image and the second bird's eye view image to align the first bird's eye view image to the second bird's eye view image. The processor is further configured to run the optimization program to determine a transformation matrix between the first bird's eye view image and the second bird's eye view image that minimizes a difference between a first intensity of a first pixel in the first bird's eye view image and a second intensity of a second pixel in the second bird's eye view image. The processor is further configured to maturate the first camera-to-ground transformation matrix to generate a camera-to-vehicle transformation matrix for the first camera.

In yet another exemplary embodiment, a vehicle is disclosed. The vehicle includes a first camera for obtaining a first image, the first camera having a first coordinate system, a second camera having a second coordinate system, and a processor. The processor is configured to obtain a first camera-to-ground transformation matrix for the first camera using the first image, wherein the first camera-to-ground transformation matrix relates the first coordinate system to a ground coordinate system, obtain a camera-to-camera transformation matrix between the first coordinate system of the first camera and the second coordinate system of the second camera, calculate a constructed camera-to-ground transformation matrix for the second camera using the first camera-to-ground transformation matrix and the camera-to-camera transformation matrix, and update the second coordinate system of the second camera using the constructed camera-to-ground transformation matrix.

In addition to one or more of the features described herein, the processor is further configured to extract a roll angle from the constructed camera-to-ground transformation matrix, obtain a motion vector and a normal vector from a second image obtained using the second camera, and rotate the motion vector and the normal vector using the roll angle to generate a rotated motion vector. The processor is further configured to generate a pitch angle and a yaw angle using the rotated motion vector and a rotated normal vector. The processor is further configured to determine a first bird's eye view image for the first image and a second bird's eye view image for a second image from the second camera and align the first bird's eye view image to the second bird's eye view image. The processor is further configured to run an optimization program on overlapping regions of the first bird's eye view image and the second bird's eye view image to align the first bird's eye view image to the second bird's eye view image. The processor is further configured to run the optimization program to determine a transformation matrix between the first bird's eye view image and the second bird's eye view image that minimizes a difference between a first intensity of a first pixel in the first bird's eye view image and a second intensity of a second pixel in the second bird's eye view image.

The above features and advantages, and other features and advantages of the disclosure are readily apparent from the following detailed description when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features, advantages and details appear, by way of example only, in the following detailed description, the detailed description referring to the drawings in which:

FIG. **1** shows a vehicle schematically in plan view in an exemplary embodiment;

FIG. **2** shows an image obtained from a camera of the vehicle, in an illustrative embodiment;

FIG. **3** shows a pair of images illustrating a method of extracting a camera-to-camera transformation matrix;

FIG. **4** is a diagram illustrating a rotated motion vector within a coordinate system;

FIG. **5** shows a flowchart of a method for aligning cameras of a vehicle using the method discussed in FIGS. **2-4**;

FIG. **6** shows a flowchart of a method for aligning cameras of the vehicle using multi-camera optimization;

FIG. **7** shows a collection of bird's eye view images associated with multiple cameras of the vehicle;

FIG. **8** shows a flowchart of a method for checking a robustness of transformation matrix parameters;

FIG. **9** shows a flowchart for camera-to-vehicle alignment using the methods disclosed herein; and

FIG. **10** shows a flowchart of a method for camera alignment, in an illustrative embodiment.

DETAILED DESCRIPTION

The following description is merely exemplary in nature and is not intended to limit the present disclosure, its application or uses. It should be understood that throughout the drawings, corresponding reference numerals indicate like or corresponding parts and features.

In accordance with an exemplary embodiment, FIG. **1** shows vehicle **100** schematically in plan view. The vehicle **100** can be an autonomous vehicle or a vehicle operating in a suitable cruise control mode. The vehicle **100** includes a front camera **102**, a rear camera **104**, a left side camera **106** and right-side camera **108**. The selection of four cameras is for illustrative purposes only. It is understood that any number of cameras can be arranged on the vehicle **100**.

Each camera has an associated coordinate system that defines a reference frame for the camera. Front coordinate system **122** is associated with front camera **102**. Rear coordinate system **124** is associated with rear camera **104**. Left coordinate system **126** is associated with left side camera **106**. Right coordinate system **128** is associated with right-side camera **108**. The vehicle **100** can also have an associated vehicle-centered coordinate system **130**. Similarly, a ground-centered coordinate system **132** defines a reference frame of the ground or terrain outside of the vehicle **100**.

For each camera's coordinate system, the z-axis generally extends away from the camera along the principal axis of the camera and the y-axis points toward the ground. The coordinate systems are right-handed. Thus, for the front camera **102**, the x-axis extends to the right of the vehicle, for the rear camera **104**, the x-axis extends to the left of the vehicle, for the left side camera **106**, the x-axis extends to the front of the vehicle, and for the right-side camera **108**, the x-axis extends to the rear of the vehicle. The coordinate systems shown in FIG. **1** are for illustrative purposes only. In various embodiments, the axes of the coordinate systems can be selected based on the needs or desires of the manufacturer.

Each camera is in communication with a controller **110** of the vehicle. The controller **110** may include processing circuitry that may include an application specific integrated circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group) and memory that executes one or more software or firmware programs, a combinational logic circuit, and/or other suitable components that provide the described functionality. The controller **110** may include a non-transitory computer-readable medium that stores instructions which, when processed by one or more processors of the controller **110**, implement a method of aligning the coordinate systems of the cameras with each other according to one or more embodiments detailed herein.

Each camera can capture one or more images and send the one or more images to the controller **110** for processing. The controller **110** determines a transformation matrix between reference frames and can be used to align the coordinate system of one or more cameras to the vehicle's reference frame. The transformation matrix can be between a coordinate system of a first camera and a coordinate system of a second camera, between a coordinate system of a camera and the vehicle-centered coordinate system or between a coordinate system of a camera and the ground-centered coordinate system. The controller **110** can then use information based on an object present in images from multiple cameras and as understood through the aligned coordinate systems to perform various operations.

FIG. **2** shows an image **200** obtained from a camera of the vehicle **100**, in an illustrative embodiment. For illustrative purposes, the image **200** is from the front camera **102** and includes a view of an area in front of the vehicle **100**. By obtaining multiple images during motion of the vehicle **100**, the controller **110** determines a motion vector **202** that indicates a direction of motion of the vehicle. The controller **110** also determines a ground normal vector **204** extending perpendicular to the ground using the multiple images. From the ground normal vector **204** and the motion vector **202**, a transformation matrix can be determined between the camera-based coordinate system for the front camera **102** (front coordinate system **122**) and the ground-centered coordinate system **132**. The camera-to-ground transformation matrix may be referred to herein as T_{C2G}.

FIG. **3** shows a pair of images **300** illustrating a method of extracting a camera-to-camera transformation matrix. The pair of images **300** includes first image **302** obtained from a first camera and a second image **304** obtained from a second camera. For illustrative purposes. The first image **302** is a front view image obtained using the front camera **102** and the second image **304** is a left side image obtained using the left side camera **106**. Because the fields of view of the cameras overlap, an object **306** can be located within each of the first image **302** and the second image **304**. The controller **110** can locate and identify features of the object **306** in each of the first image **302** and the second image **304** and generate feature pairs between a feature in one image and the same feature in another image. Several feature pairs are shown and represented by connecting lines **308**. Once the feature pairs have been generated, the controller **110** can use the feature pairs to extract a camera-to-camera transformation matrix between the first camera (e.g., the front camera **102**) and the second camera (e.g., the left side camera). The camera-to-camera transformation matrix may be referred to herein at T_{C2C}.

FIG. **4** is a diagram **400** illustrating a rotated motion vector **404** within a coordinate system **402**. The coordinate system **402** includes the x-axis, y-axis and z-axis. A rotated motion vector **404** is shown within the coordinate system **402**. The rotated motion vector **404** is a result of rotation of an original motion vector by a rotation through a roll angle (i.e., about the x-axis). The rotation can be through a roll angle that aligns a ground normal vector within the first image with the ground normal vector within the second image. The original motion vector is located within an image from a camera that is associated with the coordinate system **402**. Once the original motion vector has been rotated to generate the rotated motion vector **404**, a pitch angle and yaw angle can be determined using the rotated motion vector. Referring to FIG. **4**, coordinates (x, z) are coordinates of the rotated motion vector **404** along the X-axis and Z-axis, respectively, of the coordinate system **402**. A pitch angle θ can be determined from these coordinates, as shown in Eq. (1):

$$\theta = \arctan(z/x) \qquad \text{Eq. (1)}$$

It is noted that when the coordinate system **402** is that of a side camera of the vehicle, the rotated motion vector **404** lies close to the X-axis after the roll rotation. Thus, the related x-coordinate is large enough so that the pitch angle calculated using Eq. (1) does not suffer from inaccuracies due to small values of x. however, when the coordinate system **402** is that of a front (or rear) camera, the motion vector lies close to the Y-axis. As a result, the value for the x-coordinate can be small, which can introduce inaccuracies into the calculation of pitch.

Line OD is a projection of the rotated motion vector **404** into the XY plane. Coordinates (x', y') are coordinate of the line OD along the X-axis and Y-axis, respectively, of the coordinate system **402**. A yaw angle ψ can be determined from these coordinates, as shown in Eq. (2):

$$\psi = -\arctan(y'/x') = -\arcsin(y') \qquad \text{Eq. (2)}$$

The roll angle, pitch angle and yaw angle are thus able to be used to generate a transformation matrix for the coordinate system based on the motion vector.

The roll angle is generally constructed using a first image from a first camera while the coordinate system shown in FIG. **4** is that of a second camera. The rotation of the motion vector aligns the motion vector as seen in the first image with the motion vector as second in a second image from the second camera.

FIG. **5** shows a flowchart **500** of a method for aligning cameras of a vehicle using the method discussed in FIGS. **2-4**. In box **502**, a camera-to-ground transformation matrix $[T_{C2G}]_1$ is determined for a first camera (e.g., a front camera) using a first image obtained from the first camera. In box **504**, a camera-to-camera transformation matrix $[T_{C2C}]$ is extracted between the first camera and a second camera (e.g., left side camera). In box **506**, the camera-to-ground transformation matrix for the first camera and the camera-to-camera transformation matrix between the first camera and the second camera are used to generate a constructed camera-to-ground transformation matrix for the second camera $[T_{C2G}]_2$.

In box **508**, the roll angle is extracted from the constructed camera-to-ground transformation matrix for the second camera generated in box **506**.

In box **510**, a motion vector is extracted from within a second image obtained at the second camera. In box **512**, the motion vector is rotated through the roll angle to generate the rotated motion vector **404**. In box **514**, pitch and yaw angles are determined based on the rotated motion vector **404**. In box **516**, a modified rotation transformation matrix is formed using the roll, pitch and yaw angles. The modified rotation transformation matrix can be used to adjust the second camera, thereby aligning the coordinate system of the second camera to the coordinate system of the first camera.

FIG. **6** shows a flowchart **600** of a method for aligning cameras of the vehicle using multi-camera optimization (MCO). In box **602**, an image is received from N cameras, where N is an integer greater than one. In box **604**, a check is made as to whether the images from the N cameras are synchronized to each other such that images that are meant to be obtained at the same time are indeed obtained at the same time. If the images are not synchronized, the method can return to box **602**. Otherwise, the method proceeds to box **606**. In box **606**, the images are cropped or downsized in a pre-processing step. In box **608**, the images are stored in a running buffer. The images can be saved until a selected time period has elapsed or until a selected number of the images have been obtained.

In box **610**, after the time period has elapsed, a check is made as to whether enough images have been accumulated during this time period. If the number of images is less than a threshold value, the method returns to box **602** for collection of more images. Otherwise, the method proceeds to box **612**. In box **612**, the buffered images are loaded into a program. In box **614**, the camera-to-ground transformation for each of the cameras are loaded into the program. In box **616**, the camera-to-ground transformations are applied to their respective images to obtain bird's eye view images for each of the images from the cameras.

In box **618**, an optimization algorithm is performed on the bird's eye view images in order to align the bird's eye view images to each other. The optimization algorithm adjusts the spatial relation between the bird's eye views, to determine a camera-to-camera transformation matrix between them. In an embodiment, the optimization algorithm determines a transformation matrix between a first bird's eye view image and a second bird's eye view image using regions of overlap between the first bird's eye view image and the second bird's eye view image. In box **620**, the transformation vector obtained using the optimization process is used to update alignment results.

FIG. 7 shows a collection of bird's eye view images **700** associated with multiple cameras of the vehicle, illustrating a multi-camera optimization method for aligning cameras. The collection of bird's eye view images **700** includes a first set **702** of four bird's eye view (BEV) images in which the images are unaligned. A second set **704** of four BEV images shows the four BEV images of the first set **702** in an aligned state (i.e., after a determined transformation matrix has been applied). The first set **702** and second set **704** both include a front BEV image **706**, a right side BEV image **708**, a rear BEV image **710** and a left side BEV image **712**. Adjacent BEV images have overlapping regions. Blank region **705** is a blind spot representing the location of the vehicle **100**.

The optimization algorithm (box **618**, FIG. **6**) is used to determine the transformation matrix. In the optimization algorithm, a cost function is generated using the values of pixel intensities of pixels in overlapping regions of the images (e.g., overlapped regions of the front BEV image **708** and the right side BEV image **710**, overlapped regions of the first BEV image **710** and the second BEV image **712**, etc.). The optimization algorithm adjusts transformation parameters (i.e., pitch, roll, yaw) between adjacent BEV images to locate those transformation parameters for which the cost function reaches a minimum, as shown in Eq. (3):

$$\hat{T} = \underset{T}{\operatorname{argmin}} \sum\nolimits_{i=1}^{N} \sum\nolimits_{j=1}^{M} \sum\nolimits_{k=1}^{P} \operatorname{abs}\left(I^1_{i,j,k,f_{T(C_1)}} - I^2_{i,j,k,f_{T(C_2)}}\right) \qquad \text{Eq. (3)}$$

where T is a camera to vehicle transformation, I is the pixel intensity, i is the index of images, j is the index of common area, k is the index of pixels in the common area, C is the camera, and f is a mapping from the original image to the bird's eye view image.

As an example, feature **720** is shown in both the first set **702** and the second set **704**. The feature **706** occurs in an overlap region between the front BEV image **706** (for the front camera) and a second BEV image **708** (for the right-side camera). In the first set **702**, a discontinuity appears in the feature **720** at an intersection between the front BEV image **706** and the right side BEV image **708**. In the second set **704**, the discontinuity has disappeared or been reduced.

FIG. **8** shows a flowchart **800** of a method for checking a robustness of a transformation matrix parameters. For illustrative purposes, a vehicle-to front camera transformation is represented by transformation matrix ${}_F^V T$ and a vehicle-to-left side camera transformation is represented by transformation matrix ${}_L^V T$. These two matrices can be combined to construct a vehicle camera-to-camera transformation between the front camera and the left side camera, as shown in Eq. (4):

$${}_L^F T = {}_F^V T^{-1} {}_L^V T \qquad \text{Eq. (4)}$$

where ${}_L^F T$ is the constructed transformation matrix between the front camera and the left side camera. Each transformation matrix can be written as a collection of a rotation matrix R and a translation matrix t, where:

$$T = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \qquad \text{Eq. (5)}$$

The rotation matrix R can be written in terms of pitch, roll and yaw angles as shown in Eq. (6):

$$R = \begin{bmatrix} \cos\theta * \cos\psi & \cos\theta * \sin\psi & -\sin\theta \\ \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi & \sin\varphi\sin\theta\sin\psi + \cos\varphi\cos\psi & \sin\varphi\sin\theta \\ \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi & \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi & \cos\varphi\cos\theta \end{bmatrix}. \qquad \text{Eq. (6)}$$

where θ is a pitch angle, φ is a roll angle and ψ is a yaw angle.

In box **802**, a first camera to ground transformation matrix (${}_F^V T$) is obtained for a first camera. In box **804**, a second camera to ground transformation matrix (${}_L^V T$) is obtained for a second camera. In box **806**, a constructed camera-to-camera transformation matrix ${}_L^F T$ is obtained between the first camera and the second camera.

In box **808**, the first camera to ground transformation matrix (${}_F^V T$) and the second camera to ground transformation matrix (${}_L^V T$) are used to determine a constructed camera to camera transformation matrix (${}_L^F T'$) (using Eq. (6)). In box **810**, the Euler angles (pitch', roll', yaw') and the translation vector t' are obtained from the constructed camera-to-camera transformation matrix (${}_L^F T'$). In box **812**, Euler angles (pitch, roll, yaw) and the translation vector t are obtained from the camera-to-camera transformation matrix ${}_F^L T$ obtained in box **806**.

In box **814**, the two sets of Euler angles are compared to each other. If the difference between the Euler angles is greater than a selected threshold, the method returns to boxes **802**, **804** and **806** to obtain new matrices. Otherwise, in box **814**, if the difference between the Euler angles is less than the selected threshold the method proceeds to box **816**. In box **816**, the results (i.e., the Euler angles or one of the Euler angles) are published.

FIG. **9** shows a flowchart **900** for camera-to-vehicle alignment using the methods disclosed herein. In box **902** a set of first images is obtained using a first camera, such as one or both of a front camera or a rear camera. The first images are obtained over a selected time period. In box **904**, a plurality of camera-to-ground alignment matrices are determined for the first camera using the set of first images. In box **906**, a maturation process is applied to the set of camera-to-ground matrices. In an illustrative maturation process, a maturated camera-to-ground matrix is created using a moving average of the set of matrices. Thus, the process of obtaining images and determining camera-to-ground matrices is a continuous process. Other maturation methods can be used in alternative embodiments. In box **908**, the maturated camera-to-ground matrix is used to produce a stable camera-to-vehicle alignment matrix for the first camera.

Meanwhile, in box **910**, a set of second images is obtained using a second camera, such as one or both of a left side camera and a right-side camera. The second set of images is obtained over the selected time period. In box **912**, a plurality of camera-to-ground alignment matrices are determined from the second camera using the set of second images.

In box **914**, camera-to-camera transformation matrices are calculated using the set of first images and the set of second images. Each camera-to-camera transformation matrix is calculated using a first image and a second image that are synchronized or taken simultaneously or near simultaneously. In box **916**, a maturation process is applied to the plurality of camera-to-camera transformation matrices to create a maturated camera-to-camera transformation matrix. In box **918**, an adjustment matrix is determined for the second camera, using both the results of box **912** (the camera to ground matrix for the second camera) and the results of box **916** (the maturated camera-to-camera transformation matrix). In box **920**, a maturation process is applied to the adjustment matrices of box **918**. In box **922**, the maturated adjustment matrix is used to produce a stable camera-to-vehicle alignment matrix for the second camera.

Meanwhile, in box **924**, the multi-camera optimization process is performed on at least the first images from the first camera(s) and the second images from the second camera(s). In box **926**, the results of the multi-camera optimization can be maturated to produce a maturated transformation matrix between the first camera and the second camera. In box **928**, the maturated transformation matrix can be used to generate stable camera-to-camera alignment matrices (i.e., generated based on the bird's eye view images).

The maturated camera-to-camera values obtained in box **916** can be used during the calculation of the stable camera-to camera values obtained in box **928**. Also, the stable camera-to-vehicle alignment matrices for the front and rear cameras and the stable camera-to-vehicle alignment matrices for the left side and ride side camera that are obtained in boxes **908** and **922**, respectively, can be used in subsequent multi-camera optimization processes in box **924**. Also, the stable camera-to-camera alignment matrices that are obtained in box **928** can be used in subsequent calculations of the side camera adjust matrix (in box **918**).

In box **930**, a maturation process can be used on the results of boxes **908**, **922** and **928**. In box **932**, the results of the maturation process are published to the vehicle, which can be used in box **934** to control subsequent perception and motion planning operations of the vehicle.

FIG. **10** shows a flowchart **1000** of a method for camera alignment, in an illustrative embodiment. In box **1002**, a camera to ground alignment process (FIG. **2**) is used to extract a motion vector and a ground normal vector from an image obtained at the first camera to form an alignment matrix for the first camera. The alignment matrix is maturated the maturated alignment matrix is used generate an initial camera-to-vehicle transformation matrix for the first camera. In box **1004**, a camera-to-camera algorithm (FIG. **3**) is used to extract camera-to-camera transformation matrix between the first camera and the second camera. In box **1006**, the camera-to-camera transformation matrix is used to correct an alignment of the second camera. In box **1008**, the multi-camera optimization is performed to generate final camera-to-vehicle transformation matrices.

The terms "a" and "an" do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item. The term "or" means "and/or" unless clearly indicated otherwise by context. Reference throughout the specification to "an aspect", means that a particular element (e.g., feature, structure, step, or characteristic) described in connection with the aspect is included in at least one aspect described herein, and may or may not be present in other aspects. In addition, it is to be understood that the described elements may be combined in any suitable manner in the various aspects.

When an element such as a layer, film, region, or substrate is referred to as being "on" another element, it can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly on" another element, there are no intervening elements present.

Unless specified to the contrary herein, all test standards are the most recent standard in effect as of the filing date of this application, or, if priority is claimed, the filing date of the earliest priority application in which the test standard appears.

Unless defined otherwise, technical and scientific terms used herein have the same meaning as is commonly understood by one of skill in the art to which this disclosure belongs.

While the above disclosure has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from its scope. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the disclosure without departing from the essential scope thereof. Therefore, it is intended that the present disclosure not be limited to the particular embodiments disclosed, but will include all embodiments falling within the scope thereof.

What is claimed is:

1. A method of aligning a first camera of a vehicle and a second camera of the vehicle to a reference frame of the vehicle, comprising:

obtaining a first camera-to-ground transformation matrix for the first camera using a first image obtained using the first camera, wherein the first camera-to-ground transformation matrix relates a first coordinate system of the first camera to a ground coordinate system;

extracting a first ground normal vector from the first image;

obtaining a second camera-to-ground transformation matrix for the second camera using a second image obtained using the second camera, wherein the second camera-to-ground transformation matrix relates a second coordinate system of the second camera to a ground coordinate system;

extracting a second ground normal vector from the second image;

obtaining a camera-to-camera transformation matrix between the first coordinate system of the first camera and the second coordinate system for the second camera by determining a roll angle that aligns the first ground normal vector with the second ground normal vector;

obtaining a motion vector from the second image;

rotating the motion vector within the second coordinate system using the roll angle to generate a rotated motion vector;

determining a pitch angle and a yaw angle from the rotated motion vector; and

calculating a modified camera-to-ground transformation matrix for the second camera using the roll angle, the pitch angle and the yaw angle.

2. The method of claim **1**, further comprising rotating the first image to obtain a first bird's eye view image, rotating the second image to obtain a second bird's eye view image, and aligning the first bird's eye view image to the second bird's eye view image.

3. The method of claim **2**, wherein aligning the first bird's eye view image to the second bird's eye view image further comprises running an optimization program on overlapping regions of the first bird's eye view image and the second bird's eye view image.

4. The method of claim **3**, further comprises running the optimization program to determine a transformation matrix between the first bird's eye view image and the second bird's eye view image that minimizes a difference between a first intensity of a first pixel in the first bird's eye view image and a second intensity of a second pixel in the second bird's eye view image.

5. The method of claim 1, further comprising maturating the first camera-to-ground transformation matrix to generate a camera-to-vehicle transformation matrix for the first camera.

6. The method of claim 1, wherein the first camera is a front camera of the vehicle and the second camera is one of: (i) a left side camera; and (ii) a right side camera.

7. The method of claim 1, further comprising synchronizing the first image with the second image.

8. A system for aligning a first camera of a vehicle and a second camera of the vehicle to a reference frame of the vehicle, comprising:

a processor configured to:

obtain a first camera-to-ground transformation matrix for the first camera using a first image obtained using the first camera, wherein the first camera-to-ground transformation matrix relates a first coordinate system of the first camera to a ground coordinate system;

extract a first ground normal vector from the first image;

obtain a second camera-to-ground transformation matrix for the second camera using a second image obtained using the second camera, wherein the second camera-to-ground transformation matrix relates a second coordinate system of the second camera to a ground coordinate system;

extract a second ground normal vector from the second image;

obtain a camera-to-camera transformation matrix between the first coordinate system of the first camera and the second coordinate system of the second camera by determining a roll angle that aligns the first ground normal vector with the second ground normal vector;

obtain a motion vector from the second image;

rotate the motion vector within the second coordinate system using the roll angle to generate a rotated motion vector;

determine a pitch angle and a yaw angle from the rotated motion vector; and

calculate a modified camera-to-ground transformation matrix for the second camera using the roll angle, the pitch angle and the yaw angle.

9. The system of claim 8, wherein the processor is further configured to rotate the first image to obtain a first bird's eye view image, rotate the second image to obtain a second bird's eye view image, and align the first bird's eye view image to the second bird's eye view image.

10. The system of claim 9, wherein the processor is further configured to run an optimization program on overlapping regions of the first bird's eye view image and the second bird's eye view image to align the first bird's eye view image to the second bird's eye view image.

11. The system of claim 10, wherein the processor is further configured to run the optimization program to determine a transformation matrix between the first bird's eye view image and the second bird's eye view image that minimizes a difference between a first intensity of a first pixel in the first bird's eye view image and a second intensity of a second pixel in the second bird's eye view image.

12. The system of claim 8, wherein the processor is further configured to maturate the first camera-to-ground transformation matrix to generate a camera-to-vehicle transformation matrix for the first camera.

13. The system of claim 8, wherein the first camera is a front camera of the vehicle and the second camera is one of: (i) a left side camera; and (ii) a right side camera.

14. The system of claim 8, wherein the processor is further configured to synchronize the first image with the second image.

15. A vehicle, comprising:

a first camera for obtaining a first image, the first camera having a first coordinate system;

a second camera having a second coordinate system;

a processor configured to:

obtain a first camera-to-ground transformation matrix for the first camera using the first image, wherein the first camera-to-ground transformation matrix relates the first coordinate system to a ground coordinate system;

extract a first ground normal vector from the first image;

obtain a second camera-to-ground transformation matrix for the second camera using a second image obtained using the second camera, wherein the second camera-to-ground transformation matrix relates a second coordinate system of the second camera to a ground coordinate system;

extract a second ground normal vector from the second image;

obtain a camera-to-camera transformation matrix between the first coordinate system of the first camera and the second coordinate system of the second camera by determining a roll angle that aligns the first ground normal vector with the second ground normal vector;

obtain a motion vector from the second image;

rotate the motion vector within the second coordinate system using the roll angle to generate a rotated motion vector;

determine a pitch angle and a yaw angle from the rotated motion vector; and

calculate a modified camera-to-ground transformation matrix for the second camera using the roll angle, the pitch angle and the yaw angle.

16. The vehicle of claim 15, wherein the processor is further configured to rotate the first image to obtain a first bird's eye view image, rotate the second image to obtain a second bird's eye view image, and align the first bird's eye view image to the second bird's eye view image.

17. The vehicle of claim 16, wherein the processor is further configured to run an optimization program on overlapping regions of the first bird's eye view image and the second bird's eye view image to align the first bird's eye view image to the second bird's eye view image.

18. The vehicle of claim 17, wherein the processor is further configured to run the optimization program to determine a transformation matrix between the first bird's eye view image and the second bird's eye view image that minimizes a difference between a first intensity of a first pixel in the first bird's eye view image and a second intensity of a second pixel in the second bird's eye view image.

19. The vehicle of claim 15, wherein the first camera is a front camera of the vehicle and the second camera is one of: (i) a left side camera; and (ii) a right side camera.

20. The vehicle of claim 15, wherein the processor is further configured to synchronize the first image with the second image.

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